Dear Editor of Biogeosciences

We would like to thank the two reviewers for their careful reviews with constructive comments and criticism of our manuscript "Turbulence measurements suggest high rates of new production over the shelf edge in the north-eastern North Sea during summer". We have addressed all the issues raised by the reviewers in the revised manuscript. Our replies (in normal font) to the reviewers' comments (shown in italics) are found below.

In the revised manuscript, we have included a new figure (a new Figure 8 and the previous figure 8 is now moved to Supplementary figure S2) showing data from a timeseries station at the shelf edge. These data were requested by both reviewers and we find that it strengthens the paper because both spatial and temporal variability are now considered. In addition, we have included a new table (Table 2), as suggested by one of the reviewers, to show the distributions of the parameters across the shelf edge. Several figures have been amended with additional information (for example, nutrient distributions and satellite images, also requested by the reviewers). We have also added supplementary information describing statistical analyses of the data. The revised manuscript, thus, provides more detailed information on the observed distributions of turbulence and vertical nutrient flux. This information strengthens the conclusions from the paper, i.e., that processes occurring near the shelf edge are important for new production (NP) in the area.

I am looking forward to hearing from you.

Kind regards,
Jørgen Bendtsen

*Reviewer 1: The paper presents data from an intensive series of stations and transects in the eastern North Sea, reaching from the shelf into the Norwegian trench, to suggest that the edge of the shelf is a site of significantly higher new primary production compared to deeper and shallower regions. The results are certainly interesting, as this shelf edge region is relatively isolated from the open ocean and so is far less influenced by typical shelf edge processes (e.g. internal tides and breaking internal waves). The results appear to be generally sound, but there is a lack of detail in key areas that needs to be addresses.*

*General Points:*
*1. The turbulence data presented is incomplete. Sections on turbulence parameters are presented (Fig. 5), but there is almost no consideration of the typical temporal variability in turbulence. Were the microstructure stations single profiles? Normally turbulence data is collected over a series of profiles to try to capture the chaotic nature of mixing events, and I would expect to see turbulence present with confidence intervals reflecting any variability. Are tidal flows important here? In which case, was there any attempt to provide some average turbulence measurement over a tidal cycle? There is a short statement in the discussion that implies additional data was collected to indicate the amount of temporal variability – if that is the case, it should be included more explicitly in the paper. Also, there is very limited presentation of the nitrate flux data – one profile, and plots of the max flux along transects. A section of the fluxes would be very useful. The paper at times mentions quite strong fluxes below the SCM, which implies a divergence in nitrate flux that needs to be considered.*

Response:
We would like to thank the reviewer for a careful positive review with constructive comments and criticism of our manuscript.
The reviewer's concerns put in focus several important issues that we now address in more detail in the revised manuscript. Specifically, we have added more information from the two time series stations (T1, T2) which were only briefly described in the original version of the manuscript. We use time series data from T1 (and further details in Supplementary information and figure S1) to estimate the significance of the epsilon-estimates and for analyzing the temporal variability at the shelf edge. The time series data set includes 107 profiles made in three sequences at one site over a 22-hour period with a time interval of about 3 minutes. With this data set, we analyse the variability between the two simultaneous measurements from the two shear-sensors and we estimate the uncertainty associated with the differences between the two shear probe measurements. In the Supplementary Information we show that the differences are in qualitative accordance with a normal distribution characterized by the absolute deviation of the samples. This allows us to apply a quality criterion on the data included in the study, i.e., that the differences between sensor readings should be less than three times the absolute deviation. We apply this criterion to all of the measurements used in the study. A very limited number of measurements did not meet the criterion described above. This supports the validity of our approach of using the average value of the two shear probes from a single profile as providing a representative turbulence value for the stations visited on our transects. The relatively close station spacing on our transects as well as the spatial distribution also indicates a consistent distribution pattern for vertical mixing parameters in the area. In addition, we use the time series data from T1 to consider the temporal variation between subsequent profiles separated by only 3 minutes. These new analyses are described in the text in the revised manuscript and the details provided in the revised Supplementary Information section and in Supplementary figure 1.

Further information on spatial variability is also now included in figure 6, where the measurements from four stations, separated by 5 km, and made within four hours are presented. In addition, we

have added a new figure 8, as suggested by the reviewer, where data from the second time series station are analysed (this time series station was previously only described in the text). We also analyse temporal variability in water column characteristics in relation to tides and other energy sources. This analysis shows that increased mixing in the boundary layer is in phase with tidal energy input but also that energy from non-tidal currents may be important in this area. For example, a short-term change of T, S and O2 can be associated with advection of ambient water masses, i.e. not directly related to tidal flow.

Nitrate fluxes are now shown for four stations in figure 6 and the spatial distribution of the maximum nitrate flux is also now added to figure 7. Finally, average values for nitrate concentration in three depth intervals are presented in the new Table 2.

*Reviewer 1: 2. The discussion is somewhat unsatisfactory. Quite a broad range of alternative processes are suggested as underpinning some of the observations, but they are often vague and rather descriptive. Some better quantification of these would help to determine how likely they are as playing important roles.*

Response: We believe that explaining the observed distributions of, for example, nitrate, in our study requires knowledge of seasonal nutrient dynamics in this area that we do not have. Therefore, our considerations of nutrient distributions are to some extent qualitative and we refer to previous studies to provide background information on these aspects. Nevertheless, we have now considered the specific points raised by the reviewer below and clarified the considerations in the Discussion section.

*Reviewer 1: For instance:*
*(i) On page 12 denitrification is suggested as a mechanism for reducing the shallow water nitrate, with a global mean rate from Yool 2007 mentioned. There are shelf/coastal estimates available, and a quick calculation could be done to assess the feasibility of this process.*

Response: We originally referred to the global nitrification rate of Yool et al. (2007) to explain the potential for recycling of ammonium in the water column. In this revised version of the manuscript, we have also included a reference from Fan et al. (2015) on denitrification rates and show that the apparent loss of nitrate recorded here could be explained by these rates.

*Reviewer 1: (ii) The mechanism for the elevated turbulence at the shelf edge is never discussed. It seems to be a boundary-layer process – is it due to a slope current or tides? Also, the boundary turbulence seems fairly consistent along the transect (e.g. Fig. 5c) – so is the shelf edge nitrate flux really a result of increased turbulence, or is it because the sloping isopycnals bring the nutricline down towards the turbulence (almost implied on page 15). The latter idea seems to be suggested by Fig. 9 (though without better information on the turbulence data, I'm not convinced that the bed turbulence over the shelf edge is significantly greater than bed-driven turbulence elsewhere – in which case the deepening of the nutricline is vital).*

Response: The reviewer's points here are in accordance with our understanding of the processes at the shelf edge. We have added more material to clarify and support this point. A figure has been added (Fig. 8) showing the temporal variability at the shelf edge where mixing in the bottom boundary layer is seen to increase and elevated mixing in periods reaches the bottom of the euphotic zone. Thus, interference between a deep nutricline and bottom mixing may provide a mechanism for enhancing diapycnal nitrate fluxes. We have also added Table 2 in which it is shown that the nutricline is significantly deeper above the shelf edge than in the deeper areas. This is also seen in figure 2d (where we have added the nitrate concentration along Tr4) and shown in figure 3 (where

we have added isopycnals to illustrate the link between the nutricline, chlorophyll and the density fields) and in the conceptual figure 9. Thus, the deepening of the nutricline, together with increased mixing in the bottom boundary layer, is probably an important mechanism for the elevated nutrient fluxes above the shelf edge. We speculate on this in the Discussion, in particular in relation to figure 9 where the potential dynamic feedback between currents along the shelf-edge, the depth of the nutricline and nutrient fluxes into the euphotic zone is outlined. Thus, this proposed mechanism is, indeed, a result of the deepening of the nutricline and elevated mixing above the shelf edge area.

*Reviewer 1: (iii) Isopycnal transport of organic material is suggested as a way of supplying nutrients (page 13), but is not estimated in any way – some reasonable numbers would help in determining its likely use.*

Response: It is difficult to provide better information than the time scales for the decay of organic matter we describe in the text. The relevant time scales are of the order days to weeks and we refer to a previous study where we analysed these time scales; Thus, even small cross-shelf transports may contribute with isopycnal fluxes. However, we do not have any measurements of the labile fraction of organic matter in the area. In addition, we have only limited information on the cross-shelf exchange. So, rather than speculating further on this issue, we prefer to relate to the information on the time scales described in the text.

*Reviewer 1: (iv) On page 15, "other transport processes" apart from vertical turbulent mixing are required, and motility of phytoplankton is suggested. This again is rather vague – why not quantify the possibility (e.g. use the turbulence data and an estimate of phytoplankton swimming speed to get a Peclet number)?*

Response: We have now added an example at the end of Section 4.4, based on swimming speeds of dinoflagellates (Raven and Richardson,1984), to illustrate the potential of diel vertical migration to provide access to nutrients. In addition, we now also estimate the associated Peclet number in the area north of the shelf edge where vertical diffusion coefficients are very low and show that Pe >> 1.

*Reviewer 1: (v) A link to a coastal bloom off Norway, seen in a MODIS image, is invoked on page 15. Why not show this image, rather than simply assert its likely relevance based on the proximity of the sampling?*

Response: We have followed this suggestion and added the MODIS-derived fields of chlorophyll a and SST in figures 1a and 1b, respectively. We refer to the satellite images in the discussion.

*Reviewer 1:*
Specific Points:
*1. Page 2 line 7 (also discussion, page 11 line 29): Linking localised NP to higher trophic levels needs to be more nuanced that implying a simple "more production leads to more fish". Scott et al note that the increased chl arises due to internal wave mixing, and the internal waves might also affect prey aggregation – i.e. the correlation with chl is not causal, but chl and prey aggregation are both a result of internal waves.*

Response: We have clarified the paragraph. We agree with the view that Scott et al related increased NP to increased mixing, and this was also the intention with the paragraph.

*Reviewer 1: 2. The introduction/background is very much focused on the North Sea. However, the issues being investigated have much broader significance – it would raise the profile and readership of the paper if a stronger, broader context was provided rather than such a localised*

*one.*

Response: We have followed the suggestion by the reviewer and added a paragraph in the end of the Introduction where we relate to the more general implications of shelf-edge processes and to conditions in similar shelf-regions.

*Reviewer 1: 3. Page 3, line 18: a 1 km station spacing was used (which is impressive), bit how does that fit alongside the tidal excursion?*

Response: A rough estimate of the tidal excursion, based on SST-evolution in forecast models of the North Sea, is ~5 km, and this has to be considered when samples from closely spaced stations are analyzed. The station spacing was gradually decreased along a section of Tr2 for analyzing sub-mesoscale changes in plankton communities. This aspect is not the focus of this study and, therefore, not discussed further in this manuscript.

*Reviewer 1: 4. Page 4, line 10. The mixing efficiency is assumed to be constant, but there's a good deal of recent literature that suggests this is not the case (e.g. Shih et al., J. Fluid Mechanics, 525, 193-214, 2005; Bouffard & Beogman, Dynamics of Atmospheres and Oceans, 61, 14-34, 2013). Both provide a way of estimating efficiency knowing the turbulence intensity – I suspect that the region of data in this N Sea study probably sits where efficiency = 0.2, but it would be good to check this.*

Response: The reviewer's comments have now been considered. We have added a paragraph in the Methods section where we show that the range where a constant mixing efficiency of 0.2 is valid encompasses the values we apply in the calculation of the nutrient fluxes into the euphotic zone. We have also added the two references brought to our attention by the reviewer.

*Reviewer 1: 5. Page 4, line 16: "the depth of the SCM was sampled" – do this mean the peak of the SCM?*

Response: Yes, and we have added a comment to clarify this.

*Reviewer 1: 6. Page 4, line 20. Nutrient analyses are mentioned, but no methods – I assume standard methods, but at least cite the usual papers.*

Response: We have added more information on the nutrient analysis and included a reference to Grasshoff et al. (1983).

*Reviewer 1: 7. Page 4 line 25: Why assume that the deep fluorescence signal is not chlorophyll? If you have boundary-driven turbulence acting at the base of the SCM and nutricline then it will draw chl down into the deeper water.*

Response: The background value was determined from a deep station (522 m) where a relatively constant fluorescence value was observed between 100 m and 500 m. We see no reason to assume that chlorophyll would be uniformly distributed throughout this deep layer. Therefore, we treated this relatively small background fluorescence as being derived from an unknown source and it was subtracted from the fluorescence signal before the calibration. We have reformulated the sentence to clarify this.

*Reviewer 1: 8. Page 5, lines 14-17. I'm not sure why this scaling of observed PAR to the MODIS product was done.*

Response: We have added "during the day" to clarify this. The integral in Eq. 3 includes the daily variation of the insolation and this influences the integrated primary production significantly because of the non-linear terms in the equation. It has also been clarified by adding the time and depth dependence, i.e. (t,z), of the variables in the integral.

*Reviewer 1: 9. Page 6, line 25-26: The assumption of Redfield is a critical part of the results of the paper. Some justification needs to be made to show that the assumption is OK, or to indicate the likely variability of C:N.*

Response: The Redfield ratio is characterized by a C:N ratio of 106:16, and this ratio is widely used in observational and model studies, although variation of the ratio is known to occur. Thus, applying a constant ratio introduces an additional error-source in the calculations. We have added the original reference of Redfield et al. (1963) where a general relationship between the elemental stoichiometry of C:N:P in plankton is documented.

*Reviewer 1: 10. Page 7, lines 3-5. I struggled to decipher this sentence, please clarify.*

Response: We have clarified the introductory sentences.

*Reviewer 1: 11. Page 7, lines 17-20. Re-phrase – this is a very long sentence with inconsistent use of brackets.*

Response: We have reformulated the sentence.

*Reviewer 1: 12. Page 9, line 14. The highest nitrate flux is reported at a depth below the photic zone. This implies some divergence of the nitrate flux – where does it go if there is no sink for it?*

Response: To answer this question, we would need more measurements from the area around the station and in the boundary layer. There is a temporal change, likely associated with the tidal currents, as shown in the new figure 8. Figure 6 in the original manuscript has now been replaced with a section showing more profiles taken across the shelf edge at Tr4 obtained over a short period. However, the divergence is likely associated with transient currents and an example of this is now shown and discussed in relation to the time series station in the new figure 8.

