Author comment to Anonymous Referee #1

We thank anonymous Referee #1 for his/her constructive criticism and valuable comments. In the following we address the points raised, with referee comments in boldface and author responses in normal typeface.

General comment:

Frigstad et al. present data from the PAP site in the northeast Atlantic, with estimates of seasonal NCP and new production that will be useful for the scientific community. A particle tracking method is used to examine source regions of material within a sediment trap, and the manuscript demonstrates that the site shows high flux attenuation by calculating the export ratio and transfer efficiency. Time-series stations such as the PAP site are of great importance in evaluating changes in the environment and understanding these important biogeochemical processes. With further clarification and inclusion of the errors involved, and mixing influences this paper could be a valid contribution to productivity estimates in this region. If the following issues are addressed, I support the publication of this manuscript.

We thank the reviewer for the positive comment, and have addressed the errors involved with calculating NCP and the contribution from mixing in the responses below.

Specific comments:

p.5176 line 25. The error associated with the calculation of DIC from calculated TA and measured CO2 should be quantified. The error quoted as 3 µmol kg^{-1} is the measurement uncertainty if DIC were measured discretely, which is not the case in the method presented. Please quantify this error and calculate how this error propagates into the NCP estimates.

We have calculated the total error associated with the calculation of DIC from estimated TA and measured fCO2 of ±0.85 mol C m^{-2}. This was determined by propagation using the method described in Dickson and Riley (1978), together with the errors in the estimated TA values (±6.4 µmolkg^{-1}; Lee et al. 2006) and measured pCO2 (±2 µatm; Wanninkhof et al., 2013). The propagated probable error is larger than the uncertainty due to monthly variation in NCP_{MLD} of ±0.27 mol C m^{-2}, and we have chosen to use the propagated error to give a conservative estimate of the uncertainty in our NCP estimates. We have therefore updated the uncertainty in NCP estimates in the results section.

The text has been revised as follows:

"A different source of uncertainty in NCP and new production estimates come from measurement uncertainty, which propagates into calculated values. However, for new production, the variability associated with measurement uncertainty is negligible compared to the natural variability. The measurement uncertainty for the NO3 sensor given by the manufacturer (Satlantic ISUS V3 sensor) was 2 µmolkg kg^{1}. This gives a propagated probable error in the $NO3_{MLD}$ estimates of < 0.05 mol N m^{-2} (calculated from the square root of the sum of squared errors), which is considered negligible compared to the uncertainty associated with monthly variation of ±0.14 mol N m^{-2}. Therefore we present the uncertainty related to monthly variation in $NO3_{MLD}$. Conversely, the total uncertainty associated with monthly variations in NCP_{MLD} was ±0.27 mol C m^{-2}, which is smaller than the total error associated with the calculation of DIC from estimated TA and measured fCO2 of ±0.85 mol C m^{-2}. The latter was determined by propagation using the method described in Dickson and Riley (1978), together with the errors in the estimated TA values (±6.4 µmolkg^{-1}; Lee et al. 2006) and measured pCO2 (±2 µatm; Wanninkhof et al., 2013). We have therefore chosen to present the propagated probable error as a conservative estimate of the uncertainty in our NCP estimates.

p.5178 line 11 Please include justification/reference for why all particles are assumed to have a sinking speed of 100 m d^{-1}.
Observations at the PAP observatory have estimated the particle sinking speed as between 60 and 180 m day^{-1} (Riley et al., 2012; Villa-Alfageme et al., 2014). The value we choose of 100 m day-1 falls in the middle of this range. Faster particle sinking speeds would result in a smaller source region and vice versa for slower sinking particles.

The text has been revised as follows: "…, which is chosen because it falls in the middle of the range observed for particle sinking speeds at the PAP observatory of between 60 and 180 m day^{-1} (Riley et al., 2012; Villa-Alfageme et al., 2014)…"

p.5177 line 4 and figure 3 How can mixing be assumed negligible? Kortzinger et al. (2008) demonstrate that mixing plays an important role in increasing NO3 and DIC concentrations in the mixed layer during winter months at the PAP site. Using the method presented, the positive NCP and new production values in figure 3 are not necessarily solely due to biological drawdown, but are actually where the biological drawdown exceeds mixing and remineralisation. This assumption should be discussed further, and made clearer to the reader.
This is a valid comment, and an issue we discussed frequently in the preparation of this manuscript. It is stated in Sect. 2.3 that the monthly changes in DIC and NO_3 can be attributed to changes caused by air-sea gas exchange (for DIC), physical mixing processes and biological drawdown. The physical mixing processes, such as vertical entrainment, diffusion and advection are difficult to account for without proper measurements. In Kortzinger et al. (2008) they also assume that the contribution from these three mixing processes are small and negligible in the calculation of NCP, but acknowledges that a "full mixed layer budget cannot be constructed". Only a simplified budget is possible, under certain limitations and for restricted periods. We have followed the same rationale, calculating NCP and new production for the period when the MLD is stable and where biological drawdown is believed to play a dominating role in monthly changes in DIC and NO_3. We do, however, acknowledge the limitations in this approach, and will elaborate on the uncertainties associated with mixing in the manuscript.

The manuscript has been revised as follows:
Physical mixing processes, such as vertical entrainment, diffusion and advection, will to some degree contribute to monthly DIC changes, however are difficult to quantify without information on vertical and horizontal gradients. Following the approach by Kortzinger et al. (2008) we have performed a simplified calculation of seasonal NCP and new production for the summer period when the mixed layer is relatively stable and the biological drawdown in DIC (and NO_3) is strong. Therefore, the contribution of ΔDIC_{mix} was assumed negligible, and ΔDIC_{BP} was assumed to be largely determined by NCP (excluding the effect of calcification).

Figure 3. Why are the productive periods (grey shaded) different for NO3MLD and NCPMLD? Using the MLD it should be possible to determine if the mixed layer is deepening, and therefore give an indication of when high concentrations of DIC and nutrients are being entrained in to the mixed layer. The summer months before the mixed layer deepens may be a better period to calculate NCP and new production
The period $NO3_{MLD}$ and NCP_{MLD} are positive, is when there is a net decrease in NO_3 or DIC concentrations, respectively, in the mixed layer caused by biological drawdown. As can be seen in the monthly climatology in Fig. 2, DIC concentrations starts increasing from August, which causes the sign of the NCP_{MLD} to change, from positive to negative. NO_3 concentration has a very small decrease from July to August, before there is a small increase from August to September. Therefore the $NO3_{MLD}$ becomes negative in September, one month later that for NCP_{MLD}. These months with very small changes in concentrations have error bars that are almost as large as the $NO3_{MLD}$ and NCP_{MLD} itself, and it is therefore little use in speculating

into a reason for the difference in timing of negative values.

The MLD climatology is also shown in Fig. 2, and the MLD shallows rapidly from around 250m in March to 50m in May. The MLD remains fairly stable at 50m until October. We chose to use the difference in MLD between consecutive months, and not to integrate over a fixed time period. We find the strongest NCP_{MLD} and $NO3_{MLD}$ before the onset of shallow stratification in summer, however believe it gives value to show the monthly changes, and the stabile MLD and nutrient depletion in summer indicates that there is not a large contribution from entrainment during these months.

Figure 3. Please include a table of the different years used to calculate the monthly values and the inter-annual variability. This would be useful to the reader and might also explain why some of the error bars are so small in the figure.
We have compiled a table (se below) with monthly mean, SD and number of samples (n) for each year we have data (taking the years vs. months would mean that the table is very large). The means and SDs are identical to the values given in Fig. 3, and from this table it is clear that for most months we have data from 2-4 different years. This is also described on p. 5176 l. 3-16, where the method of calculating the $NO3_{MLD}$ and NCP_{MLD} is explained. However, one small error was discovered in the compilation of this table. For NCP_{MLD} there is only data from one year (2004) in March and April, and therefore we cannot calculate the SD, and consequently there is no error bar in Fig. 3. This is now explicitly described in the revised manuscript. In addition, we added which months are lacking error bars in Fig. 3 in parenthesis in the text:
"However, for most months of the year data from at least two to four different years were available, and NCP_{MLD} and $NO3_{MLD}$ was estimated two to four times for each of these months. This allowed the quantification of the average seasonal NCP_{MLD} and $NO3_{MLD}$ and variability (expressed as one standard deviation; SD) from the PAP time series. With the exception of March and April for NCP_{MLD}, when there was only data for one year (2004) and consequently SD could not be calculated (error bars missing in Fig. 3). The monthly changes in equations 3 and 4 (below) were computed in a circular manner i.e. the change in the 12^{th} month is the difference January minus December. For $NO3_{MLD}$ there was only data for one year in December, and consequently the SD could not be calculated. For NCP_{MLD} there was data from two different years in December and three years in January, however they coincided only for 2004. Therefore, the variability could not be determined for December for either NCP_{MLD} and $NO3_{MLD}$ (error bar missing for December in Fig. 3)."

In addition, we add which months are lacking error bars in the caption to Fig. 3:
"Figure 3. Monthly changes in MLD integrated NO_3^- (top) and NCP (bottom) with ± 1 SD (vertical bars). The shaded grey area indicates the months over which the seasonal new production (0.37 ± 0.14 mol N m^{-2}) and NCP (4.57 ± 0.27 mol C m^{-2}) were calculated. For NCP_{MLD} no SD could be calculated in March and April, and SD is also lacking for December for both NCP_{MLD} and $NO3_{MLD}$ (see Sect. 2.3 for calculations)."

Seeing as how the information in the table is identical to Fig. 3, and we have expanded on the which months there are no error bars due to missing data we feel that adding this table to the revised manuscript would not justify the extra space this would require.

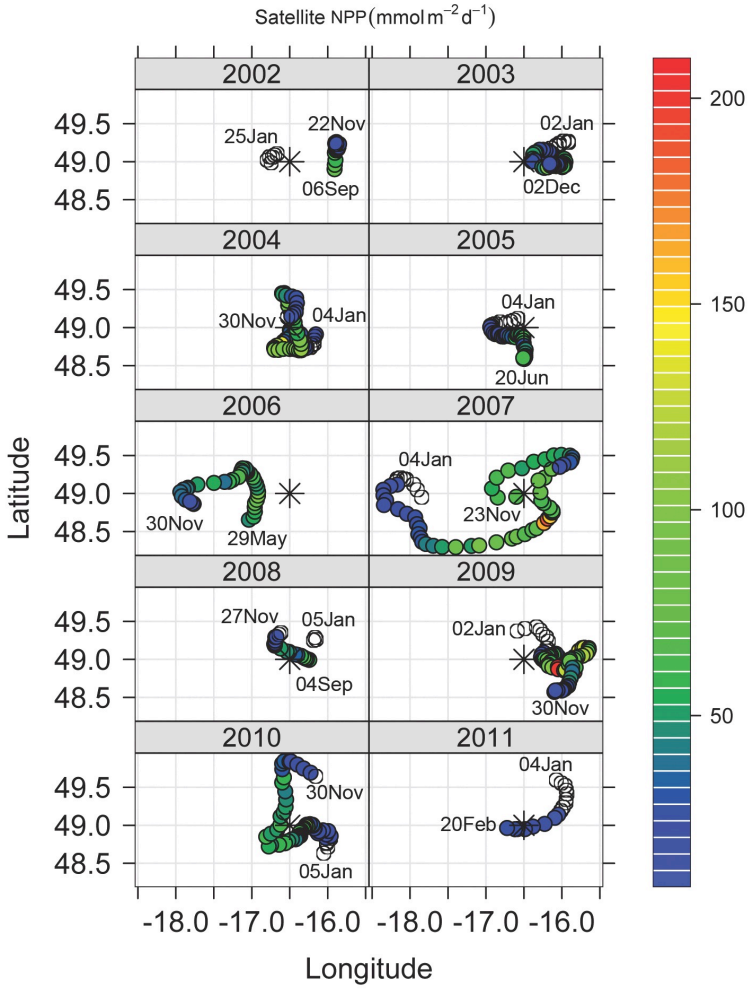
	Jan	feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Okt	Nov	Des
$NO3_{MLD}$												
	-								-	-	-	-
Mean	0,179	0,126	0,107	0,064	0,031	0,029	0,016	0,002	0,013	0,161	0,070	0,142
SD	0,372	0,072	0,109	0,032	0,001	0,017	0,008	0,001	0,012	0,109	0,229	NA
n	3	3	2	2	2	2	2	2	3	3	3	1

NCP_{MLD}												
	-							-	-	-	-	-
Mean	0,713	0,294	2,351	0,768	0,667	0,265	0,220	0,202	0,261	0,934	1,463	1,532
SD	0,822	0,267	NA	NA	0,010	0,041	0,027	0,153	0,244	0,404	1,072	1,065
n	3	3	1	1	2	3	3	4	4	4	4	2

p.5192 figure 1. The MLD looks like it goes shallower than 30 m during the summer, would this influence your calculations of NCP and new production within the mixed layer as your sensors are at 30 m? Please clarify this and discuss if necessary.
It is the difference in MLD between consecutive months that is used to calculate the NCP_{MLD} and $NO3_{MLD}$, and from May-August this is shallower than 30m (23.7m, 17.1m, 16.3m and 21.3m, respectively). When the MLD is shallower than the sensors measuring NO_3^- and DIC concentrations, this could imply that the drawdown from biological activity within the mixed layer is stronger (and thereby reaches lower concentrations) than what is actually measured by the sensors at 30m. However, the NO_3^- concentrations in the mixed layer could become depleted, and thereby limit further biological drawdown. On the other side, the biological drawdown could be stronger at 30m than in the mixed layer due to more supply of nutrients than what is available within the mixed layer. Which of these processes would be dominating at the PAP observatory is impossible to determine without the nutrient data. The former process could imply that our estimates of NCP and new production are on the low side (because additional drawdown takes place within the mixed layer), however the latter could imply that our estimates are higher than within the mixed layer due to more readily available nutrients. This is an additional source of uncertainty, and we have added a short description of this in the discussion in Sect 4.1:
"… during this period of rapid stratification. From May to August the MLD is slightly shallower than the depth of the sensors at 30m, which could influence our estimates of NCP and new production. This uncertainty is impossible to quantify without measurements from within the mixed layer, although the effect is believed to be minor. It could potentially overestimate biological production due to more readily available nutrients at 30m than within the mixed layer, or lead to an underestimate due to additional drawdown within the mixed layer. …"

Figure 3 and figure 4. It would be beneficial to the reader if the units of CO2 flux, NCP, new production, Satellite derived NPP were all in mmol m^{-2} d^{-1} so that they are more easily comparable. Please make units consistent throughout the manuscript.
We agree with the comment by the reviewer and have converted the units in Fig. 4 to mmol m^{-2} d^{-1}.