*Reviewer 1: 13. Page 9, lines 26-30. I'm not convinced that the chl-normalised production rates are useful. Chl per cell in the SCM is likely to be higher than in the surface, so comparing chl-normalised parameters does not tell us much. Or does it and I have missed the point? Normalised per cell or per C would make sense (though not clear this is possible).*

Response: Primary production is, as here, frequently calculated from the model of Platt et al. (1980) in Eq. 3. We have clarified this procedure by adding the integral over the vertical depth range (from the bottom of the euphotic zone to the surface) and during the day (24h, i.e. only daytime PAR-values contribute). Thus, the integral considers the vertical chlorophyll a concentration (we now specify the depth-and time-dependence of the parameters in the integral) and, therefore, the PBmax-values are normalised in the equation. We sample data from both the surface and the SCM (cf. Table 1) to take the potential vertical variation of the phytoplankton characteristics, as mentioned by the reviewer, into account - both in relation to photosynthetic parameters and chlorophyll content. The normalisation implies that when PBmax(z) is multiplied with the chlorophyll concentration in Eq. (3) then this variation is accounted for.

*Reviewer 1: 14. Page 10, line 7: units needed for 4.76 and 1.72.*
Response: The unit has been added.

*Reviewer 1: 15. Page 11 line 8. ". . .coastal upwelling. . ." This is rather vague. What mechanisms or evidence do you have?*

Response: In addition to our measurements showing increased vertical fluxes, satellite images also indicate that coastal upwelling may be significant along the Norwegian coast. We now refer to the new figure 1b, showing SST from a MODIS-image and we have added the following to the text: ("also indicated by relatively cold Norwegian coastal water masses observed from satellite in Fig. 1b").

*Reviewer 1: 16. Page 14, line 29. The two Sharples refs deal with breaking internal tides/waves. The Burchard & Rippeth ref deals with wind-driven shear spikes and mixing by inertial waves. This is an important aspect of the discussion – most regions of the shelf edge are reported to have high nitrate fluxes due to breaking internal tidal waves. In the present study this is not the case – which is worth pointing out.*

Response: We have corrected the description of the references. From our data, we cannot identify the specific processes behind the mixing, and this is now clarified in the paragraph.

*Reviewer 1: 17. Page 16, line 1: ". . .indicate increased mixing, upwelling, or eddy activity. . ." This is very vague. What evidence do you have, or is there citable work that supports this?*

Reponse: We have reformulated the sentence to: "A tendency towards a thicker chlorophyll layer around the SCM and a deeper nutricline at Tr4 and Tr5 also indicates increased production and supply of nutrients near the coast."
We now refer to the upwelling elsewhere in the text where we refer to the SST seen in the new figure 1b. Therefore, this is not repeated in this section.

*Reviewer 1: 18. Page 20, caption to Fig. 5: (c,d) rather than (b,d).*

Response: This has been corrected.

*Reviewer 1: 19. Figs 1 and 7. The bathymetry contours are hard to read. Better labelling needed, also perhaps mark the shelf edge?*

Response: The font size has been increased in the figures so it is easier to read the depth contours (it should now be easier to identify the shelf edge so no additional lines are included).

*Reviewer 1: 20. Figs. 2, 3, 4, 5, 7, the colourbars need units.*

Response: The units of the color bar have now been added to the figures and described in the figure legends.

*Reviewer 1: 21. Fig. 3: parallel sections of density would help a lot in understanding the chl distributions.*

Response: Contour lines of density have been added, as suggested, to all the panels in figure 3.

*Reviewer 1: 22. Fig. 8: the different colours presumably indicate different transects. Legend needed.*
Response: Line legends for all the panels are shown in panel (f) and this information is now also added to the figure legend.

*Reviewer 2: The manuscript presents an extensive characterization the spatial variability of different variables related to primary and new production across the eastern North Sea shelf. The main conclusion pointed out by the authors is that nitrate turbulent fluxes into the photic layer (ie. new production rates) are enhanced close to the shelf edge, with potential implications for the ecosystem, as enhanced transfer towards higher trophic levels. The larger turbulent fluxes at the shelf edge do not relate to localized internal wave breaking (as reported for other locations, i.e. the Celtic Sea shelf, Sharples et al. 2007), but to a penetration of the nutricline into the bottom boundary layer following isopycnals, which in turn seem to adjust to the baroclinic flow of Atlantic Water along the shelf edge. The dataset presented is impressive, with a unique collection of biological, chemical and physical parameters, and the results are certainly interesting. The quality of the figures and writing are overall good. However, the manuscript has some significant weak-points that need to be addressed before acceptance. My main comment is that, in my opinion, the results do not convincingly support the main conclusions, at least in the form in which they are presented now (see below).*

*General comments*

*1. The main conclusion that the shelf edge is an area of localized nitrate fluxes leading to new production (and increased fishing activity) is not convincingly supported by the results, at least in the way in which they are presented and discussed. If I interpret the text and figures correctly, the integrated values of chlorophyll and primary show a distinct cross-shelf distribution, being minimum close the shelf edge (Page 11, line 6, Figure 7). The authors must explain and discuss why this happens and how this relates to their statement that new production and transfer towards higher trophic levels is enhanced at the shelf edge. I could understand that larger NP may not necessary result in larger PP but this needs to be discussed at least. From figures 7 and 8 it is not entirely clear if f-ratios are larger there because primary production rates are relatively low or because nutrient fluxes are larger. Reporting mean/median values of PP and FNO3 at the different regions (shelf, shelf edge, Norwegian Trench) in Figure 9 would definitely help. Also, a statistical analysis/error assessment would be needed to show that the differences between regions are significant, particularly in the case of turbulent nitrate fluxes, which are highly uncertain due to the chaotic nature of turbulent mixing. Hence, the presentation and discussion of the results need to be significantly improved. Until then, the title of the manuscript ("Turbulence measurements suggest high rates of new production over the shelf edge in the north-eastern North Sea during summer") is not justified.*

Response: We would like to thank the reviewer for a careful positive review with constructive comments and criticism of our manuscript.
We reply to all the comments below:
a) We have added a new panel of the spatial distribution of the nitrate flux in figure 7c.
b) We have added more text explaining the chlorophyll and PP distribution around the shelf edge region. In the end of section 4.3 we add: "Thus, the tendency to increased chlorophyll and PP on either side of the shelf edge could also be explained from the gradual build-up of biomass as nutrients are transported away from the shelf-edge region by isopycnal mixing. Alternatively, the tendency to low values could also be explained by a larger grazing pressure above the shelf edge. Thus, a full explanation of the tendency to low chlorophyll and PP above the shelf edge area cannot be determined from these data."
c) To clarify that it is primarily an increase in nitrate fluxes that explains the variation in the f-ratios, we have added a new figure 7c where the nitrate flux is shown. From this figure, it can be seen that the elevated nutrient fluxes are in accordance with the distribution of the f-ratios.
d) we have now assessed the distribution of the nitrate fluxes in a more quantitative manner by

including Table 2, where the median values are related to the distributions of the parameters across the shelf edge. The table supports the discussion of the distributions shown in figure 7 and 8. Based on the statistical analysis in Table 2, we have now modified the depth range of the shelf edge zone to be between 80 - 130 m. The nitrate flux is largest in the depth interval representing the shelf edge (80-130). However, the average values are not significantly larger than in the other two depth intervals. This does not rule out that the fluxes are larger at the shelf edge, because of the transient nature of short-term term mixing events. We now show and analyse data from a time series station at the shelf edge at Tr4 (Fig. 8) where temporal changes associated with tides and other short-term variations can be seen. Thus, even though the average value is not significantly higher at the shelf edge the fact that the largest fluxes are observed in this area supports the interpretation of figure 7 and 8.

*Reviewer 2: 2. The mechanisms that cause the nutrient fluxes to be larger at the shelf edge are not sufficiently discussed. In particular, it is not clearly shown if larger nitrate fluxes are related to enhanced turbulent dissipation, reduced stratification or enhanced nitrate gradient. I think this is important for the interpretation of the NP dynamics in the area. Additional figures showing the nitrate and buoyancy frequency distribution would help. In the discussion (Section 4.3), the authors point out that the dynamics of the shelf edge in the study area is different from similar locations, where enhanced turbulence and nutrient supply is sustained by internal tide dissipation at the shelf edge (eg. Sharples et al 2007). The authors say that they have carried out some time-series measurements to study the internal wave activity at the shelf edge and they have not found any signal of enhanced mixing (why not show this data at least as Supplementary Information?). They suggest, instead, that the enhanced nutrient fluxes at the shelf edge relate to the deepening of the nitracline at the shelf edge, reaching the bottom boundary layer. This deepening would be related to the baroclinic flow of the nutrient-rich AW at the shelf slope. This could be a very interesting point of the manuscript but it needs to be more clearly demonstrated with data allowing for a more thorough characterization of the site's dynamics, i.e. some current measurements (if available), or at least discussed in more depth with additional support from the literature.*

Response: We referred only to the mixing of nutrients in our comments on the time series stations. We have clarified that we cannot identify the specific mixing process, thus we cannot disregard the influence from internal waves or tides based on the present data set. After our references to the papers of Sharples, Burchard and Rippeth in the start of section 4.3 we clarify this by adding: "Mixing associated with wind and tides (e.g. Burchard and Rippeth, 2009) as well as breaking internal waves (Sharples et al, 2007; 2009) has been shown to be important for vertical nutrient fluxes in shelf areas. The specific physical processes behind increased turbulent mixing cannot be identified from the present data set. Measurements on the time series station at the shelf edge showed that elevated mixing occurred in phase with the tidal energy input but also that additional energy sources likely contributed to the elevated mixing, e.g. energy from non-tidal currents. Short term variability associated with advection of ambient water masses was also observed. This could possibly be related to sub-mesoscale eddies or other transport processes occurring below the pycnocline. The time series station T2 at Tr4 showed an important feature where mixing associated with the bottom boundary layer increased and intersected the bottom of the euphotic zone. Thus, the combined effect from a deep nutricline and elevated mixing provide a mechanism for increased diapycnal nutrient fluxes along the shelf edge."

We have added a new figure from the time series station at the shelf edge on Tr4 which includes the distribution of the buoyancy frequency. N2 is also now shown in figure 6. The nitrate concentration has now been included in figure 2d where the distribution along Tr4 is shown. Nitrate concentrations at stations at the shelf edge are also shown in figure 6.

*Reviewer 2: 3. Lack of important information: the authors have omitted some relevant information*

*in the methods section and others (see specific comments). Also, at least two figures, which are very relevant for the scientific content of the manuscript, must be added: (1) the distribution of nitrate concentration along at least one of the transects and (2) a comparison of the modeled vs. measured PP values at in situ conditions for the stations where they are available.*

Response: We have added the information to the Methods section and Supplementary information, as described below. (1) We now show the nitrate distribution along Tr4. (2) we explain the calculation of PP in more detail and include references to two papers on uncertainties related to photosynthetic parameters. The photosynthetic parameters are derived from laboratory experiments and, therefore, the uncertainty on these parameters are the relevant measure in this context. This is discussed in detail in section 4.2. To further clarify this issue, we have now included the following paragraph in the section. "Primary production estimates at individual sites are dependent upon the value for maximum rate of photosynthesis ($P^B_{max}$). However, $P^B_{max}$ (and all other measured photosynthetic parameters) represent the physiological condition of the phytoplankton community at the time of sampling. This means that $P^B_{max}$ may vary as a function of time of sampling (Richardson et al., 2017) or during different light conditions (e.g., photo-inhibition). Normalisation of the photosynthetic parameters with chlorophyll also represents an uncertainty in the PP estimates at individual stations as, for example, division with low chlorophyll values (e.g. some surface values were ~0.1 mg chl m$^{-3}$) may result in large uncertainty of the normalised values due to relatively large absolute errors. This uncertainty error has been shown to potentially have a significant impact on the estimation of photosynthetic parameters (e.g., Kumari, 2005; McKee et al., 2015). Finally, the fact that photosynthetic parameters were determined from incubations carried out on only one water sample from each sampling depth represents a source of uncertainty with respect to the estimates of PP at individual stations. Therefore, in order to compare PP estimates from the stations we sampled, we applied average values (median for all stations) of photosynthetic parameters in the surface layer (5 m) and in the SCM in the calculation of PP. The uncertainties associated with the photosynthetic parameters are further considered in the Discussion. Surface values were assumed to represent the photosynthetic parameters in the upper 10 m and average values from the SCM were assumed to represent the parameters for the water column below 10 m."

*Reviewer 2: 4. Structure: The structure of the manuscript is not always linear. I suggest some reorganization of the text/figures (eg. see specific comment 17)*

Response: We have considered the specific comments in 17.

*Reviewer 2:* Specific comments
*1. Abstract: "Estimated nitrate fluxes due to turbulent vertical mixing into the euphotic zone were up to 0.5 - 1 mmol N m-2 d-1 over the shelf-edge (f-ratios > 0.1) while values of < 0.1 mmol N m-2 d-1 were found in the deeper open area north of the shelf-edge." If this refers to figure 8, those numbers are not easy to read from this figure. A logarithmic scale must be used. Mean/median values (and uncertainties) could be reported in Figure 9.*

Response: The maximum nitrate flux is now also shown in figure 7c and the large values in the shelf area are seen by the color shading (yellow-red) while the low values in the deeper open area appears as blue. We report median values in the new Table 2.

*Reviewer 2: 2. Section 2.2. Important information is lacking in this section. What was the final vertical resolution of the TKE dissipation rate? How many casts were performed at each station?*

Response: The resolution was ~3 m and this information is now added to the Methods section. In general, one cast was made at the relatively closely spaced stations and average values from the two shear sensors were reported. A quality criterion is, in the revised manuscript, now placed on the

measurements used in the analyses. The derivation of this criterion is explained supplementary information, figure S1 and described in the Methods section.