The revised Fig 4 is shown below; here we have also included the other issues brought up by the reviewer regarding this figure:



p.5199 Figure 4. Please add a time dimension to this plot, it is difficult to trace the particle with time without knowing which month the coloured dots are representing. It may also be useful to include a 100km box around the PAP site for reference, and to demonstrate that the source region is outside of the box in some years.
Time labels have been added to mark the start and end of data for each year in Fig. 4 (se above). We did experiment with adding a 100 km box around the PAP site, however there is all ready a lot of information on this plot and unfortunately the box made the figure too cluttered and difficult to interpret for the reader.

The caption to Fig. 4 has been revised as follows: "…The start and end dates of the data for each year is indicated in the panels".

Technical corrections:

p.5171 line 1 Is nitrate being measured, or nitrate + nitrite as it is in Hartman et al. 2012. On first use of NO3 please clarify this within the manuscript.
It is nitrate+nitrite, and this has been clarified in the revised text.

p.5171 line 15 closing brackets missing
The text has been revised accordingly.

p.5196 Figure 2. Add '(black dots)' to legend
The text has been revised accordingly, and now reads: "Monthly climatology (black dots)…"

p.5199 Figure 4. Make text on axes bigger, and add label to the colour bar including the units

See the revised Fig. 4 above. The font size for the axis labels has been increased, and a label has been added to the top of the figure with variable name and units (not under the color bar due to space constraints).

Author comment to Anonymous Referee #2

We thank anonymous Referee #1 for his/her constructive criticism and valuable comments. In the following we address the points raised, with referee comments in boldface and author responses in normal typeface.

General comment:

Frigstad et al. present observations from the Porcupine Abyssal Plain (PAP) time series station / observatory and related interpretation. The dataset presented covers up to a decade of data of observations from automated devices in the surface mixed layer (euphotic zone) and from sediment traps at 3000m. The PAP site is one of the very few open ocean time series sites outside oligotrophic waters. Though parts of the data have been published earlier this is a timely overview, providing also interesting additional analysis of the combined dataset. Using data from Argo, remote sensing and ocean circulation models this, by nature, spatially limited data are set into a wider context. Running such a site and putting such a dataset together is clearly a significant effort of the group lead by the senior author, Richard Lampitt. I recommend publication with minor corrections as indicated below. My largest concern is related to the interpretation of particle tracking, NPP and flux. See the comments on section 2.4, 4.2 below.
We thank the reviewer for the positive comment, and have addressed the issue regarding particle tracking in the response below.

Specific comments:

Abstract
p5170: The Redfield C:N ratio is 6.6. The observed C:N ratio of NCP was 12, I suggest to not confuse younger readers and the speak about 'C:N-ratio of 12' and not to refer to Redfield here.
We agree with the reviewer, and have revised the text accordingly: "The C:N ratio was high (12) …"

Introduction
p 5170, l 26 (and elsewhere): delete 'full depth'
We have deleted "full depth" throughout the revised text.

p5171, l 9-10: The Sabine reference for the phrase 'biological carbon pump is key to understanding the global carbon cycle' is not justified. In the last paragraph Sabine speaks about potential biological feedbacks to OA in a very general sense. Hence you shouldn't use that reference here. You should refer to papers that give evidence to this statement and not just use such a phrase themselves in either the intro or the outlook! The Falkowski reference is well suited here, perhaps refer to Volk and Hofferts centennial paper in addition, or some significant post-1998 overview paper.
We have deleted the Sabine reference in the revised text, and the sentence now reads: "and therefore quantifying the biological carbon pump is key in understanding the global carbon cycle (Falkowski et al. 1998)."

l22-24: Is it really the 'multitude of methods …" that lead to a poor understanding of NCP…? I understand Quay rather in the following sence 'Unfortunately, there are only a few sites where multiple NCP methods have been compared (e.g., JGOFS study sites, BATS and ALOHA time series sites).' (p2). Multiple methods may be rather an advantage, in the absence of a gold standard'.
We agree that this sentence can be misunderstood, and have revised the text to: "It can be challenging to compare between techniques and there is …"

p5171, l24 – p 5172, l6 may be shortened
We go into a bit of detail explaining the differences in NCP and export flux in this paragraph. We felt it was important to explain these differences, because the study computes both NCP and export flux, and compare the two variables in the results and discussion sections. We therefore believe that it is important to give the reader some background, and that these sentences can be justified.

p 5172, l 13-15: Is the correct reference for Lampitt et al 2018 given? From my memory (but the senior author should know better), the Royal Society paper from the same year is referred to here, right?
The reviewer is correct, and we have inserted the correct reference and updated the reference list.

l 21-24: suggest to write: 'transfer efficiency has often been used to describe the efficiency'. Rational: a) the POC based metric ignores DOM, b) see papers by Marinov and co-authors Overall, DOM as a pathway is ignored completely in the paper. Its role in sequestration may be less understood, but you might want to mention this pathway (and your ignorance of it in the analysis) at least once in the intro.
The manuscript has been revised as suggested: "… and has often been used to describe the efficiency of the biological pump …"

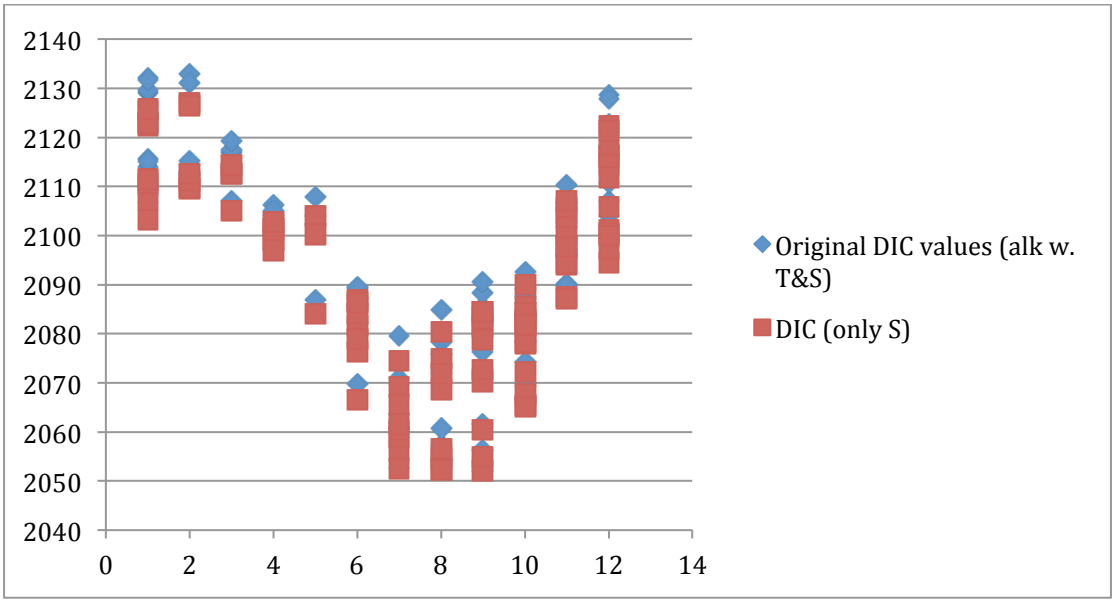
It is noted in p 5171, l 27 – p 5172, l 1 that one of the differences between NCP (as calculated in this study) and export flux (calculated as POC flux at a nominal depth), is that the NCP estimate will include the contribution of DOC. However, have added to the revised manuscript that the POC-based metric of calculating export flux and transport efficiency does not include the DOM pathway. Revised text on p. 5172, l 23: "It should be noted that the POC-based metric of calculating export flux and transfer efficiency does not include the contribution from DOC."

Data and methods
p 5173, l24: rewrite: "(2010). Briefly …"
The text has been revised accordingly.

Same paragraph: Perhaps mention at least two more details: a) why is formaline addition not an issue for POC measurements (with reference to a study that gives respective evidence). b) what about losses of POC to the supernatant in the cup until splitting of samples, losses e.g. to DOC (see e.g. Kähler and Bauerfeind, L&O, 2001). This is (evidently ?) no issue in your traps?
a) We use analytical grade (AnalR or NORMAOUR) formalin as directed by the JGOFS protocols for preservation. There are numerous unpublished studies that show that somewhat surprisingly formalin does not affect POC. The most cited paper (Knauer et al 1984) indicated some losses.
b) Kähler and Bauerfeind worked with shallow sediment traps, which are much more susceptible to swimmer contamination. At PAP traps are at 3000m and 100mab and have few swimmers therefore negligible DOC leaching.

p5175, l23-24: I am not really sure about the meaningfulness of Lee's T-S to Alk relationship. In particular the T-part. See e.g. Friis et al., 2003, GRL. In your data, (Fig. 2) what is driving the seaonality of ALK? T or S? How sensitive is your DIC seasonality to the computed ALK. What if you assume no seasonality of ALK, e.g. by taking the annual mean of your computed ALK together with your seasonally varying pCO2 data? Hopefully, that gives almost identical DIC values, compared to the presented ones. Please check into this.
This is a very relevant issue raised by the reviewer. In Lee's T-S to Alk relashionship, the

salinity coefficients are several orders larger than those of the temperature-part. Thus, the seasonality is driven mainly by salinity. To verify this, we have recalculated Alk from salinity alone (following Nondal et al. (2009)), and there was still seasonal variation in calculated Alk values. Furthermore, this change in the calculation of Alk had only a negligible effect on the seasonal variation in DIC values (figure below).



For this reason, and since Lee originally included temperature to account for the nutrient cycle, we chose to keep Alk values obtained with Lee's relationship. We also note that the main issue in Friis et al. (2003) concerned the use of zero intercept during the normalization of Alk values to constant salinity. This normalization is not used in this manuscript.

p5176, l 6 (and elsewhere!!) Kon"rzinger has an o-Umlaut, also Kan"hler has an a-Umlaut. Please check the ms carefully for correct spelling of authors! Go back to the original papers to check, if needed.
The text has been revised accordingly.

p5176, l 24-27: You should include the error from ALK-S-T in your error budget, and refer to what I proposed above in the text.
This is the same issue raised by reviewer#1, and the text has been revised to include the error from calculated Alk (from temperature and salinity) instead of measured Alk as in the previous version of the manuscript:
"… which is smaller than the total error associated with the calculation of DIC from estimated TA and measured fCO2 of ±0.85 mol C m^{-2}. The latter was determined by propagation using the method described in Dickson and Riley (1978), together with the errors in the estimated TA values (±6.4 µmolkg^{-1}; Lee et al. 2006) and measured pCO2 (±2 µatm; Wanninkhof et al., 2013)."

p 5177, l 4: 'contribution from delDICmix was assumed negligible': can it be? If I recall correctly Gruber et al. 1998 (DSR ?) used 13C-CO2-data at Bermuda to constrain the role of mixing to a seasonal surface ocean DIC budged. There it was important, I think. I suggest, that you at least discuss this limitation of your estimate briefly, in particular in terms of sign for C:N – NCP estimate, and mention the Gruber and related studies.
This is the same issue as raised by reviewer#1, and we repeat the response given on this issue: It is stated in Sect. 2.3 that the monthly changes in DIC and NO_3 can be attributed to changes caused by air-sea gas exchange (for DIC), physical mixing processes and biological drawdown. The physical mixing processes, such as vertical entrainment, diffusion and

advection are difficult to account for without proper measurements. In Kortzinger et al. (2008) they also assume that the contribution from these three mixing processes are small and negligible in the calculation of NCP, but acknowledges that a "full mixed layer budget cannot be constructed". Only a simplified budget is possible, under certain limitations and for restricted periods. We have followed the same rationale, calculating NCP and new production for the period when the MLD is stable and where biological drawdown is believed to play a dominating role in monthly changes in DIC and NO_3. We do, however, acknowledge the limitations in this approach and will elaborate on the uncertainties associated with mixing in the manuscript.

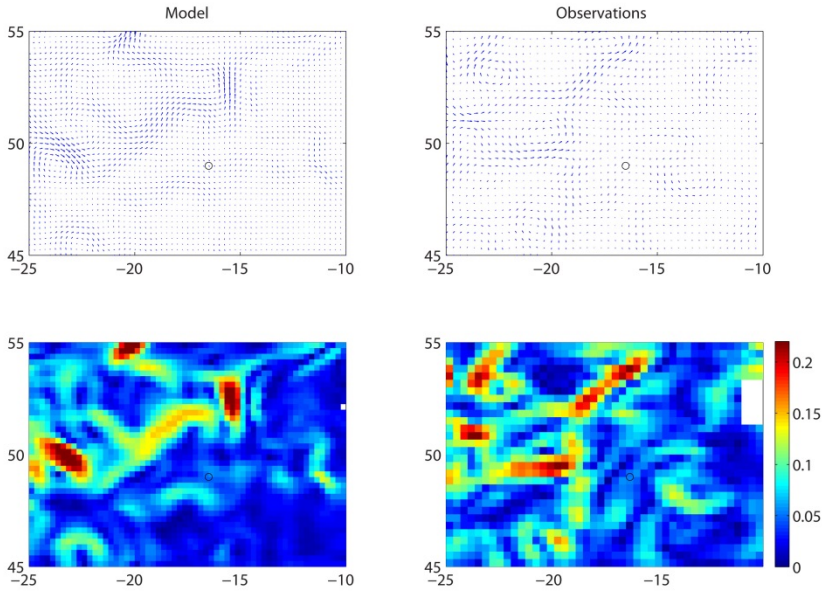
The manuscript has been revised as follows:
Physical mixing processes, such as vertical entrainment, diffusion and advection, will to some degree contribute to monthly DIC changes, however are difficult to quantify without information on vertical and horizontal gradients. Following the approach by Kortzinger et al. (2008) we have performed a simplified budget calculation for the summer period when the mixed layer is relatively stable and the biological drawdown in DIC (and NO_3) is strong. Therefore the contribution of ΔDIC_{mix} was assumed negligible, and ΔDIC_{BP} was assumed to be largely determined by NCP (excluding the effect of calcification).

l 7 vs. p 5176 l 28-29. This is a little unclear. I suggest you rewrite Equ3 to explicitly include the gas exchange term.
The changes in DIC concentrations caused by air-sea gas exchange are calculated from the air-sea flux and MLD in Eq. 2. We have revised the text to show how this is included in the terms of Eq. 3 (the contribution of air-sea gas exchange is added to the DIC concentrations because the flux is positive throughout the year):
".. corrected for the effects of air-sea gas exchange ($\Delta DIC^{GasCorr} = \Delta DIC_{obs} + \Delta DIC_{gas}$)"

l 21-23: Please clarify in the text whether you computed NPP, or downloaded it from the web site.
The NPP data were downloaded from the website listed in Table 1, and this is already stated in the text. We have clearified this sentence:
"The NPP data were downloaded … ".