*Reviewer 2: 3. Section 2.3. How many nutrient and chlorophyll profiles/samples were analysed? "In some cases/At some stations" are very vague expressions. What was the intended horizontal and vertical resolution for nutrients? How were the sampling stations chosen?*

Response: We have added the following to section 2.3: "In total, 649 water samples were analyzed for nutrients.". The distribution of nutrient samples in the vertical is described in the Methods section and it can now also be seen in figure 2d along Tr4 (shown with small bullets). The number of chlorophyll samples used for the calibration is reported in the end of the section: (n=205).

*Reviewer 2: 4. Section 2.4, Page 5, lines 11-12. The goodness of the fits to eq. (3) is not sufficiently demonstrated. The authors should provide any measurement of this goodness and/or some plot of the data and fitted lines.*

Response: We apply the model in Eq. 3 for calculating PP. The parameters are determined from the incubations and the three parameters at the two depth levels are shown in Table 1. Uncertainties associated with the photosynthetic parameters are discussed in section 4.2 and we also added a new paragraph about this, cf. our response to the general comment no. 3, above. In the end of Section 4.2, we evaluate the uncertainty from the photosynthetic parameters and assess the associated uncertainty on the PP-value to be +/-30%.

*Reviewer 2: 5. What is the difference between PBmax and PBmax\*?*

Response: In a simple PP-model without photoinhibition, then PBmax becomes the asymptotic maximum value of PP in a PP-Irradiance diagram (e.g. following the traditional simple PP-model of Webb et al (1974), Oecologia, 17, 281-91). However, the maximum of the PP-Irradiance curve is not exactly at PBmax when photoinhibition is included, cf. Eq. 3, and, therefore, PBmax\* is used to quantify the maximum of the curve. We have clarified this in the parenthesis in the end of the paragraph.

*Reviewer 2: 6. FNO3 calculation. If I understood correctly, the FNO3 fluxes into the photic zone at each station are reported as the maximum of the FNO3 across the nitracline. Thus, the reported fluxes are the result of a point by point multiplication of "measured" Kv values and calculated NO3 gradient. Kv has generally a patchy distribution in space and episodic in time, so that the fluxes calculated in this way my contain spurious values. How did the authors deal with this? Did they apply any averaging to the "measured" Kv values? How many casts were done at each station? The robustness of the FNO3 calculation must be assessed through a more thorough error analysis.*

Response: FNO3 is calculated as the maximum flux into the euphotic zone. It was found that using the nitracline specifically as a relevant boundary may lead to an underestimate of the flux into the photic zone. We analyze this finding and document that the maximum flux is, in general, located a little deeper than the nitracline. We agree with the considerations about Kv and vertical variation and this motivated the use of Eq. 5. There are still fluctuations but these are not influenced by uncertainties associated with Kv and division of low values of N2.

*Reviewer 2: 7. Page 7, lines 7-23, Fig. 2. The authors could identify the different water masses with a text label in Figure 2. Also, the authors may outline the main circulation patterns of the different water masses in Figure 1 and provide some geographic indications (name of the countries and some topographic) features to facilitate the orientation of the reader.*

Response: We have added the names of the countries to fig 1b as suggested by the reviewer. We find that water masses are well represented in figure 1a and figure 4. They could be added to figure 2a, as suggested by the reviewer, but it would make the figures less harmonic, in our opinion, so we have avoided adding more information in the figure. The water masses can be identified from the TS-relations described in the text. We also chose not to add more information about the general surface circulation in figure 1 as these figures already contain many layers of information.

*Reviewer 2: 8. Page 7, lines 7-23, Page 8 lines 1-23. Though extremely relevant for the study and extensively described in these lines, nitrate distributions are not shown in the manuscript. The authors must at least include the nitrate distribution of transect 4 in Figure 2.*

Response: We have followed the suggestion by the reviewer and added the nitrate distribution along Tr4 in figure 2. All nitrate measurements are also shown in figure 4a-c and observations are also now shown in figure 6 at four stations along the shelf edge.

*Reviewer 2: 9. Page 8. I don't believe that adding a new subsection (3.2.1) is necessary here.*

Response: We have removed the heading of subsection 3.2.1 and the section is now simply a part of section 3.2

*Reviewer 2: 10. Fig. 3: there is some overlapping between the red circles and orange squares and in some cases it is difficult to know whether some points are lacking or hidden. You could use different sizes*

Response: We have increased the size of the orange squares so it is easier to see the overlapping points.

*Reviewer 2: 11. Figs. 2. and 4. In the methods section, the authors say that sections 2 and 4 were repeated to study the temporal variability. Are the distributions presented in Figs. 2 and 4 a mean of the different occupations, or how were they calculated?*

Response: We carried out repeated measurements at two fixed geographic locations on Tr2 and Tr4, respectively, (referred to here as "time series stations"). Both data sets are included in the revised manuscript. We apply measurements from time series 1 (107 casts in three sequences with about 3 min intervals and over 22 hours down to 62 m) to analyze the statistical significance of the epsilon-values (described in this revised mansucript in Methods and Supplementary material and shown in Figure S1). In addition, we include the time series data from the shelf edge at Tr4 over a 36h period in the new Figure 8 to show the temporal variability and the influence from tidal currents on mixing in the bottom boundary layer.

*Reviewer 2: 12. Fig. 6. The vertical distribution of FNO3 is very difficult to appreciate in this figure because it follows the logarithmic variability of Kv. The authors may use a log-scale for FNO3 too (also in Fig. 8). The largest FNO3 are shown for the lower boundary layer, due to larger values of the diapycnal diffusion coefficient. The nitrate gradient however is very weak here, so I doubt whether these large fluxes would actually different from zero if the uncertainties in the nitrate gradient calculation and Kv were accounted for. Error bars should be added to the nitrate flux.*

Response: Figure 6 has now been expanded so it shows four stations taken within a few hours across the shelf edge at Tr4. In this area, there is a vertical gradient in nitrate, as seen in Fig 6 and also from the new figure 2d. Thus, increased fluxes here are due to the combined effects of increased mixing and nitrate gradients. We now describe uncertainties of epsilon in the supplementary information and uncertainties in nitrate determination are described in the Methods

section. However, from the large nitrate gradient and the relative increase in the epsilon-values in the deeper part of the water column (i.e. below ~40 m in fig. 6) it can be seen that the increased nitrate flux is significant. We have not attempted to show error-bars on the figures because they already contain several curves.

*Reviewer 2: 13. Section 3.3. I would have expected to find a description of the spatial distribution of the nitrate fluxes here similar to previous sections.*

Response: The new figure 2d contains the nitrate distribution along Tr4. These are described in the text at the end of section 3.1 along with a description of the other panels in figure 2. The nitrate fluxes are now shown in figure 7c.

*Reviewer 2: 14. Section 3.5 / Figure 7. Vertically integrated quantities (Chlorophyll and PP) are reported in this section/figure. However, I could not find the integration depth in the manuscript. I guess that they have been integrated in the euphotic zone but this should be specified.*

Response: This is now specified in the start of section 3.5: "The vertically integrated chlorophyll in the euphotic zone (50 m) ..."

*Reviewer 2: 15. Section 3.5, Page 10 Line 19. How do the extrapolation with equation 3 compares with measured PP at local conditions at the locations where direct measurements are available? I suggest to add a new figure where modeled and measured values are compared.*

Response: We have added more information on the photosynthetic parameters. This is described in our response to the general comment no. 3 above. We argue that the photosynthetic parameters are the relevant quantities to evaluate because these parameters are directly derived from the incubation experiments. Therefore, we have not included a new figure as suggested by the reviewer.

*Reviewer 2: 16. Figure 7c and text. There is some overlapping of the color dots here and it is difficult to see whether there is a clear background tendency towards higher fratios at the shelf edge or there are only a few large values superimposed to a generally low background. How does this relate to the episodic nature of turbulent mixing? I would suggest to calculate average f-ratios for the shelf, the shelf-edge and the Norwegian Trench based on the mean (or median values) of PP and FNO3 in the different regions, instead of the point-wise calculation presented here. This numbers could be shown in Figure 9. This would also allow for a quantitative evaluation of the significance of the differences in NP between the different areas.*

Response: The size of the color dots for the low values are slightly larger than for the larger values, to make it clearer to see the distribution. Regarding the episodic nature of the mixing, we expect that the spatial distribution will be influenced by this. However, because of the relatively large number of stations, we consider the distribution to reflect the general distribution of mixing in the area. We have now added a Table 2 where the parameters are calculated in different depth sections across the shelf edge, as suggested by the reviewer. The Table is analysed in section 3.6 where we have added the following:" The distributions were analysed across the shelf edge by dividing the stations into three depth ranges characterising the shallow area (50 - 80 m), the shelf edge zone (80 -130 m) and the deep area (> 130 m), respectively (Table 2). Although the shelf edge was characterised by the largest nutrient fluxes, the averaged values were not significantly higher than observed above the deeper areas. However, the depth of the maximum flux was found to be significantly deeper (~43 m) above the shelf edge than in the deeper area (~32 m). This can be explained by the significantly deeper nutricline at the shelf edge (~35 m) than observed above the deeper area (~27 m). Distributions of vertically integrated chlorophyll and PP support that minimum values are found above the shelf edge. However the low values are not significantly

different from the larger values above the deeper and shallower part of the area.". The episodic nature of mixing is considered in the final paragraph in section 3.7.

*Reviewer 2: 17. Sections 3.5 an 3.6 / Figures 7 and 8: The information about the spatial distribution of PP and integrated chlorophyll-a is somehow dispersed and repeated in these two figures/sections. On the other hand, in my opinion, the description of the spatial variability of the nitrate fluxes -which seems to be a central topic of the manuscript- is insufficient. I would replace the f-ratio in Fig. 7 by the actual nitrate flux and describe its variability and drivers (changes in nitrate gradient, stratification and TKE dissipation) in section 3.3, for example.*

Response: We have added a new panel to figure 7 (Fig. 7c) where the flux is shown, as suggested by the reviewer. We have moved the previous figure 8 to the Supplementary information (Figure S2) because most of the information now is contained in figure 7. However, the figure shows the quantitative distribution more precisely and it also contains information of the temporal variation in, for example, PP along Tr4.

*Reviewer 2: 18. Figure 8. The location of the shelf edge is not evident at all in this figure and this weakens the authors' main point (new production is enhanced at the shelf edge). I would suggest to represent the different variables as a function of the distance to the shelf edge instead of latitude. The smooth cross shelf distribution of FNO3 and the f-ratio outlined in Figure 9 and the abstract (see first comment) is not clear in this figure due to the large short-scale variability of these quantities. I would suggest to use logarithmic scale or even add a representation of FNO3 in figure 7, report mean values in Figure 9, and remove figure 8.*

Response: We have followed the suggestion about adding FNO3 to figure 7 and now also report median values in Table 2. We have moved figure 8 to the Supplementary Information as described above in lines 644-648. We have kept the reference to latitude in the figure instead of distance to the shelf edge for simplicity. The location of the shelf edge along the five transects can be seen in figures 1 and 3.

*Reviewer 2: 19. Figure 9. This figure is promising but it definitely needs more information. I would add mean values of primary production and nitrate fluxes (at least). From Figures 7 and 8 it is very difficult to know if the larger f-ratios at the shelf edge are mostly due to enhanced nitrate fluxes or reduced primary production in this area. How were the f-ratios calculated, are they mean/median values or just an estimate of their order of magnitude? This is the main message of the manuscript and the authors should provide a solid quantification (and some error assessment) of the f-ratio.*

Response: Median values of PP and nitrate fluxes are now reported in Table 2. Figure 7 has been improved by the addition of the distribution of FNO3max. From this, it can be seen that it is the enhanced nitrate fluxes that explain the distribution of the f-ratios. The f-ratios were calculated as the ratio of the maximum nitrate flux into the euphotic zone (converted to units of carbon by the C:N ratio) and divided by the PP. This was done for every station and is described in the end of section 2.5.

*Reviewer 2: 20. Section 4.1. This section could be much improved if a comparison between modeled and measured PP values was shown.*

Response: This is described in our response to the general comment no. 3 above.

*Reviewer 2: 21. Page 14, lines 10. "Finally, estimates of new production imply a conversion from*

*nitrate to carbon and a fixed ratio may not be representative for the different communities in the area." Is not there any quantification of plankton stoichiometry in the area available to assess the validity of the chosen C:N ratio?*

Response: We rely on the Redfield C:N ratio and have added the original reference to the Methods section. The C:N ratio of phytoplankton has been investigated in numerous studies and, in general, a ratio of 106:16 is a good representation of the stoichiometry of the plankton. Variation is known to occur due to various causes, for example due to varying nutrient conditions and, therefore, previous values from the area would not necessarily be a better representation than simply using the "original" C:N ratio. We do not regard this to be the most critical assumption in our analyses and we have shortened the description of various error-sources in the Discussion accordingly.

*Reviewer 2: 22. Page 14, line 29-30: "Mixing from tides (Sharples et al, 2007; 2009) and breaking internal waves (e.g. Burchard and Rippeth, 2008) has been shown to be important for vertical nutrient fluxes in shelf areas." This sentence is imprecise. In Sharples et al. (2007) mixing is enhanced due to internal wave breaking (in particular to the dissipation of the internal tide) and in Burchard and Rippeth (2009) enhanced turbulence is due to the the alignment of the shear vectors induced by different sources (inertial oscillations, wind and tidal bed friction). Also, the Burchard paper is from 2009, not 2008. In general this section has great potential, but needs to be improved (see General comment 2)*

Response: We have corrected the introduction to the section so now it reads:"Mixing associated with wind and tides (e.g. Burchard and Rippeth, 2009) and breaking internal waves (Sharples et al, 2007; 2009) ...."

*Reviewer 2: 23. Page 15, Lines 18-26. This paragraph does not match the section heading*

Response: We have added a new heading to this paragraph so it now is referred to as: "Vertical nutrient fluxes in the euphotic zone"

*Reviewer 2: Technical comments*
*1. Page 6, line 21 and Page 9 line 10. There are too much ")"*

Response: These sentences have been changed to avoid double parenthesis.