Section 2.4: The particle tracking analysis is done here much better than in some older papers of the senior author which used moored current meters. This is acknowledged by the reviewer. However, here and also later in the paper, you seem to take the transports in the model to be fully consistent with the real ocean patterns and distribution of NPP as seen by the satellite. Why should that be the case? The best you may hope for, I think, is that the applied physical model has the right statistics of transports compared to the real ocean. Whether the eddies (etc.) are at the right place at the right time in the model vs. the real ocean is not known. Hence, the combination of particle tracking, remote sensing, and the deep traps stands on somewhat slippery ground. You need to mention and discuss that – unless you can provide hard remote sensing evidence (e.g altimetry, sst, sss patterns) supporting that your model behaves perfectly in that sense. Recently, Jamie Wilson and co-authors had a very nice paper (currently in review in BGD, I think) demonstrating how deficient similar combinations of models and reality can be.
To demonstrate that the NEMO model produces currents that are consistent with observations, we have plotted below the surface currents (geostrophic + Ekman) derived from satellite altimetry and wind data (downloaded from http://www.oscar.noaa.gov/). The mean observed current vectors (top panels) and speed (lower panels) for 2008 are plotted alongside the modelled currents in the figure below. The model reproduces well the main features of the circulation in the region, i.e. the band of strong northeastward currents in the NW quadrant of the domain and the relatively quiescent SE quadrant. The magnitude of the currents are also in a very similar range in the model and observations. Note that satellite observations can necessarily only supply information on the surface currents and so the

analysis we present in the manuscript would not be possible without relying on modelled currents. The paper mentioned by the reviewer by Wilson et al. discusses the issues of accurate model circulation in the context of thousand year spin-ups and attempts to reproduce the 3-D distribution of phosphate in the oceans, i.e. very different time and space scales than we consider here.



p 5179, l 24-25: Could you explain a little further from your data why there is no seasonal signal in CO2-fluxes?
The air-sea CO_2 flux does not show corresponding winter to summer variations as for example pCO_2 in Fig. 2, largely because of the balancing effect of the seasonal cycles in pCO_2 and wind speed (U_{10}). During spring and summer the reduction in wind speed is compensated by the effect of increased ΔfCO_2 leading to overall small variations in air-sea flux of CO_2 throughout the year.

l 25: delete: 'also'. There is no (causal) relationship between the two issues, I think.
p 5181, l 11: rewrite: 'for surface sea-water pCO2 …'
The text has been revised accordingly: "The sediment fluxes had high…"

p 5183, l8: Schneider was not the first to report this. Please check for example papers of Cindy Lee from the early 80s, e.g. Lee and Cronin, 1984 and Wakeham et al. 1984. Please do not cite only convenient references, but also the original literature.
The text has been updated to include the Lee and Cronin (1984) reference: "Studies have shown an increasing C:N of sinking material due to preferential remineralization of nutrients (Schneider et al. 2003; Lee and Cronin 1984) …"

l9: rewrite 'ratio may influence … by about 20 ppm …'
The text has been revised accordingly: "ratio may influence atmospheric CO_2 concentrations by about 20 ppm"

l 17: 'basin was too complex' is awk and not to the point. I guess GS's mixing model did not resolve more than 2 or 3 endmembers? Please check and present carefully.
We agree with reviewer, and deleted this part of the sentence as it is not essential to the argument. The revised text now reads: "However, the deep ocean remineralization rates of Anderson and Sarmiento (1994) did not include the Atlantic Ocean."

p 5183 l 22 to p 5184, l 9. I think this paragraph can be deleted. You follow an idea that does not work out well, for reasons published by others decades ago.
We agree with reviewer that this paragraph does not give added value to the manuscript, and have deleted it in the revised text.

p 5184, l 17; '64 and 207' is a little awk, explain with one more sentence why the difference is so large.
The Lampitt et al (2008) is an integrated estimate based on the deployment of the Pelagra sediment trap during summers of 2003 to 2006, while the estimate from Tomalla et al. (2008) is based on a simple sample close to the PAP-site (48.6N;where material was collected using a pump). The samples therefore represent different time (and also spatial scales, due to the location not being identical), and therefore represent the natural variability in POC flux. The different time scales is emphasized in the revised text:
"determined to be in the range between 64 and 207 mg C m^{-2} d^{-1} (based on measurements from a single cruise and long-time trap data; Lampitt et al. 2008, Thomalla et al. 2008)."

l21: is De La Rocha and Passow the appropriate reference for 'export ratio'. This term is much longer in use! Also the reference of that paper given reference section is not complete!
We have changed the reference in this sentence to Dugdale and Goering (1967), which is the reference given in the introduction where the term is introduced. The revised text now reads:
"… divided by the NPP (Dugdale & Goering 1967)."

l 22: '115', please give error bar of your mean value
The standard deviation of the literature values given in the text is ± 61 mg C m^{-2} d^{-1}. This uncertainty is added to the revised text:
"Using an average of the above values for POC flux out of the surface layer of 115 ± 61 mg C m^{-2} d^{-1}".

Section 4.2 & Conclusion. See my comments on section 2.4. You need to discuss the issue stated above.
Se response to Sect. 2.4 above.

References: See my comment of on" and an" for Korzinger, Kahler, (but Koeve is correct,
:-)
These references have been corrected in the reference list as well

Overall, I enjoyed reading the paper.
Thank you!

References (not cited in article):
Kähler P, Bauerfeind E. Organic particles in a shallow sediment trap: substantial loss to the dissolved phase. Limnol Oceanogr 2001, 46:719–723

Knauer, George A.; Karl, David M.; Martin, John H.; Hunter, Craig N. In situ effects of selected preservatives on total carbon, nitrogen and metals collected in sediment traps. Journal of Marine Research, Volume 42, Number 2, May 1984, pp. 445-462(18)
Nondal, Gisle; Bellerby, Richard G. J. ; Olsen, A; Johannessen, T. Optimal evaluation of the surface ocean CO_2 system in the northern Atlantic using data from voluntary observing ships. Limnology and Oceanography: Methods. 7, 2009, 109-118

Author comment to Anonymous Referee #3

We thank anonymous Referee #3 for his/her constructive criticism and valuable comments. In the following we address the points raised, with referee comments in boldface and author responses in normal typeface.

General comments

This study provides a decade long time series data set on hydrography, biogeochemistry and sediment traps for the PAP site in the North Atlantic. Results are valuable for understanding the present and future functioning of the biological pump in the PAP site. They also suggest that there might be changes in export as the PAP site transitions into subpolar conditions. However there is little discussion on the actual implications of the results in that context. Although I just have some minor comments on the ms, I recommend the authors to further develop the implications of their study.

We thank the reviewer for the positive comment, and have expanded on the potential changes in export regime at the PAP site in the revised manuscript.

Abstract

Line 10 please specify that a Redfield ratio of 12 is higher than the expected value of 6.6.

The text has been revised accordingly: "The C:N ratio was high (12) compared to the Redfield ratio (6.6), …"

Introduction

I am surely not well informed on the dynamics of the PAP site but I have trouble with the sentence "It is at or near the boundary between the sub-polar and sub-tropical gyres of the North Atlantic". Is it or is it not? And if both are true how is it explained? This is important for data interpretation.

The text has been changed to: "The PAP observatory is near the boundary between the sub-polar and sub-tropical gyres of the North Atlantic". Please also see figure 8 of Henson et al. (2009).

Slide 5171 line 1 (and throughout the text) please include the correct formula of nitrate (NO3-).

The formula has been corrected to NO_3^- throughout the manuscript.

Lines 10 to 15: These are valuable motivations for the study but I though you already named those before. Please regroup your arguments at the end of the introduction section for clarity.

We agree with the reviewer, and have deleted the sentence in the revised manuscript, as this argument is already given at the end of the introduction section. The revised text now reads: "global carbon cycle (Falkowski et al. 1998). These factors are currently not fully understood, so it is therefore difficult to predict how they will respond to climate change (e.g. Passow & Carlson 2012)."

Line 23: "multitude" is vague and you cite only one reference. Please detail or rephrase.

This sentence has been revised in response to a comment made by reviewer#2, and now reads: "It can be challenging to compare between these techniques, and there is … ".

Slide 5172: consider giving acronyms to concepts such as transfer efficiency, new production, sequestration flux and export flux.

We considered doing this in the preparation of the manuscript, however we believe that not using too many acronyms in the text makes it easier to follow for the reader.

Materials and Methods

Section 2.1: I think details are missing here. For instance, what sensors for nitrate were

used during the last 10 years? What is the detection limit? I understand that this information can be found in a variety of papers but it is best not to force the reader to look for sparse information. A Table sumarising limits of detection, techniques and periods of use can be useful here.
We feel that adding a table containing this information would take up a lot of space, however agree that more information could be beneficial, especially on NO_3^- measurements (for which the instruments changed over time). We have added the text below to the manuscript. Regarding detection limits, both the methods below claim to measure zero NO_3^-. However, PAP is not an oligotrophic site, so this should not be an issue in our data.

Text added to the revised manuscript: "NAS nutrient analysers (Envirotech LLC) were used in the period from 2002 until 2012, which measures NO_3^- plus NO_2^- (hereafter referred to as NO_3^-) with a precision of ±0.05 umol l^{-1}. The NAS was used alongside an optical nitrate sensor from 2009 to 2012, after that time all NO_3^- measurements were made with optical sensors (Satlantic ISUS), with a precision of 2umol l^{-1}. For the remaining variables a Seabird MicroCAT was used for temperature and salinity …".

Slide 5176 line 9 "an explanation for December to be followed shortly". Delete. One supposes you are going to explain this later.
This parenthesis has been deleted from the revised text.

Slide 5177: Please justify your assumption of negligible mixing.
This issue was raised by the other reviewers, and we have expanded on the contribution from mixing in the manuscript.

It is stated in Sect. 2.3 that the monthly changes in DIC and NO_3 can be attributed to changes caused by air-sea gas exchange (for DIC), physical mixing processes and biological drawdown. The physical mixing processes, such as vertical entrainment, diffusion and advection are difficult to account for without proper measurements. In Kortzinger et al. (2008) they also assume that the contribution from these three mixing processes are small and negligible in the calculation of NCP, but acknowledges that a "full mixed layer budget cannot be constructed". Only a simplified budget is possible, under certain limitations and for restricted periods. We have followed the same rationale, calculating NCP and new production for the period when the MLD is stable and where biological drawdown is believed to play a dominating role in monthly changes in DIC and NO_3. We do, however, acknowledge the limitations in this approach and will elaborate on the uncertainties associated with mixing in the manuscript.

The manuscript has been revised as follows:
Physical mixing processes, such as vertical entrainment, diffusion and advection, will to some degree contribute to monthly DIC changes, however are difficult to quantify without information on vertical and horizontal gradients. Following the approach by Kortzinger et al. (2008) we have performed a simplified budget calculation for the summer period when the mixed layer is relatively stable and the biological drawdown in DIC (and NO_3) is strong. Therefore the contribution of ΔDIC_{mix} was assumed negligible, and ΔDIC_{BP} was assumed to be largely determined by NCP (excluding the effect of calcification).

Slide 5178 line 11: Why did you use 100 m d-1 for all particles?
This same issue was raised by reviewer#1. Observations at the PAP site have estimated the particle sinking speed as between 60 and 180 m day^{-1} (Riley et al., 2012; Villa-Alfageme et al., 2014). The value we choose of 100 m day-1 falls squarely in the middle of this range. Faster particle sinking speeds would result in a smaller source region and vice versa for slower sinking particles. The manuscript has been revised: "…, which is chosen because it

falls in the middle of the range observed for particle sinking speeds at the PAP observatory of between 60 and 180 m day^{-1} (Riley et al., 2012; Villa-Alfageme et al., 2014)…"

Results. Slide 5180 line 14. Particle tracking shows considerable interannual variability. You don't mentioned mesoscale variability as a cause of this variability. Please comment.
This is a valid comment, and mesoscale variability could contribute to the variability in source location of material arriving at the sediment trap, both between and within years. This has been added to the discussion, in Sect. 4.2

Revised text at p. 5185, l 9: "… reflecting the seasonal cycle. Mesoscale variability will also contribute to the variability in source location of particles, both between and within years."

Discussion
Slide 5182 lines 20-23. Maybe a table compiling previous N:C estimate would help here.
We believe a table giving these values would take up too much space, especially since comparing with previous C:N estimates is not a central part of this study.

Line 23: N2 fixation could be (and references will show you that it is) important in the North Atlantic. Assuming the opposite can be misleading. Please discuss its possible effect on your observed C:N. Also discuss your choice of assuming negligible N2 fixation.
Although N_2 fixation is known to be significant, especially in the subtropical North Atlantic gyres, many studies show that it is not likely to be so at the latitude of the PAP observatory. Figure 2a of Moore et al. (2009) has a transect over the PAP observatory (unfortunately, the plot is cut off at 40N), and shows that N_2 fixation is close to zero from 30-40N, a pattern that is likely to continue at higher latitudes. Reynolds et al. (2007) suggest that N2 fixation plays a minor role in supplying N to the "northern subtropical gyre", the northern boundary of which they call 40N.

The text has been revised as follows: "Studies have found N_2 fixation to be low or zero at latitudes >40°N (PAP observatory is at 49°N) in the North Atlantic (Moore et al. 2009, Reynolds et al. 2007), therefore N_2 fixation is not thought to be an important factor for C overconsumption. Therefore … ".

Slide 5185 line 20. Transfer efficiency is already defined in the text. Also, please discuss a little bit more the implications of the 4% you report here.
We have deleted the definition of transfer efficiency in this sentence.

We have also added more description of what the relatively low transfer efficiency found at the PAP observatory implies in the revised text: "region by Henson et al. (2012), indicative of regions where the available nitrate is not fully consumed and with strong seasonal mixing."

Slide 5186 last paragraph of discussion. This is a speculative statement and I don't think it's a good way to finish your paper. Either you discuss this point in more detail or you replace it with a more conclusive statement that is actually supported by the data.
We believe it is relevant to mention that the export regime at the PAP observatory (with high export ratio and low transfer efficiency) could alter as a result of climate change. We have elaborated on the causes of the changes and potential effects.