*Reviewer 2: 2. Page 17, line 7. Rippith ! Rippeth*

Response: This has been corrected.

# Turbulence measurements suggest high rates of new production over the shelf edge in the ~~north-east~~northeastern North Sea during summer

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**Abstract.** New production, i.e., that driven by allochthonous nutrient inputs, is the only form of primary production that can lead to net increases in organic material and is, therefore, important for understanding energy flow in marine ecosystems. The spatial distribution of new production is generally, however, not well known. U~~Here, u~~sing data collected in July, 2016, we analyse the potential for vertical mixing to support new production in the upper layers of the north~~-~~eastern portion of the North Sea. Estimated nitrate fluxes due to turbulent vertical mixing into the euphotic zone were up to 0.5 - 1 mmol N m$^{-2}$ d$^{-1}$ over the shelf-edge (f-ratios > 0.1) while values of < 0.1 mmol N m$^{-2}$ d$^{-1}$ were found in the deeper open area north of the shelf-edge. The low vertical mixing rates (dissipation rates of turbulent kinetic energy below 10$^{-8}$ W kg$^{-1}$, corresponding to vertical turbulent diffusion coefficients of 10$^{-6}$ - 10$^{-5}$ m$^2$ s$^{-1}$) implied f-ratios of < 0.02 in the open waters north of the shelf-edge. In the shallow (< 50 m) southern and central part of the study area, inorganic nutrients were low and nitrate undetectable suggesting negligible new production here, despite relatively high concentrations of chlorophyll a being found in the bottom layer. Thus, high rates of new production seem ~~generally during summer~~ to be concentrated around the shelf-edge zone and in association with locali~~s~~zed features exhibiting enhanced vertical mixing. We find that the nutricline depth is significantly deeper at the shelf edge and interference with increased mixing in this deeper depth range can explain the increased diapycnal nitrate fluxes. Overall, this suggests that the shelf-edge zone may be ~~was~~ the major nutrient supplier to the euphotic zone in this area during the period of summer stratification.

## 1 Introduction

New Production (NP), i.e. primary production (PP) based on inorganic nutrients recently introduced to a system, balances net losses of organic material in the euphotic layer when considered over longer periods (Dugdale and Goering, 1967). Net loss of biomass from the surface layer may be due to sinking phytoplankton or transfer to, and subsequent losses from, higher trophic levels such that this cycle between nutrient input, PP and remineralisation of organic matter constitutes an organic biological pump in the upper ocean (Volk and Hoffert, 1987). In addition to NP, total PP is comprised of photosynthesis driven

by nutrients recycled within the system, itself. The ratio of NP to total PP is referred to as the f-ratio (Eppley and Peterson, 1979). This ratio is known to vary both seasonally and spatially.

Given that NP can lead to a net increase of organic material, its occurrence can be expected to have important consequences for food webs and the distribution of marine organisms. Scott et al. (2010) analysed the distribution of marine mammals and seabirds in the north-western North Sea and they found the distribution of these organisms to be best explained by the presence of a sub-surface chlorophyll maximum (SCM). They furthermore speculated that bathymetric features induced vertical mixing that could bringing nutrients to depths containing the chlorophyll peak, which then could lead to localised NP. This potential link between localised increased NP in sub-surface layers and the highest trophic levels may, therefore, be an important feature in ecosystem functioning. The distribution of NP, especially over small spatial scales, is however not well understood. The purpose of this study, therefore, was to describe the potential for NP based on the vertical mixing of nutrients into the euphotic zone to occur in the northeastern North Sea, a highly productive temperate ocean region. The summer season was chosen for the study as this region is thermally stratified at this time and surface waters characterised by low or undetectable concentrations of inorganic nutrients and low phytoplankton biomass. Thus, it is generally assumed that little NP is occurring in these waters at this time.

The northeastern North Sea is characterised by the transition from a relatively shallow southern region (depth ~ 40 m) across a shelf-edge (depth ~80 - 130 m) towards the deep (> 400 m) Norwegian Trench leading into Skagerrak (Fig. 1). The general cyclonic circulation is characterised by inflow from the Atlantic along the shelf-edge, either from mainly wind-driven inflow between the Shetland and Orkney Islands or from transports along the Norwegian Trench (Winther and Johannessen, 2006). Outflow takes place along the Norwegian coast, partly as less saline water masses in the Norwegian Coastal Current, and with an estimated net transport of about 1 Sv in either direction (Danielssen et al., 1990). The relatively large cyclonic flow has also been found in model studies (Winther and Johannessen, 2006; Pätch et al., 2017) where current speeds along the northeastern shelf-edge towards the Skagerrak intensify (Holt and Proctor, 2008) and are found to be associated with a large eddy-activity (Røed and Fossum, 2004). This dynamic area was chosen as the study area as it is a potential location for increased vertical mixing and nutrient transports due to, for example, eddy-activity, breaking internal waves, and upwelling at the shelf-edge.

A large part of the central and northern North Sea becomes stratified during the summer season with an SCM between ~20-40 m depth. Richardson et al. (2000) found that a significant amount of PP occurs at the SCM and argued that much of this could be NP supported by fortnightly tidally driven input of nutrient rich deep water to the SCM. Fernand et al. (2013) found that up

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to 60% of PP took place in the SCM in the central and northern North Sea during the summer. Those workers also reported a distinct SCM in the northern North Sea where the depth was larger than ~40 m, i.e. areas where tidally induced mixing cannot break the stratified water column. The northern North Sea is relatively productive during the summer season with PP levels of ~0.5 - 0.9 g C m$^{-2}$ d$^{-1}$ (Weston et al, 2005; Fernand et al., 2013). However, few studies have been made of PP at the northern shelf-edge and the distribution of NP is unknown.

Shelf areas, in general, constitute an important link between the large reservoirs of dissolved substances in the open ocean and coastal water masses and shelf processes play an important role in global cycles of nutrients, oxygen and carbon (Gattuso et al., 1998). Transports across the shelf edge bring nutrient-rich deep-water masses into more shallow and well-mixed areas and stimulates production above the shelf. Various cross-shelf transport processes can facilitate this exchange (Brink, 2012), thus different exchange processes may dominate in different shelf-edge regions. However, shelf-edge areas share common dynamical features due to their relatively steep bathymetric slopes and the separation between coastal and open ocean water masses. T and, therefore, the conditions in at the north- eastern North Sea, considered in this study, may be representative for similar shelf-edge regions not directly exposed to the open ocean basins.

Here, we analyse the physical and biological processes affecting PP and NP during the stratified summer period across the shelf-edge in the north eastnortheastern North Sea based on data collected during the VERMIX cruise in July 2016. First, we describe the distribution of water masses, nutrients and vertical mixing in the area. Then, we present results from PP-incubations and, based on averaged representative photosynthetic parameters, calculate PP for the whole study area. Nitrate fluxes and NP are calculated and compared with PP to derive f-ratios. Finally, the implications for NP in the North Sea are discussed.

## 2 Methods

### 2.1 Study area and hydrographic measurements

The VERMIX study covered an area around the shelf-edge in the north –eastern North Sea from the shallow shelf area (depth <50 m) across the western part of the Norwegian trench (~500 m) towards the coast of Norway (Fig. 1a). In this study, we define the shelf-edge zone as being where depths are between 850 m and 1300 m and refer to areas south and north of this zone as the shallow shelf area (<850 m) and the area off the shelf edge zone (>1300m), towards Norway, respectively.

The cruise was carried out on boardwith R/V Dana (Technical University of Denmark) during the period 12 - 31 July 2016. Stations were placed along five transects between 56.2 - 57.8° N and along 8.25° E (Tr1), 7.75° E (Tr2), 7.25° E (Tr3), 6.75°

E (Tr4) and 6.25° E (Tr5), respectively (i.e. ~25 km between transects). Wind and light conditions were typical for the period with windy conditions during the first week (along Tr1 and Tr2 with wind speeds up to 20 m s$^{-1}$) and relatively calm conditions during the rest of the cruise (Tr2-5). In total, 132 stations were sampled along the transects with a general distance between stations of 10 km and at sections. Additional stations along Tr2 and Tr4 decreased this distance was decreased down to ~1 km. Measurements along these two transects were made several times during the cruise to examine temporal variability. Measurements over 22 - 36 hours were made at two time series stations (T1, T2) located at Tr2 and Tr4, respectively. Hydrographic measurements of conductivity, temperature and depth (CTD) were made with a Seabird SBE911 plus system, including two sets of temperature, conductivity and oxygen sensors (SBE43) and equipped with a SCUFA fluorometer, a PAR-sensor (Licor) and 12 Niskin bottles (30 l) for water sampling. All salinity values are reported as practical salinity (S$_P$) and referred to as salinity (S) and TEOS10 (IOC et al., 2010) was applied for calculating properties of seawater.

**2.2 Measurements of turbulence and micro-structure**

Micro-scale turbulence was measured with a loose-tethered free-fall Rockland Scientific International (RSI) VMP-250 microstructure vertical profiler equipped with two shear probes, a FP07 thermistor and a micro-conductivity sensor. Microstructure of temperature and salinity only supported the analysis of shear-induced turbulence and are not discussed further here. The profiler was also equipped with a CT- and pressure-sensor (JFE Advantech). The JFE-CTD data were binned in 0.1 dbar and the conductivity sensor was aligned with temperature by a delay of 0.14 s. Microstructure measurements were made at 512 Hz and stored at 64 Hz and the CT-sensor operated at 16 Hz. Turbulence profiles were obtained while the ship was freely drifting. In total, 253 casts down to about 5 m from the bottom, or to a maximum depth of 200 m above deeper areas, were made during the cruise. Every cast provided two shear-measurements and, in general, there was relatively small deviation between the two shear probes. Therefore, all measurements were included in the analyses and values from the two shear-probes were averaged. The dissipation rate ($\varepsilon$) of turbulent kinetic energy (TKE) was calculated with software provided by Rockland Scientific. Dissipation of TKE was estimated from below 10 m depth in order to exclude possible disturbances from the ship (depth of ship was 5.7 m) and analysed in bins of 8 seconds with 50% overlap, corresponding to a resolution of ~3 m, following the method described by Wolk et al. (2002) and revised by Lueck (2016).

The uncertainty and short-term temporal variability of the calculated $\varepsilon$-values were assessed from a time series station (T1) at Tr2 where $\varepsilon$-values were calculated from 107 casts carried out in three sequences over a 22 hours period (Supplementary material). In general, there was a good accordance between estimates of $\varepsilon$ obtained from the two sensors and the error-distribution, defined from the difference of the logarithm (to the base 10 and in units of W kg$^{-1}$) between the two estimates, had an absolute standard deviation of 0.14 (Fig. S1). In order for measurements to be included in the analysis, we applied theA criterion was applied to the whole data set that the difference between the measurements made by the two sensors on a single profile should be less than three times the absolute deviation. T and this led only to the removal ofremoved only a few pairs of

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ε from the data set. Short term variation at T1 was also found to be relatively small and temporal changes between subsequent casts were considered to have a littlesmall influence on the calculated ε-values. Therefore, ε-values were, in general, derived from a single cast between the relatively closely spaced stations, and the ε-value obtained by averaging the calculated value from the two shear-probes was reported.

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The vertical turbulent diffusion coefficient ($k_v$) was estimated from the dissipation rate of TKE (Osborn, 1980):

$$k_v = \eta\Gamma \, \frac{\varepsilon}{N^2} \tag{1}$$

with a mixing efficiency ($\Gamma\eta$) equal to 0.2 and the Brunt-Väisälä frequency ($N^2$) determined by linear regression of density (ρ) with depth in 10 m intervals:

10  $$N^2 = -\frac{g}{\rho_0}\frac{\partial\rho}{\partial z} \tag{2}$$

where $\rho_0$ is a reference density (1027 kg m$^{-3}$) and g is the gravitational acceleration.

The mixing efficiency, Γ, is here assumed constant and equal to 0.2 and this is within the range Γ ≤ 0.20 suggested by Osborn (1980). The value of 0.2 is supported by numerical studies when the turbulent intensity, defined by $Re_b = \varepsilon/(\nu\, N^2)$ where ν is

15  the molecular viscosity, is within the range 7-100 (Shih et al., 2005), and the model by Bouffard et al. (2013), also validated against field data, finds the valid range to be between 20 and 400. Outside this mixing regime, the mixing efficiency is less than 0.2. We apply the range of Bouffard et al. (2013) and this implies that our calculated diffusion coefficients with a constant mixing efficiency of 0.2 are valid in the range between $0.5\cdot10^{-7}$ - $1.0\cdot10^{-4}$ m$^2$ s$^{-1}$ (we use $\nu = 1.2\cdot10^{-6}$ m$^2$ s$^{-1}$). T and this range encompasses theour data used for calculating vertical nitrate fluxes in the euphotic zone collected in our studyfrom the area.

20  **2.3 Measurements of nutrients and chlorophyll a**

Water samples were taken at CTD stations from standard depths (5, 10, 30, 40, 60, 100, 200 m and close to the bottom). In addition, the a sample from the depth (i.e. peak) of the subsurface chlorophyll a maximum (SCM) was sampled. At some stations, a distinct second chlorophyll peak or "extreme" (i.e, a subsurface chlorophyll a extremum, SCE) was observed above the SCM. In some cases, water for photosynthesis incubations and inorganic nutrient (nitrate, nitrite, ammonia, phosphorous and silicate) determination was taken from these SCEs. However, in this study we refer only toto the subsurface samples as

25  from the SCM. Water samples for nutrient determination were tapped from the Niskin bottles and immediately frozen immediately frozen. The sample was subsequently thawed, filterede seawater (Milipore Millex-GP Hydrophylic PES 0.22 μm), and was analysed for nitrite, nitrate, ammonia, phosphorous and silica by wet-chemistry methods according to Grasshoff (Ed.) et al. (1983) (detection limits were 0.04, 0.1, 0.3, 0.06 and 0.2 μM, respectively) atNutrient analysis was carried out by

30  Aarhus University, Department of Bioscience. In total 649 water samples were analysed for nutrients.

Chlorophyll a (GF/F filtered and extracted in 90% ethanol) was determined fluorometrically (Trilogy, Turner Designs) and used to calibrate the rosette mounted fluorometer (chlorophyll a is simply referred to as chlorophyll below). A relatively constant ~~In total 649 water samples were analyzed for nutrients. Detection limits for nitrite, nitrate, ammonia, phosphorous and silica were 0.04, 0.1, 0.3, 0.06 and 0.2 µM, respectively.~~

~~The~~ background fluorescence was measured ~~measured~~ in the deep profiles (>200 m). As we see no reason for at constant distribution of chlorophyll in waters down to depths of ~500 m, we ~~was~~ considered this fluorescence to be generated by ~~other~~ material other than chlorophyll ~~a~~. Therefore, the fluorescence was averaged between 100-500 m at a deep station on Tr1 (57.83 °N, average value of 0.023 volt). ~~and t~~This relatively small value was treated as an unknown background and subtracted from the fluorescence signal (F) ~~from surface waters at all of the stations~~. The chlorophyll concentration (chl, mg chl m$^{-3}$) was then determined from a linear regression between fluorescence (F) and filtered chlorophyll samples as chl = 3.23 F - 0.08 (R$^2$ = 0.71, n = 205).

**2.4 Calculation~~s~~ of photosynthetic parameters and PP**

Primary production (PP) was determined from incubations made with Photosynthetic Available Radiation (PAR) at 12 different light intensities from 0 - ~800 µE m$^{-2}$ s$^{-1}$. In total, 64 incubations were made with water sampled from the surface and/or SCM at 41 stations and 23 and 25 incubations were selected to represent the conditions at the surface (5 m) and SCE, respectively (Table 1). Total PP was then calculated according to Platt et al. (1980):

$$PP(chl(z), PAR(t,z)) = \int_{24h} \int_{-Deu} P_{max}^{B}(z)\, chl(z) \left(1 - exp\left(-PAR(t,z)\, \frac{\alpha^{B}(z)}{P_{max}^{B}(z)}\right)\right) exp\left(-PAR(t,z)\, \frac{\beta^{B}(z)}{P_{max}^{B}(z)}\right)\ dz\ \ dt$$

(3)

where the integral is carried out in the vertical (z) from the euphotic depth, ~~(~~ Deu~~)~~, (assumed to be 0.1 % PAR, see below) to the surface and during a 24-hour period (t). ~~where t~~The photosynthetic parameters (P$^{B}_{max}$, α$^{B}$ and β$^{B}$) were determined by fitting the photosynthesis (P) vs. E curves generated from the incubations to the PP expression, i.e. the terms in the integral in Eq. (3), by a non-linear Levenberg-Marquardt least-squares routine (Press et al., 1992) and normali~~s~~zed with *in situ* chlorophyll ~~a~~ concentration obtained from the calibrated CTD-fluorescence measurement. The case without photo-~~-~~inhibition, i.e. β = 0 (Webb et al., 1974), in general, resulted in a poorer representation of the data (except for six incubations where the photo-inhibition term was set to zero) and the incubation experiments were, therefore, analysed with the photo-inhibition term included in Eq. (3). These model fits were found to be in very good accordance with the incubation data~~s~~. The maximum rate of photosynthesis, ~~(~~defined as P$^{B}_{max}$*~~)~~, was calculated for each P vs. E curve (note that P$^{B}_{max}$ only describes the maximum PP in the case without photo-inhibition).

Irradiation was measured continuously during the cruise and the hourly averaged insolation curve during the day was scaled to equal the daily averaged photosynthetically available radiation (PAR) measured from the MODIS-Aqua satellite measurements (Frouin et al., 2024) where the daily averaged PAR for July 2016 in the study area (13-28 July, 6.2° - 8.3° E, 56.2° - 58° N) was 506 $\mu$-E m$^{-2}$ s$^{-1}$. The vertical light extinction coefficient ($k_d$) was determined by linear regression of the log-transformed PAR-measurements from each CTD-cast. The average value from all the CTD-casts was found to be $k_d = 0.139 \pm 0.031$ m$^{-1}$ (std.dev, n=177), corresponding to a 0.1 % PAR depth level of 50 m. The 0.1 % PAR depth level was in this study assumed to represent the bottom of the euphotic zone.

Primary production estimates at individual sites are dependent upon the value for maximum rate of photosynthesis ($P^B_{max}$). However, $P^B_{max}$ (and all other measured photosynthetic parameters) represent the physiological condition of the phytoplankton community at the time of sampling. This~~e~~ means that $P^B_{max}$ ~~may~~ vary as a function of time of sampling (Richardson et al., 2017) or during different light conditions (e.g., photo-inhibition). Normalisation of the photosynthetic parameters with chlorophyll also represents an uncertainty in the PP estimates at individual stations as, for example, division with low chlorophyll values (e.g. some surface values were ~0.1 mg chl m$^{-3}$) may result in large uncertainty of the normalised values due to relatively large absolute errors. This uncertainty error has been shown to potentially have a significant impact on the estimation of photosynthetic parameters (e.g., Kumari, 2005; McKee et al., 2015). Finally, the fact that photosynthetic parameters were determined from incubations carried out on only one water sample from each sampling depth represents a source of uncertainty with respect to the estimates of PP at individual stations. Therefore, in order to~~However, photosynthetic performance is known to be influenced by the in situ light conditions (From et al., 2014) due to the potential for photoinhibition and the time of day that sampling takes place (Richardson et al., 2016). In order to directly~~ compare PP estimates from the stations we sampled, we ~~therefore~~ applied average values (median for all stations) ~~Average values~~ of photosynthetic parameters in the surface layer (5 m) and in the SCM ~~were calculated for the whole cruise and these average values were applied~~ in the calculation of PP. The uncertainties associated with the photosynthetic parameters are further considered in the Discussion. Surface values were assumed to represent the photosynthetic parameters in the upper 10 m and ~~whereas~~ average values from the SCM were assumed to represent the parameters for the water column below 10 m.

## 2.5 Vertical nutrient fluxes and f-ratios

Nitrate was depleted in the surface layer at almost every station and, therefore, assumed~~nitrate was considered as~~ to be the limiting nutrient. This assumption was ~~also~~ supported by the distribution of other nutrients (shown below). The nutricline was defined as the depth where nitrate equalled 0.5 $\mu$mol kg$^{-1}$ (the chosen threshold value had, in general, only a minor influence on the nutricline depth because nutrients were so~~of the nutrient~~ depleted in the surface layer). In general, water samples were taken close to the nutricline, i.e. within +/- 10 m. However, at 5 stations where the nutricline was not resolved well by the

sampling depths, samples from the neighbouring station (i.e. within 5-10 km) wereas included toat five stations increase the resolution. However, tTo minimisze the uncertainty of the nutricline depth estimate associated with the linear interpolation between two neighbouring water samples, the nutricline depth was found by linear interpolation between the corresponding potential density anomalies ($\sigma_\theta$) of the sample depths, and the nutricline depth was then identified from the corresponding $\sigma_\theta$ in the CTD-profile (an example is shown in Fig. 6). This approachmethod is based on the assumption that the nitrate concentrations between two water samples are more closely related to water mass characteristics than linearly to depth changes, i.e. a sharp pycnocline, not resolved by the water samples, is taken into account when the nutricline depth is estimated by this method. A comparison was made fororm the whole data set between nutricline depth estimates based on linear interpolation using depth and potential density anomaly levels, respectively., and tThe difference between the two methods averaged -1.4 $\pm$ 2.5 m (std. dev., n=77) and the differences ranged between -9.9 - 2.4 m. Thus, in general, the depth level-based method resulted in a deeper nutricline (-1.4 m) than the applied $\sigma_\theta$-method.

At all stations where nitrate was present (n=73), the nutricline was found to be located above the depth of the 0.1% PAR light level and, therefore, the flux of nitrate ($F_{NO3}$) for NP was found by calculating the maximum flux into the euphotic zone (only transports from vertical turbulent mixing were measured, thus, contributions from vertical advection were not considered). The vertical nitrate flux ($F_{NO3}$) due to turbulent mixing is defined as:

$$F_{NO3} = -k_v \frac{\partial NO_3}{\partial z} = -k_v \frac{\partial NO_3}{\partial \rho} \frac{\partial \rho}{\partial z} \qquad (4)$$

where the vertical nitrate gradient is reformulated in terms of density (Sharples et al., 2007). By applying this reformulated relationship, together with the definition of the vertical turbulent diffusion coefficient in Eq. (1), an expression for the nitrate flux in terms of the measured dissipation rate of TKE becomes:

$$F_{NO3} = \frac{\eta\Gamma \, \varepsilon \, \rho_0}{g} \frac{\partial NO_3}{\partial \rho} \qquad (5)$$

The advantage of this expression, compared to simply applying $k_v$ and the vertical nitrate gradient directly, is the dependence on the measured dissipation rate, rather than the derived $k_v$-value. The latter includes the calculation of the Brunt–Väisälä frequency, cf. (Eq. (2)). This term becomes close to zero in very turbulent conditions and, thereby, $k_v$ becomes sensitive to rounding errors and other uncertainties in the measurements. The gradient of nitrate at a given depth was determined linearly from the nearest water sample depths.

PP was related to the vertical nitrate flux by estimating the f-ratio, calculated as: $f = \eta_{N:C} \, F_{NO3}/PP$, where $\eta_{N:C}$ is the Redfield ratio between nitrogen and carbon, i.e. 16:106 (Redfield et al., 1963).

8

# 3 Results

## 3.1 Water mass distributions

The northern North Sea is a region in which North Atlantic water transported towards the Skagerrak, water masses formed in the shallower part of the North Sea and outflowing low-saline water from the Baltic Sea come together. Water masses and the general circulation in the area have been described by Danielssen et al. (1990) based on measurements in the Skagerrak and the north eastern North Sea in 1990-91, and the general water mass characteristics they identified are included in the description below. Their analysis was based on measurements obtained in the Skagerrak and the north-eastern North Sea in 1990-91.

The inflow of Atlantic water to the northern North Sea, in general, takes place between the Orkneys and Shetland, above the shelf east of the Shetland and in the deep Norwegian channel and the deep inflow in the Norwegian channel dominates during the summer period (Winther and Johannesen, 2006).

Atlantic water masses (AW) are characteris<del>s</del>zed by salinities > 35 and can be further delineated as upper Atlantic water (AWu, S = 35.00 - 35.15 and T = 8 - 10 °C) and a slightly colder and more saline deeper Atlantic water mass (AWd, S = 35.15 - 35.32, T = ~7 - 10 °C, Fig. 1b). The AWd was observed on the westernmost transects (Tr4 and Tr5) between 100 - 300 m along the shelf edge. High saline AWd was also present in the depth range 120 - 200 m on Tr1 (not shown). AWu was observed at the shelf edge at depths below 60 m on Tr2 - 5 whereas it was found at depths below 80 m on Tr1 (Fig. 2). An upward doming of the AWu was seen to reach to ~ 30 m between the shelf-edge and the Norwegian coast from where isotherms and isohalines tended to deepen towards Norway. Central North Sea water (CNSW, S = 34.80 - 35.0 and T = 8 - 10 °C), a mixture of Atlantic water and Scottish coastal water, was located above AWu and a distinct frontal zone between the two water masses was seen along the shelf-edge where bottom depths ranged between 40 and 60 m.

The influence of southern North Sea water (SNSW, S = 34.50 - 34.8, T = 8 - 12 °C) and low nitrate concentrations (note the larger temperature interval in mid-summer than defined in Danielssen et al. (1990)) and low nitrate concentrations, originating from the English Channel, was seen at the shallower stations (< 40 m) on all transects except Tr1. , where wWarm subsurface water between 20 - 40 m at Tr1 indicated an influence from the Jutland coastal water mass (JCW, S = 32 - 34 and T = 10 - 15 °C) on this transect. The surface mixed layer varied between 5 - 15 m with the lowest salinities seen in the Norwegian coastal water mass (S < 28) and the highest surface salinities being found above the well mixed shallow parts of the North Sea (S ~ 34.5).

A distinct subsurface oxygen maximum ($O_2$ > 240 μmol kg$^{-1}$) between ~15 - 35 m depth characteris<del>s</del>zed the deeper area north of the shelf-edge whereas a less well-defined maximum was present above the shelf-edge and in the shallow North Sea (Fig.

2c). The bottom water (~20 - 60 m) in the shallow areas exhibited~~had a~~ relatively low oxygen concentrations, i.e., < 200 µmol kg$^{-1}$. High nitrate concentrations character~~isz~~ed Atlantic water masses whereas very low nitrate concentrations were observed in the surface layer and above the shallow southern part of the area (Fig. 2d).

## 3.2 Chlorophyll ~~a~~ and nutrient distributions

The subsurface chlorophyll concentrations were relatively high (> 2 mg chl a m$^{-3}$) in the shallower regions of the study area ~~northern North Sea~~ (Fig. 3). A narrow well-defined subsurface chlorophyll maximum extended from the shelf-edge towards the Norwegian coast, i.e. close to the 27 kg m$^{-3}$ isopycnal. The depth of the subsurface chlorophyll maximum tracked the nutricline from the shelf-edge, where the nutricline was separating the nutrient-depleted surface layer from the nutrient rich Atlantic water (Fig. 4a, b).

In general, a sharp nutricline separated the nutrient depleted surface layer from the nutrient rich Atlantic water with nitrate concentrations above 6 µmol kg$^{-1}$. For example, an increase from values below the detection limit (0.1 µmol nitrate kg$^{-1}$) to values above 2 µmol kg$^{-1}$ was observed across a 5 m distance (35 - 40 m depth) at the shelf-edge on time series station T2 at Tr4 (57.31 °N~~, not shown~~). The nutricline between CNSW and AWu was located at density-anomalies of ~27.3 kg m$^{-3}$, whereas the nutricline was located below the 26.5 kg m$^{-3}$ isopycnal in areas influenced by SSW and Norwegian coastal water masses. Thus, high nutrient concentrations were found in the cold (< 8 °C) Atlantic water masses and low concentrations were associated with CNSW, SNSW and SSW.