The final paragraph of the discussion now reads: "The PAP observatory currently sits near the boundary between the sub-polar and sub-tropical gyres of the North Atlantic. Seasonably variable areas, like the sub-polar region, are thought to export a higher fraction of labile material than sub-tropical regions (Lutz et al. 2007). As climate change is predicted to result in the oligotrophic gyres expanding over the next century (Sarmiento et al. 2004), the

PAP observatory will likely transition into more sub-tropical conditions. This could result in more refractory material being exported at the PAP observatory, potentially reversing the pattern we report here with a high export ratio and low transfer efficiency. In addition, a more strongly positive NAO index is predicted due to climate change (Gillett 2003), which is expected to increase diatom abundance at the PAP observatory, and result in reduced organic carbon flux to the deep ocean (Henson et al., 2012a). Although the precise response of the biological carbon pump to climate change is as yet unclear, transition-zone regions between gyres (such as the PAP observatory), could be among the systems that are most strongly affected by climate change (Henson et al. 2013)."

Slide 5186, Line 10: Change how?
Into a sub-tropical export regime with more refractory material exported out of the euphotic zone, see above.

Figure 5: Please clarify what the axes are.
The caption to Fig. 5 has been revised as follows: "Cross-correlations between sediment trap data (top: volume flux, middle: dry weight, bottom: POC) and NPP in the source regions defined by particle tracking (left) or in a 100 km box around the PAP observatory (right). See Sect. 2.4 for calculations."

Links between surface productivity and deep ocean particle flux at the Porcupine Abyssal Plain (PAP) sustained observatory.

H. Frigstad[1,*], S. A. Henson[2], S. E. Hartman[2], A. M. Omar[1,3], E. Jeansson[1], H. Cole[4], C. Pebody[2] & R. S. Lampitt[2]

[1] {Uni Research Climate, Allégaten 55, 5007 Bergen, Norway}
[2] {National Oceanography Centre, Waterfront Campus, European Way, Southampton SO14 3ZH, UK}
[3] {Geophysical Institute, University of Bergen, Allégaten 79, 5007 Bergen, Norway}
[4] {Ocean and Earth Science, University of Southampton Waterfront Campus, European Way, Southampton, SO14 3ZH, UK}

[*]{Now at the Norwegian Environment Agency, Grensesvingen 7, 0661 Oslo}

Correspondence to: H. Frigstad (helene.frigstad@miljodir.no)

Abstract

In this study we present hydrography, biogeochemistry and sediment trap observations between 2003 and 2012 at Porcupine Abyssal Plain (PAP) sustained observatory in the northeast Atlantic. The time series is valuable as it allows for investigation of the link between surface productivity and deep ocean carbon flux. The region is a perennial sink for CO_2, with an average uptake of around 1.5 mmol m^{-2} day^{-1}. The average monthly drawdowns of inorganic carbon and nitrogen were used to quantify the net community production (NCP) and new production, respectively. Seasonal NCP and new production were found to be 4.57 ± 0.27 mol C m^{-2} and 0.37 ± 0.14 mol N m^{-2}. The C:N ratio was high (12) compared to the Redfield ratio (6.6), and the production calculated from carbon was higher than production calculated from nitrogen, which is indicative of carbon overconsumption. The export ratio and transfer efficiency were 16% and 4%, respectively, and the site thereby showed high flux attenuation. Particle tracking was used to examine the source region of material in the sediment trap, and there was large variation in source regions, both between and within years. There were higher correlations between surface productivity and export flux when using the particle-tracking approach, than by comparing with the mean productivity in a 100km box around the PAP site. However, the differences in correlation coefficients were not significant, and a longer time series is needed to draw conclusions on applying particle tracking in sediment trap analyses.

Introduction

The Porcupine Abyssal Plain (PAP) sustained observatory is situated in the northeast Atlantic Ocean (49°N 16.5°W) in a water depth of 4800 m. It is near the boundary between the sub-polar and sub-tropical gyres of the North Atlantic (Henson et al. 2009). A time series of particle flux measurements at 3000 m depth are available back to the early 1990's (Lampitt et al. 2010), and since 2003 there has also been a

Unknown
Field Code Changed

Unknown
Field Code Changed

Unknown
Field Code Changed

Helene Frigstad 25.8.15 18.26
Deleted: Redfield

Helene Frigstad 25.8.15 19.48
Deleted: at or near

multidisciplinary mooring with instruments at approximately 30 m depth recording hydrography, nitrate (NO_3^-), partial pressure of CO_2 (pCO_2) and Chlorophyll *a* (Chl *a*) (Hartman et al. 2012). The simultaneous observations of surface and deep ocean biogeochemistry make this time series ideal to study linkages between surface ocean productivity and deep ocean particle flux.

The pathway by which a small fraction (<1%; Martin et al. 1987) of the carbon fixed by photosynthesis in the sunlit upper ocean is exported to great depths, thereby constituting a sink for atmospheric CO_2, is referred to as the biological carbon pump. Carbon sinking to the deep ocean is sequestered on long time scales (100s to 1000s of years), and therefore quantifying the biological carbon pump is key in understanding the global carbon cycle (Falkowski et al. 1998). These factors are currently not fully understood, so it is therefore difficult to predict how they will respond to climate change (e.g. Passow & Carlson 2012).

Primary production in the surface ocean can be measured by several techniques (broadly separated into vitro incubations or changes in bulk properties; Platt et al. (1989)), however, from the perspective of the oceanic carbon cycle the most important rate is the net community production (NCP). NCP is the net primary production (NPP) minus heterotrophic respiration, and represents the sum of the particulate and dissolved organic carbon available for export or utilization by higher trophic levels. NCP is traditionally measured by bottle O_2 incubations (Gaarder & Gran 1927), but has also been estimated from oxygen or carbon budgets, ^{234}Thorium, sediment traps and O_2/Ar ratios. It can be challenging to compare between techniques and there is a poor understanding of NCP rates in many regions of the ocean (Quay et al. 2010). In many studies, the steady-state NCP is equated with the export flux at the base of the euphotic zone (Platt et al. 1989, Lee 2001, Long et al. 2011, Nevison et al. 2012), based on the rationale that NCP is the organic material available for export out of the mixed layer. However, it is not directly comparable to the most common definition of export flux (i.e. the downward flux of POC at a nominal depth) as NCP represents a bulk measurement integrated over the mixed layer and long time scales (and also includes the contribution of DOC to export). The export ratio (ie. Dugdale & Goering 1967) is used to quantify the proportion of the organic material produced that is exported below the euphotic zone, and is often calculated as the flux of POC at 100 m divided by the NPP (Henson et al. 2012b). Global estimates of the export ratio range from 10% (Henson et al. 2011) to 40% (Eppley & Peterson 1979), and is well correlated with temperature, and thereby also latitude (Laws et al. 2000).

New production (Dugdale & Goering (1967) is the production supported by the input of new nitrogen into the euphotic zone through upwelling and horizontal mixing, but also by processes such as atmospheric deposition and nitrogen fixation (Sarmiento & Gruber 2006, Gruber 2008). On an annual basis, assuming the system is in steady state, export production is considered equivalent to new production (Eppley & Peterson 1979).