### 3.2.1 Nitrate limitation and denitrification

Nitrate was not detectable at the southernmost stations south of 56.88° N at Tr5, 57.00° N at Tr4 and Tr3 and 57.21° N at Tr2, whereas the southernmost station at Tr1 showed detectable nitrate (0.2 - 0.3 µmol kg$^{-1}$ between the surface and 30 m) at the near-coastal station, likely influenced by nutrient-rich JCW (Fig. 1). Bottom samples were typically made down to ~5 m from the bottom, i.e. within the benthic boundary layer, and, considering the relatively large turbulent diffusion coefficients in the benthic boundary layer, this supported the interpretation that no detectable nitrate was present in the water column at the southernmost stations along Tr2-Tr5.

The assumption that nitrate was the limiting nutrient for phytoplankton was supported by the phosphate distributions, in that the N:P-ratio was found to be significantly below Redfield (16:1) at all stations and all depths, with the exception of a few samples above the shallow area (Fig. 4c). Nitrate depletion was observed at stations above the shallow southern North Sea, where excess phosphate compared to the Redfield N:P ratio suggested significant denitrification to be occurring. There was, in general, no indication of silicate limitation because relatively high~~large~~ values (up to 10 µmol kg$^{-1}$) were observed above

the nitrate-depleted shallow area and low silicate values in the deeper part were also associated with low nitrate concentrations (not shown).

## 3.3 Mixing and vertical nitrate fluxes

5   Dissipation of TKE was low, i.e., $< 10^{-9}$ W kg$^{-1}$, below ~40 m in the deeper areas north of the shelf-edge but increased by an order of magnitude above the shelf-edge, where values up to ~$10^{-6}$ W kg$^{-1}$ in the benthic boundary layer were recorded (Fig. 5a, b). Dissipation rates of TKE in the 20 – 40 m depth range varied between $10^{-8}$ - $10^{-9}$ W kg$^{-1}$ above the deeper areas and increased to $10^{-7}$ - $10^{-8}$ W kg$^{-1}$ above the shallow areas along Tr2. In the upper part of the water column, between 10 - 20 m depth, the dissipation rate of TKE increased to $10^{-5}$ - $10^{-7}$ W kg$^{-1}$ due to mixing induced by wind and waves. The distribution

10  of the vertical turbulent diffusion coefficient showed a characteristic pattern along all transects where very low $k_v$-values of $<10^{-6}$ m$^2$ s$^{-1}$ between 15 - 30 m depth characteri~~s~~zed the deeper open areas, i.e. around the pycnocline. E~~, while~~ elevated mixing was seen at the shelf-edge and in the ~10 m thick benthic boundary layer further south above the shallow shelf (Fig. 5c,d; note that the shallow turbulence profiles on Tr4 did not resolve the benthic boundary layer). The highest $k_v$-values, i.e., >~~above~~ $10^{-4}$ m$^2$ s$^{-1}$~~-~~. were observed at the shelf edge and in the benthic boundary layer above the shallow part of the shelf.

15

Vertical nitrate fluxes were calculated for all stations where both nutrients and turbulence profiles were measured. Examples are shown for four stations across the shelf edge on~~at~~ Tr4, obtained 27 July between 14h and 17:30h, with a station spacing of ~5km, in an area where there is a northward increase of the depth from 82 to 122 m (Fig. 6). The nutricline was located at ~35 m and this depth was relatively close to the elevated mixing in the bottom boundary layer. Increased mixing is seen at the

20  station located at 57.404 °N (Fig. 6c, g) and this results here in a maximum nitrate flux to the euphotic layer of 0.3 mmol N m$^{-2}$ d$^{-1}$ at ~40 m. ~~An example is shown from a station at Tr5 (57.41° N, 86 m) north of the shelf edge zone (Fig. 6). The maximum vertical nitrate flux into the euphotic zone (50 m) was relatively small and the largest values (~0.2 mmol N m$^{-2}$ d$^{-1}$) were associated with an increased mixing around 45 m (Fig. 6b), i.e. well below the nutricline depth at 35 m (this vertically localized increase in mixing around ~45 m was associated with the upper interface of a ~10 m thick and relatively homogeneous layer~~

25  ~~with a slightly lower temperature (not shown)).~~ In general, the maximum vertical nitrate flux into the euphotic zone in the deeper parts along the five transects was located 5-10 m below the nutricline (Fig. 3, orange squares). whereas the ~~However, the~~ SCM was~~, in general,~~ located at the nutricline (Figs. 3, 6a). Although the nitrate flux at this depth was relatively low, this showed the close relationship between SCM and nutricline depth. ~~Elevated mixing at this station was observed towards the bottom (below the euphotic zone) in the benthic boundary layer and resulted in nitrate fluxes of ~3 mmol N m$^{-2}$ d$^{-1}$.~~

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### 3.4 Photosynthetic parameters

Photosynthetic parameters can vary as a function of sampling time and in situ light conditions. Therefore, in order to be able to compare the potential PP at different stations, we averaged photosynthetic parameters for the surface layer (5 m) and from the SCM, respectively. In total, 64 incubations were made. Fifty eight of the incubations were fitted with the photo-inhibition
5    term whereas 6 incubations did not show any significant decrease for increasing light levels. Therefore, the inhibition term was excluded in these calculations. To make the data set representative for the whole study area, incubations from the closely spaced (1-3 km) stations on Tr2 were excluded (i.e. 14 stations between the two stations shown with incubations at Tr2 in Fig. 1a) and, to reduce the impact from outliers, representative values are calculated as median and median absolute deviation values (Table 1).

10

The median chlorophyll concentrations at the surface and SCM were 0.16 and 1.68 mg chl a m$^{-3}$, respectively. This reflected the general increase in chlorophyll with depth observed over the entire area. The chlorophyll-normali~~s~~zed photosynthetic parameters of the photosynthetic rate constant ($P^B_{max}$) and the slope of the PE-curve ($\alpha^B$) in the surface layer were 5.48 µg C (µg Chl h)$^{-1}$ and 0.041 µg C (µg Chl h µE m$^{-2}$ s$^{-1}$)$^{-1}$, respectively, and the corresponding values of $P^B_{max}$ and $\alpha^B$ at the SCM
15    were 2.33 and 0.027. Thus, $P^B_{max}$ was significantly lower at the SCM, in general accordance with previous studies (see review in Richardson et al., 2016) whereas $\alpha^B$ showed a weak decrease with depth (with overlapping uncertainty intervals between the two depth levels). In general, $\alpha^B$ has been found to increase with depth (resulting in a more efficient photosynthetic response at low light levels) and inspection of the vertical distribution showed at tendency to higher values between 15 -25 m depth (i.e. 2 - 3 e-folding depth of PAR) and lower values below 30 m resulting in a lower median value from SCM level. It was noted
20    that a similar pattern of $\alpha^B$, with a subsurface maximum, has been observed at the European shelf in the Celtic Sea (Hickman et al., 2012).

There was a significant averaged photo-inhibition ($\beta^B$) at both depth levels (1.70 and 3.00 (10$^{-3}$ µg C (µE m$^{-2}$ s$^{-1}$ h)$^{-1}$)). However, the average values at these depths were not significantly different. The maximum PP was ~~characterized~~ characterised by $P^B_{max}{}^*$-
25    values of 4.76 and 1.72 µg C (µg Chl h)$^{-1}$ at the surface and SCM, respectively, corresponding to maximum PP at PAR-levels of 413 and 192 µE m$^{-2}$ s$^{-1}$. The averaged parameters for the two depth levels of $P^B_{max}$, $\alpha^B$ and $\beta^B$ were applied for calculating PP in the water column according to Eq. (3). A comparison was made between the resulting PE-curves and the maximum averaged PP from all the incubations (i.e. the $P^B_{max}{}^*$ and $E_{max}$ in Table 1). T~~and t~~hese values were found to fit the averaged curves for the two depth levels within 5% and, therefore, the PE-curve based ~~on the~~ values in Table 1 were assumed to be
30    representative of~~for the~~ average conditions and applied in the calculation~~s~~ of PP for all of the stations.

### 3.5 Vertically integrated chlorophyll a, PP and NP

The vertically integrated chlorophyll in the euphotic zone (50 m) showed a local maximum south of the shelf-edge along all transects and a decrease in chlorophyll further south at the two westernmost transects, i.e. Tr4 and Tr5 (Fig. 7a). Relatively low values were observed in the area north of the shelf-edge with the exception of an area close to Norway where high values were observed. The averaged vertically integrated chlorophyll from all stations was 29.9 ± 7.8 mg chl a m$^{-2}$ (std. dev., n = 128).

The distribution of vertically integrated total PP showed a similar pattern with increased PP-levels south of the shelf edge and a somewhat reduced PP further south at the two westernmost transects (Fig. 7b). A tendency to minimum values was observed at the shelf edge with an increasing tendency towards Norway with high PP-values being observed at a few stations near the Norwegian coast. The averaged vertically integrated PP from all stations was 476 ± 110 mg C m$^{-2}$ d$^{-1}$ (n=128).

The maximum nitrate flux into the euphotic zone (F$_{NO3}$) and the f-ratio wereas calculated for each station where nitrate and turbulence measurements were made and where nitrate was present in detectable concentrations. Elevated fluxes and f-ratios were found along the shelf-edge on Tr2-Tr5 (nitrate fluxes were not measured at the shelf edge and at shallow stations at Tr1) and also near the Norwegian coast at Tr1 and Tr4, and low nitrate fluxes and f-ratios characterized characterised the open area between the shelf edge and Norway (Fig. 7c, d).

### 3.6 Distributions across the shelf-edge

A comparison of distributions of PP related parameters across the shelf-edge showed common trends over all five transects (Fig. 7, S28). Vertically integrated chlorophyll and PP were relatively low, with values of ~20 mg chl a m$^{-2}$ and ~400 mg C m$^{-2}$ d$^{-1}$, respectively, on the southernmost parts of the transects. A gradual northward increase towards maximum values (of ~60 mg chl a m$^{-2}$ and >1000 mg C m$^{-2}$ d$^{-1}$) was observed within a distance of ~20 km south of the shelf edge on Tr3 - Tr5. Transect 2 did not reach as far south of the shelf-edge. This could explain the southern maximum in chlorophyll and PP at Tr2. Transect 1 was influenced by nutrient rich JCW and this may be the reason for the high chlorophyll concentration (43 mg chl a m$^{-2}$) and PP (1746 mg C m$^{-2}$ d$^{-1}$) at the southernmost station on this transect.

Relatively low values of ~20 mg chl a m$^{-2}$ and 400 mg C m$^{-2}$ d$^{-1}$, respectively, characterisszed the shelf-edge zone. These values increased slightly towards Norway to ~30 mg chl a m$^{-2}$ and 5-600 mg C m$^{-2}$ d$^{-1}$, respectively. High values were observed in Norwegian coastal water masses on Tr1 and Tr4, probably due to PP being stimulated by coastal upwelling (also indicated by relatively cold Norwegian coastal surface water masses observed from satellite in Fig. 1b). Stations on Tr2 and Tr4 were visited twice within one week. Significant temporal variation of chlorophyll and PP was observed (Fig S28a,b; bullets vs. open circles)

between samplings. Chlorophyll increased by up to 40% above the shallow area near the shelf edge and a similar increase was seen in PP. Relatively large temporal variations were also seen in these parameters in the coastal Norwegian water masses.

A nutricline could, in general, not be identified above the shallow areas south of the shelf-edge except at two stations on Tr3
5 and Tr4 (cf. Fig. 2c, d, at both stations high nitrate concentrations of 0.9 - 1 μmol kg$^{-1}$ were only measured at 5 m while low values of 0.1 - 0.3 μmol kg$^{-1}$ were found below 10 m). The deepest nutricline depths (~40 m) were found near the shelf-edge. Nutricline depth decreased to ~20 m going northwards but then increased again in the coastal Norwegian water masses (Fig 8c).

10 Nitrate fluxes were generally very low (< 0.1 mmol N m$^{-2}$ d$^{-1}$) in the deeper area north of the shelf edge due to low vertical mixing in the upper 50 m. However, elevated nutrient fluxes of ~1 mmol N m$^{-2}$ d$^{-1}$ were seen in the shelf edge zone and near the Norwegian coast. This resulted in f-ratios above 0.10 in these regions compared to < 0.02 for the remainder of the study area (Fig. 7, S2~~8d, e~~).

15 The distributions were ~~analyzed~~ analysed across the shelf edge by dividing the stations into three depth ranges characteri~~s~~zing the shallow area (50 - 80 m), the shelf edge zone (80 -130 m) and the deep area (> 130 m), respectively (Table 2). Although the shelf edge was characteri~~s~~zed by the largest nutrient fluxes, the averaged values were not significantly higher than observed above the deeper areas. However, the depth of the maximum flux was found to be significantly deeper (~43 m) above the shelf edge than in the deeper area (~32 m). This can be explained by the significantly deeper nutricline at the shelf edge (~35 m)
20 than observed above the deeper area (~27 m). Distributions of vertically integrated chlorophyll and PP support that minimum values are found above the shelf edge. H~~,~~however the low values are not significantly different from the larger values above the deeper and shallower part of the area.

### 3.7 Temporal variability at the shelf edge

25 Data was collected over 36 hours from a~~A~~ time series station ~~was observed~~ located~~over 36 hours at a location~~ on the shelf edge on~~at~~ Tr4 (depth 82 m, 57.314 °N, 6.765 °E, from 29 July 7:07h to 30 July 19:25h) where CTD-casts and turbulence measurements were carried out every hour (although~~except that~~ no turbulence measurements were made during the night). Variability was related to the tidal current obtained from the barotropic OTIS model of the North Sea (Egbert and~~-~~ Erofeeva, 2002). T~~,~~the model depth (h) at the time series location was 80 m, it considers eleven tidal constituents, its general performance
30 has previously been validated and a comparison was also made against tide tables for the period from Hanstholm harbor located on~~at~~ the Danish coast (57.17 °N, 8.62 °E). The model result~~and it~~ showed ~~an~~ excellent agreement with the tidal phases. T~~) and the t~~idal energy input was estimated from the cube of the barotropic tidal current (u$^3$, e.g. Simpson and Sharples, 2012). This energy input represents the source for tidally~~-~~ induced vertical mixing and can be compared with turbulent mixing in the water column.

The water column was characteri~~s~~zed by a homogenous mixed layer in the upper 5-10 m, a pycnocline at ~20 m, and a relatively homogenous temperature and salinity distribution below ~45 m ($\theta < 8$ °C) (Fig. 8). A sharp nutricline between 38 - 40 m separated the nitrate-depleted surface layer from the nitrate rich bottom water (~ 2 µmol kg$^{-1}$, not shown). An oxygen maximum

5 layer between 20 - 40 m separated the oxygenated surface layer from the bottom layer with a relatively lower oxygen concentration. ~~WA~~ ~~w~~A weak temperature and salinity stratification wa~~sere~~s observed in the start and end of the period (i.e. between DoY 210.3-210.7 and 211.3-211.7) and a corresponding change was observed in the bottom oxygen concentration. The period between DoY 210.6-211.2 wa~~sere~~s characteri~~s~~zed by a relatively homogenous bottom layer (< 40 m). ~~I and i~~Increased turbulence ($\varepsilon$, $k_v$) and decreased stratification ($N^2$) w~~ere~~as also observed in this period (Fig. 8d-h). Mixing in the bottom layer increased

10 simultaneously with tidal energy input (Fig. 8a, b). ~~T and t~~This indicated that tidal barotropic currents overlain on baroclinic currents along the shelf edge could explain the temporal variability in~~of~~ turbulence.

Dissipation of TKE in the bottom layer at the time of the maximum observed dissipation (DoY=210.8) was comparable with the energy input from the tides (~10$^{-3}$ W m$^{-2}$). This ~~and~~ suggests~~s~~ that additional energy for turbulence may be provided from

15 non-tidal currents along the shelf-edge (strong eastward currents below 20 m were noted at the time of~~during~~ some of the turbulence profiles). A relatively large deepening of both T, S and O$_2$ below the pycnocline was observed between DoY ~ 211.25-211.4. Nutrient concentrations~~samples~~ below 60 m showed an increase from 2 - 3 to 5 - 6 µmol kg$^{-1}$. T~~, and t~~his showed~~indicated that~~ advection of water below the pycnocline could explain the short-term variation observed.

20 Thus, the observed temporal variability in water column structure and nutrient distributions at the shelf edge shows that varying mixing intensities may interfere with the bottom of the euphotic zone and, thereby, promote diapycnal nutrient fluxes and stimulate NP. The variability arises due to different physical processes, which can~~may~~ not be identified in detail from the present data set. This may ~~, and this~~ also explain the observed variability between~~among~~ stations located in the shelf edge area (Table 2). Periods of low mixing in the euphotic zone may be followed by short periods of intense mixing. Such ~~and this~~

25 temporal variability is~~, therefore,~~ a challenge to document over~~in~~ a larger area.

**4 Discussion**

The shelf edge was identified in this study as a potential area of ~~localized~~ localised NP during the stratified summer period in the ~~north east~~northeastern North Sea. Very low nitrate fluxes and f-ratios were estimated for most of the open water extending

30 northwards from the shelf edge towards Norway. Likewise, little or no NP was estimated to be occurring in the nitrate depleted shallow reaches of the southern North Sea. Previous studies have shown that ~~sS~~shelf edge areas ~~have been shown to~~can be productive regions, for example characteri~~s~~zed by ~~of~~ increased fishing activity (Sharples et al., 2013). In relation to the

15

observations reported by Sharples et al.,~~is, w~~We ~~speculate~~hypothesize that the abundance of fish in this area could be related to a ~~locali~~sed increase ~~in~~d NP relative to surrounding waters. It can also be noted that the ~~north east~~northeastern shelf edge area is characteri~~s~~zed by elevated fish species diversity (ICES, 2008), suggesting that the introduction of new nutrients to the euphotic region of the water column identified for this region may be influencing both food webs and ecosystem structure.

5 .

~~Localized~~ Localised NP at the shelf edge will also influence the oxygen concentration in subsurface water masses (Fig. 2). This can have a direct influence on ambient water with relatively low oxygen above the shallow shelf and influence conditions further downstream, where water masses from the shelf edge eventually reach the North Sea/Baltic Sea transition zone and contribute to bottom water ventilation in more eutrophic areas (Bendtsen et al., 2009).

10

The possible occurrence of l~~L~~ocali~~s~~zed NP also implies that physical processes on relatively small spatial scales (~1 km) are important for modelling NP in the area. This is in general accordance with model studies where the resolution of physical processes at high spatial scales was found to be necessary to explain observed patterns of PP in the North Sea (Skogen and Moll, 2000). Holt et al. (2012) applied a high-resolution model of the whole North Sea area and showed that nutrient transports

15 towards the shelf area were of primary importance for understanding PP and also for assessing the impact from climate change. Locali~~s~~zed NP at the shelf edge in the ~~north east~~northeastern North Sea may be representative for the open ocean - shallow shelf exchange of nutrients more generally. If so, then this NP may also impact nutrient conditions above the shallow central North Sea and may explain some of the recent decadal decline of PP in this area (Capuzzo et al., 2018).

20 **4.1 Regenerated production above the shallow shelf**

There was no measurable nitrate in the water column at stations south of the shelf-edge., i.e. an area where the whole water column was within the euphotic zone, i.e. < 50 m (Fig. 1a, yellow lines). This indicates that nitrate sinks, i.e. biological consumption or denitrification, exceed nitrate sources, i.e. nitrification, nitrogen-fixation or advective supply during summer months in this region. Significant nitrification may take place in the water column (Clark et al. 2008; Zehr and Kudela, 2011)

25 or in the sediment and, as pointed out in the work of Dugdale and Goering (1967), nitrate can, in this case, not be considered as a non-regenerated nutrient form in the euphotic zone. Yool et al. (2007) estimated a global specific nitrification rate of 0.2 $d^{-1}$, thus, even small concentrations of ammonium could lead to significant nitrification rates.

Concentrations of ammonium were, however, very low in the nitrate depleted area. For example, ammonium was undetectable

30 at all nitrate-depleted stations on Tr5 and this indicated a relatively small contribution from nitrification in the euphotic zone. O~~However, o~~bserved nitrification rates span a large range (Yool et al., 2007) and the importance of nitrification varies between

ocean regions (Clark et al, 2008; Fawcett et al., 2015). Therefore, it remains an open question whether or not significant nitrification takes place in the euphotic zone in the area.

Diazotrophy constitutes another potential source of nitrogen to the nitrate-depleted surface layer and N$_2$-fixation has been measured in the southern North Sea at Dogger Bank (Fan et al., 2015). However, the estimated nitrogen fluxes from N$_2$-fixation were very small compared to the relatively high PP. Increased nutrient fluxes and NP at the shelf-edge could also support PP in the ambient shallow areas through isopycnal transport of dissolved organic material. A substantial fraction of dissolved organic material remineralis~~z~~es on time-scales of days to weeks (Bendtsen et al., 2015; Hansen and Bendtsen, 2014) and isopycnal transport of organic matter could then supply organic nitrogen from the shelf edge zone. Both the nitrification and isopycnal supply of organic material, th~~u~~se~~reby~~, potentially provide new nitrogen to the shallow area and this confuses the concept of nitrate-based new versus regenerated production here. However, nitrification in the euphotic zone would be based on regenerated production and, therefore, we consider PP to be regenerated production in areas without detectable nitrate in the water column.

Recycling of organic matter above the shallow shelf could, th~~u~~se~~reby~~, be maintained by regenerated organic matter in the water column or sediment and we analysed whether this was in accordance with estimated carbon and nitrogen pools. The high biomass in the shallow area, indicated by chlorophyll concentrations of ~2 - 4 mg chl-~~a~~ m$^{-3}$ in the bottom layer, would rapidly consume a regenerated pool of inorganic nitrogen. The regenerated cycling could, in principle, originate from the winter concentration of nitrate of ~6 mmol DIN m$^{-3}$ in the area (Pätch and Kühn, 2008). The nitrate distribution in the shallow area indicates~~and, when accounting for the~~ a large denitrification ~~in the shallow area~~ ranging within 0 - 4 mmol DIN m$^{-3}$ (Fig. 4c), and this would correspond to a pool of more than ~2 mmol DIN m$^{-3}$ available for establishing the phytoplankton biomass. D~~Large d~~enitrification rates in the sediment of 0.02 - 0.1 mmol N m$^{-2}$ d$^{-1}$ have been observed at the Dogger B~~sb~~ank between May and August (Fan et al., 2015) and such high rates could explain the indicated nitrate sink. Assuming a Redfield C:N molar ratio of 6.6 and a C:chlorophyll-~~a~~ ratio of 1 mg C/50 mg chl-~~a~~, this would equal ~3 mg chl-~~a~~ m$^{-3}$, i.e., in general accordance with the observed concentrations~~levels of~~ of <1 and~~and~~ ~4 mg chl-~~a~~ m$^{-3}$ in the surface and bottom layers, respectively. Relatively low oxygen concentrations in the bottom layer also suggested an active bacterial respiration (Fig. 2c) to be occurring here. Thus, regenerated production could be maintained and explained by recycling of an initial nutrient pool from early spring.

### 4.2 Photosynthetic parameters and PP

Estimates of PP based on photosynthetic parameters from $^{14}$C-incubations and in situ conditions of light and chlorophyll rely on several critical assumptions, including the values used for photosynthetic parameters, the distribution of chlorophyll, light conditions and nutrient-carbon relationships. Photosynthetic parameters from individual incubation experiments were well described by the PP-model (i.e. PP described by the terms in the integrals in Eq. (3)) so uncertainty is mainly related to the

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spatial and temporal variability of these parameters. Photosynthetic parameters are bulk parameters describing the physiological response of the phytoplankton community as a whole to a given a photon flux. Thus, both algae composition and actual fitness of the cells contribute to the observed range of these parameters.

The photosynthetic parameters represent the conditions of the phytoplankton community at the time of sampling. However, these may vary during the day (Richardson et al., 2017) or during different light conditions (e.g., photo-inhibition). Thus, PP-calculations based on spatial and temporal averaging of the photosynthetic parameters from the surface and SCM (cf. Table 1) may result in a more representative PP than obtained from photosynthetic parameters obtained from a single PP-incubation. sto.the fact that only one sample was taken from each depth for the incubation experiments from which photosynthetic parameters were determined

The values reported here (Table 1) for photosynthetic parameters are comparable with those found in previous studies in the North Sea (e.g. Weston et al., 2005). However, vVariability of the photosynthetic parameters, e.g. is critical for the PP calculations. Tthe uncertainty of the surface value of $P^B_{max}{}^*$ of ~±30%, implies a corresponding uncertainty in PP. This spatial variability is not accounted for in this study where all stations were assumed to be represented by a common set of photosynthetic parameters. Thus, using a common set of photosynthetic parameters implies an uncertainty is a simplification even within this relatively small study area, and similar limitations would probably apply to other PP estimates for the North Sea area. These considerations illustrate thatwhy a better understanding of the distributions of photosynthetic parameters and the factors underlying these distributions is a prerequisite for improved estimates of PP on regional and larger scales.

Additional uncertainties are related to the chlorophyll distribution due to the application of an overall relationship (i.e. linear regression) between CTD fluorescence and measurements of GF/F filtered chlorophyll samples. Similarly, the light extinction coefficient was assumed to be constant and, although a relatively small variation was found in the area, this together with the assumption of constant daily PAR distribution during the days in July, also can introduce errors in the local PP estimates. Finally, estimates of new production imply a conversion from nitrate to carbon and a fixed ratio may not be representative for the different communities in the area.

The general limitations above could have been accounted for by increasing the number of incubations at each station but that would have been at the expense of the spatial coverage of the data set. Thus, the PP and NP estimates are limited by the above simplifications and should, therefore, be interpreted as a general representation of PP in the area, reflecting the combined influence from the vertical chlorophyll distribution and PAR.

Given the uncertainties related to the determination of the absolute rate of PP at individual stations, we believe the most robust manner by which to compare PP and NP over our study area is to use constant (average) values for photosynthetic parameters for all stations.

## 4.3 Nutrient fluxes and NP at the shelf edge zone

The largest vertical nitrate fluxes of 0.5 - 1.5 mmol N m$^{-2}$ d$^{-1}$ were restricted to the area~~localized~~ above the shelf edge where increased mixing in the bottom layer intersected the nutricline within the euphotic zone. Similar large nitrate fluxes have been observed along the European shelf where tidal~~ly~~ -induced (Sharples et al., 2001; located in the English Channel) or wind-induced mixing (Williams et al., 2013; Celtic Sea) le~~a~~ads to vertical fluxes of 1 - 2 mmol N m$^{-2}$ d$^{-1}$. Significantly larger fluxes have also been observed above steep bathymetric gradients (Tweddle et al., 2013). Wind and tidal mixing may also provide energy for intensified mixing along the ~~north east~~northeastern shelf edge in the North Sea, although the present study did not resolve the specific cause for increased mixing. Shelf-edge zones are dynamic areas where cross-shelf exchange may occur due to many different dynamic processes (Huthnance, 1995: Brin, 2012).

Mixing associated with~~from~~ wind and tides (e.g. Burchard and Rippeth, 2009) as well as~~(Sharples et al, 2007; 2009) and~~ breaking internal waves (Sharples et al, 2007; 2009) ~~(e.g. Burchard and Rippeth, 2008)~~ has been shown to be important for vertical nutrient fluxes in shelf areas. ~~These potential sources of mixing were analysed here from two time series stations (data not shown) at the shelf edge taken around spring tide and neap tide (20-21 and 29-30 July, according to OTIS tidal predictions; Egbert and Erofeeva, 2002). Elevated mixing of nutrients into the euphotic zone due to tides or short-term mixing events was not observed at these locations.~~ The specific physical processes behind increased turbulent mixing cannot be identified from the present data set. M~~However, m~~easurements on~~at~~ the time series station at the shelf edge showed that elevated mixing occurred in phase with the tidal energy input but also that additional energy sources likely contributed to the elevated mixing, e.g. energy from non-tidal currents. Short term variability associated with advection of ambient water masses was also observed. T~~ and t~~his could possibly be related to sub-mesoscale eddies or other transport processes occurring s~~ ~~below the pycnocline. The time series station T2 at Tr4 showed an important feature where mixing associated with the bottom boundary layer increased and intersected~~interfered with~~ the bottom of the euphotic zone. Thus, the combined effect from a deep nutricline and elevated mixing provide a mechanism for increased diapycnal nutrient fluxes along the shelf edge.

Other processes may be important on the ~~north east~~northeastern shelf edge due to the large in- and outflow of Atlantic water masses. It is interesting to note that the deepening of the nutricline from the open areas towards the shelf edge mirrors~~follows~~ the slope of the pycnocline. The slope of the pycnocline implies, via the thermal wind equations, an increased eastward baroclinic velocity component with depth, in accordance with the general cyclonic circulation in the area. Thus, deepening of the nutricline can potentially be explained as a dynamic response to a shelf-edge current transporting Atlantic water into the area.

The conditions across the shelf edge observed during the stratified summer season may, therefore, be considered as a stable quasi-stationary system where mixing at the shelf edge, associated with a deep nutricline and nutrient rich bottom currents,

provide nutrients to the euphotic zone stimulating localised new production in this area (Fig. 9). Isopycnal mixing may provide organic matter for increased regenerated production above the nitrate-depleted shallow shelf area and also, together with upwelling along the Norwegian coast, provide fresh organic material to the euphotic zone off the shelf edge towards Norway. Thus, the tendency towards increased chlorophyll concentrations and PP on either side of the shelf edge mightcould also be

5 explained as being a result offrom the gradual build-up of biomass as nutrients are transported away from the shelf-edge region by isopycnal mixing. Alternatively, the tendency to low values above the shelf edge could also be explained by a larger grazing pressure above the shelf edge. Thus, a full explanation of the tendency to low chlorophyll and PP above the shelf edge area cannot be determined from these data.

10 **4.4 Vertical nNutrient fluxes in the euphotic zonenorth of the shelf edge**

The position of the SCM was closely related to the depth of the nutricline (e.g. Fig. 3 and 6) and located in the middle of the euphotic zone (average nutricline depth from all stations was 29.1 ± 9.7 m, n = 83). The maximum nitrate flux was found at depth levels between 3.4 m above and 23.1 m below the nutricline. However, but, on average, it was located 6.4 ± 7.7 m (n=73) below the nutricline depth (e.g., Fig. 6). Thus, the maximum nitrate flux was, in general, within the euphotic zone but

15 significantly below the SCM (Fig. 3). This implies that internal recycling from below the SCM towards the surface of regenerated nitrogen is necessary for maintaining the phytoplankton biomass in the upper layer. Considering the relatively low vertical mixing rates around the SCM (e.g., a turbulent diffusion coefficient of $<5 \cdot 10^{-5}$ m$^2$ s$^{-1}$ implies a time scale of ~3 weeks for mixing across a 10 m thick layer, Fig. 5), this indicates that other transport processes within the euphotic zone are important in this area. One possible mechanisms could be, e.g. diel vertical migration of plankton. (e.g., Raven and Richardson, 1984).

20 Raven and Richardson (1984) showed the potential for diel vertical migration as an efficient strategy for phytoplankton to get access to both nutrients and light. Such a strategy might be particularly beneficialThis would, in particular, be a beneficial strategy for phytoplankton in the low-mixing zone in the pycnocline north of the shelf edge (e.g., Fig. 5d at ~20 m depth north of 57.4°N), where the vertical diffusion coefficient is below $5 \cdot 10^{-5}$ m$^2$ s$^{-1}$ in a ~20 m deep layer. Applying (e.g., using a typical swimming speed for some dinophytes of ~10 m day$^{-1}$ across a 10 m deep layer in such a region impliesresults in a Peclet

25 number >> 1, thus, diel vertical migration is a potential additional nitrogen transport although this cannot be documented from our data).

**4.5 Nutrient fluxes north of the shelf edge**

Nutrient fluxes and NP increased close to the Norwegian coast (Fig. 7, S28). This was in accordance with chlorophyll a

30 estimates (Hu et al., 2012) based on daily images from the MODIS-Aqua satellite: A large algal bloom was observed 6 July (not shown) and covered the area off the southern-most part of Norway. A satelliten image from 20 July (Fig. 1a) showed

increased chlorophyll concentrations~~levels~~ near the Norwegian coast and colder sea surface temperatures along the coast also indicated influence from upwelling of subsurface water masses (Fig. 1b). Although our observations were made more than 12 nautical miles from the coast, the elevated chlorophyll and PP values at Tr1 and Tr4 are likely related to these features. A tendency to a thicker chlorophyll layer around the SCM and a deeper nutricline at Tr4 and Tr5 also indicates increased
5   production and supply of nutrients~~mixing, upwelling, or eddy activity~~ near the coast. Mixing processes along the Norwegian shelf edge may, therefore, similarly contribute to NP in the area.


**5 Conclusions**

Relatively high PP and chlorophyll concentrations of 476 mg C m$^{-2}$ d$^{-1}$ and 30 mg chlorophyll m$^{-2}$, respectively, characterised the stratified ~~north east~~northeastern North Sea in July 2016. The greatest values were found above the shallow shelf and near
10  the Norwegian coast. Turbulence measurements showed maximum dissipation rates of TKE in the benthic boundary layer above the shallow shelf area and elevated mixing above the shelf edge zone, whereas very low vertical mixing rates characterised the deeper open area. Chlorophyll was concentrated in a subsurface chlorophyll maximum located near the nutricline and, on average, about 6 m above the depth of the maximum vertical nitrate flux in the deeper area north of the shelf edge. Chlorophyll was concentrated in the bottom layer above the shallow and nitrate depleted shelf area. The nutricline was
15  located significantly deeper above the shelf edge area (depth ~80 - 130 m) than in deeper water columns~~areas~~. Significant NP was found above the shelf-edge where vertical nitrate fluxes of 0.5 - 1.5 mmol N m$^{-2}$ d$^{-1}$ implied f-ratios above 0.10, whereas very low nutrient fluxes characterised the open area above the Norwegian Trench (f-ratios < 0.02). This localised NP along the shelf edge, potentially represents an important key to understanding temporal variability in~~of~~ the distribution of organisms (diversity), biological production, and ecosystem structure ~~and diversity~~ in this productive area.
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**Author contribution**

Measurements of primary production and turbulence were carried out by KR and JB, respectively, and both ~~analyzed~~analysed the data and prepared the manuscript.

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**Figure 1** VERMIX station map of the five transects in the north-eastern North Sea overlain on (a) surface chlorophyll a (mg chl m$^{-3}$) and (b) sea surface temperature (°C) from MODIS satellite images (4 km resolution) obtained 20 July 2016 (clouds are shown in dark gray). (a) CTD stations (bullets) and stations where $^{14}$C-incubations for primary production were used for

estimating photosynthetic parameters in the area (white circles) along the five transects (Tr1-5). Horizontal yellowgray bars (Tr2-5) show the separation between nitrate-deplete and nitrate-replete areas. Water masses in the area are indicated (see text). Bathymetry is contoured in meters.

**Figure 2** Distributions along Tr4 of (a) potential temperature (°C, colours and white contours, additional contours above 16 °C in 0.5 °C intervals), (b) salinity (psu, colours and white contours, additional contours between 26-34 in 0.5 psu intervals) and contours of potential density anomalies (intervals of 1 kg m$^{-3}$, orange lines) and, (c) oxygen (μmol kg$^{-1}$, colours and black contours) and (c) nitrate (μmol kg$^{-1}$, colours and white contours and orange contours of potential density anomalies as in b). Vertical lines show location of the CTD-measurements.

**Figure 3** Distributions of chlorophyll a (mg chl m$^{-3}$, colours and black contours, additional white contours are shown in intervals of 2 mg chl m$^{-3}$) along Tr1-Tr5 (a-e). Nutricline depths (red bullets) and depths with maximum nitrate flux into the euphotic zone (orange squares) were calculated at each station where water samples (black triangles) and turbulence profiles were made, respectively. Contours of potential density anomalies are shown in intervals of 1 kg m$^{-3}$ (orange lines). Note the different latitude-intervals in the figures.

**Figure 4** (a) Potential temperature-salinity diagram of all CTD-measurements and (b) a high-saline subset of the measurements (small grey bullets). Water sample concentrations of nitrate are shown with large bullets in (a,b) (μmol kg$^{-1}$, colour bar). Contour lines show isopycnals of potential density anomalies and selected water masses are indicated. (c) Nitrate vs phosphate for all water samples. The total water depth is shown with colours (m) and the relationship $[NO_3^-]= \eta_{N:P} [PO_4^-]$, $\eta_{N:P} = 16:1$, is shown with a grey dashed line.

**Figure 5** Turbulence measurements along Tr2 (a,c) and Tr4 (b,d). (a,b) Logarithm (Log$_{10}$) of dissipation of turbulent kinetic energy (W kg$^{-1}$) and (cb,d) calculated vertical turbulent diffusion coefficient (m$^2$ s$^{-1}$).

**Figure 6** Vertical profiles from a four stations across at the shelf edge of (upper panelsa) potential density anomaly, chlorophyll a and nitrate (bullets; sample depths, line; interpolated values by the σ$_\theta$ method) and (lower panelsb) dissipation of TKE (average value and values from the two shear sensors are shown with bullets and open circles, respectively), Brunt-Väisälä frequency (dashed line), turbulent diffusion coefficient and the vertical turbulent nitrate flux. The nutricline depth (DNO3) and depth of the euphotic zone (0.1% PAR) are shown.

(dashed and dotted lines) and station information of locations, D$_{NO3}$ and maximum F$_{NO3}$ to the euphotic zone are summarizszed in the tables (e-h).

**Figure 7** (a) Vertically integrated chlorophyll a (mg chl a m$^{-2}$) and (b) primary production (mg C m$^{-2}$ d$^{-1}$). Values are proportional to the diameter of the circles. (c) Distribution of maximum nitrate flux to the euphotic zone (F$_{NO3}$, mmol N m$^{-2}$ d$^{-1}$) and (e) f-ratios forin the euphotic zone (colours, no unit).

**Figure 8** Distributions along the five transects of (a) vertically integrated chlorophyll a (mg chl a m$^{-2}$), (b) primary production (mg C m$^{-2}$ d$^{-1}$), (c) nutricline depth (m), (d) maximum nitrate flux into the euphotic zone (mmol N m$^{-2}$ d$^{-1}$) and (e) f ratio in euphotic zone. Repeated stations on Tr2 and Tr4, separated in time by about a week, are shown with bullets and open circles.

**Figure 8** Time series station over 36h at the shelf edge. (a,b) Tidal current speed cubed, ctd-measurements (c, e, g, h) of potential temperature, salinity, oxygen and Brunt Väisälä frequency, respectively. Turbulence measurements of (d) dissipation rate of TKE and (f) calculated vertical turbulent diffusion coefficient. Observations are shown with small gray bullets and samples for water chemistry is shown with bullets in (g)s.

5   **Figure 9**9 Sketch of conditions across the shelf edge zone during summer. The largest f-ratios are found above the shelf-edge zone where the nutricline ($D_{NO3}$) gets in contact with elevated mixing near the bottom. Deep waters are characterized by high nitrate concentration whereas surface water and water above the shallow North Sea (NS) are nitrate depleted.

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**Table 1.** Distribution of photosynthetic parameters. Median values, and absolute median deviations (number of samples $n$ in parenthesis) of photosynthetic parameters at 5 m below the surface and at the SCM.

| Depth level | Depth | $P^B_{max}$ * | $P^B_{max}$ | $\alpha^B$ | $\beta^B$ | $E_{max}$ | Chl a |
|---|---|---|---|---|---|---|---|
| | [m] | [µg C (µg Chl h)$^{-1}$] | [µg C (µg Chl h)$^{-1}$] | $10^{-2}$·[µg C·(µg Chl h µE m$^{-2}$ s$^{-1}$)$^{-1}$] | $10^{-3}$·[µg C (µE m$^{-2}$ s$^{-1}$ h)$^{-1}$] | [µE m$^{-2}$ s$^{-1}$ h] | [mg chl m$^{-3}$] |
| Surface | 5.0± 0.0 (23) | 4.76 ± 1.33 (19) | 5.48 ± 0.87 (23) | 4.10 ± 0.90 (23) | 1.70 ± 1.70 (23) | 413 ± 76 (19) | 0.16 ± 0.06 (23) |
| SCE | 27.0± 5.0 (25) | 1.72 ± 0.38 (24) | 2.33 ± 0.64 (25) | 2.70 ± 0.80 (25) | 3.00 ± 0.90 (25) | 192 ± 26 (24) | 1.67 ± 0.73 (25) |

**Table 2** ~~Distributions across the shelf edge.~~ Median values, and absolute median deviations in three depth intervals of depth, depth of maximum nitrate flux ($Depth_{max}$), maximum nitrate flux into the euphotic zone ($FNO3_{max}$), depth of nutricline ($D_{NO3}$), vertically integrated chlorophyll a ($Chl_{int}$) and primary production (PP).

| Depth interval (m) | Depth (m) | $Depth_{max}$ (m) | $FNO3_{max}$ (mmol N m$^{-2}$ d$^{-1}$) | $D_{NO3}$ (m) | $Chl_{int}$ (mg chl a m$^{-2}$) | PP (mg C m$^{-2}$ d$^{-1}$) |
|---|---|---|---|---|---|---|
| 50 - 80 | 65±6 (25) | 39±3 (25) | 0.05±0.04 (25) | 34.5±4.5 (28) | 34.8±13.3 (69) | 476±138 (69) |
| 80 - 130 | 97±11 (18) | 43±3 (18) | 0.11±0.07 (18) | 34.5±3.5 (20) | 26.4±2.9 (24) | 419±41 (24) |
| > 130 | 263±58 (30) | 32±5 (30) | 0.06±0.03 (30) | 26.5±4.0 (31) | 26.6±4.2 (35) | 528±101 (35) |