From a climate change perspective, the long-term (> 100 years) removal of carbon from the atmosphere is important to quantify, which is often defined as the flux of carbon below 1000 meters (Lampitt et al. 2008a), known as the sequestration flux. The sequestration flux is smaller than the export flux out of the euphotic zone or mixed layer, and is ~ 6-25% of the new production based on sediment trap data (Berelson 2001, Francois et al. 2002). This large reduction in carbon flux with increasing depth is caused by intensive remineralization of organic material as it sinks through the mesopelagic zone, which is often referred to as flux attenuation (Martin et al. 1987, Steinberg et al. 2008). The ratio of deep POC flux to export flux (POC flux

Helene Frigstad 25.8.15 18.29
Deleted: full depth

Helene Frigstad 25.8.15 18.30
Deleted: , Sabine et al. 2004

Helene Frigstad 25.8.15 20.05
Deleted: The PAP time series allows an investigation of the factors controlling the flux of carbon.

Helene Frigstad 25.8.15 18.31
Deleted: The multitude of methods and difficulty in comparing techniques has lead to

Helene Frigstad 25.8.15 22.31
Deleted: [

Helene Frigstad 25.8.15 23.18
Deleted: and

at 2000m / POC flux at 100 m), is known as the transfer efficiency and has often been used to describe the efficiency of the biological pump (Francois et al. 2002, De La Rocha & Passow 2012, Henson et al. 2012b). It should be noted that the POC-based metric of calculating export flux and transfer efficiency does not include the contribution from DOC.

In this study we present a time series of surface ocean measurements and particle trap data from the PAP observatory station from 2003 to 2012. Our aim is twofold; firstly, we will quantify NCP and new production from the average monthly drawdown of dissolved inorganic carbon (DIC) and NO_3^-, respectively. This allows us to compare these two estimates of surface productivity, and derive export ratios by comparison with satellite NPP estimates and published values of shallow POC flux at the PAP observatory. Secondly, we will investigate the link between the production at the surface and particle flux at 3000 meters depth, both by investigating the transfer efficiency and by examining the source location of exported material using particle-tracking techniques.

1. Data and methods

2.1 PAP surface mooring

Hydrographical and biogeochemical parameters were measured using data from instruments at a nominal 30m depth on a mooring at the PAP observatory (49N, 16.5W). The surface mooring was first deployed in July 2003, and more information about the time series can be found in Hartman et al. (2012). Due to problems with damage to the mooring and/or failure of sensors, there is no or little data between 2005 and 2010, however, after May 2010 there is good temporal coverage for all biogeochemical parameters. The data from 2003-2005 have previously been published in Körtzinger et al. (2008) and Hartman et al. (2010). The sensors used after 2005 are described in Table 1 in Hartman et al. (2012). NAS nutrient analysers (Envirotech LLC) were used in the period from 2002 until 2012, which measures NO_3^- plus NO_2^- (hereafter referred to as NO_3^-) with a precision of ±0.05 umol l^{-1}. The NAS was used alongside an optical nitrate sensor from 2009 to 2012, after that time all NO_3^- measurements were made with optical sensors (Satlantic ISUS), with a precision of 2umol l^{-1}. For the remaining variables a Seabird MicroCAT was used for temperature and salinity, Wetlabs (FLNTUSB) for Chl *a* and PRO-OCEANUS for pCO_2. The NO_3^-, Chl *a* and pCO_2 data have all been quality controlled and calibrated against CTD data on cruises to the PAP observatory at deployment and/or recovery of the mooring, while this has not always been achieved for temperature and salinity.

2.2 Sediment trap

The sediment trap mooring at the PAP observatory was deployed in the depth range 3000 to 3200 m, which is around 1800 m above the seabed. The methodology is described in Lampitt et al. (2010). Briefly a Parflux sediment trap was used with mouth area 0.5 m^2, prefilled with hypersaline buffered formalin, following the JGOFS protocols. The collection period varied between 2 and 8 weeks depending on the time of year and anticipated flux. All fluxes are temporally and spatially integrated, and given in either ml m^{-2} d^{-1} (volume flux) or mg m^{-2} d^{-1} (dry weight and Particulate Organic Carbon (POC)).

Helene Frigstad 25.8.15 18.38
Deleted: describes the efficiency of the biological pump

Unknown
Field Code Changed

Unknown
Field Code Changed

Helene Frigstad 25.8.15 18.28
Deleted: full depth

Helene Frigstad 25.8.15 23.04
Deleted: o

Helene Frigstad 25.8.15 20.07
Deleted: and the sensors and calibrations used during these deployments will not be discussed further here

Helene Frigstad 25.8.15 20.08
Deleted: , and are

Helene Frigstad 25.8.15 20.10
Deleted: Satlantic ISUS for NO_3 (+ nitrite),

Helene Frigstad 25.8.15 18.40
Deleted: , but

Helene Frigstad 25.8.15 18.40
Deleted: b

2.3 Ancillary data and calculated parameters

To interpret and expand on the data from the PAP observatory, the following parameters were used from external data sources (see Table 1): temperature and salinity profiles from Argo floats, atmospheric CO_2 concentration, sea level barometric pressure (SLP), wind speed at 10 m height and satellite derived net primary production (NPP).

Temperature and salinity profiles were extracted from the global fields for the PAP observatory (49°N 16.5°W), made available by the Coriolis project (http://www.coriolis.eu.org). The gridded fields use temperature and salinity profiles collected by Argo floats, XBTs, CTD/XCTDs and moorings, and the irregularly sampled data are gridded onto a regularly spaced grid by the statistical objective analysis method (Gaillard et al. 2009). The North Atlantic is the region most frequently sampled by Argo floats and has good coverage in both time and space (Gaillard et al. 2009). Here we use monthly averaged temperature and salinity fields for 2002-2009 (delayed mode data), however, after 2010 only near real-time data were available, which has undergone less rigorous quality control than the delayed mode data. In the calculation of carbon parameters (below) the Argo float temperature and salinity at 30 m were used, because of data gaps in the temperature and salinity data from the PAP sensor (referred to as Argo temperature and salinity in text and Figs. 1 and 2) and the lack of consistent calibration with CTD data. Density profiles were calculated using the recently updated standard for seawater properties (TEOS-10; www.teos-10.org). The mixed layer depth (MLD) was calculated from density profiles using the same global gridded fields used for the temperature and salinity data at 30m. The depth of the mixed layer was defined by a density difference of 0.03 kg m^{-3} from the density at a reference depth (in this case 10 m to avoid diurnal changes in temperature and salinity at the surface). We followed the algorithm developed by Holte and Talley (2009), which incorporates linear interpolation to estimate the exact depth at which the density difference is crossed.

The atmospheric CO_2 concentration measurements were obtained from the observatory closest to the PAP observatory, the Mace Head land station in Ireland (53.33N 9.90W) from the Cooperative Atmospheric Data Integration Projects (GLOBALVIEW-CO2 2012). There were no measurements available after 2010, and so the annual averaged growth rate in atmospheric CO_2 for marine sites from the NOAA ESRL data for 2011 (1.69 µmol mol^{-1}) and 2012 (2.59 µmol mol^{-1}) was added to the seasonal cycle in CO_2 concentrations at the Mace Head station for 2010 (http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html). The atmospheric pCO_2 was calculated using the Mace Head station CO_2 measurements at barometric pressure (6-hourly Sea Level Pressure; Table 1) and equilibrium water vapour pressure (from Argo temperature and salinity at 30 m; Table 1).

The air-sea CO_2 flux (in mmol m^{-2} d^{-1}) was calculated from the air-sea pCO_2 difference, Argo temperature and salinity (30 m) and wind speed at 10 m height, using the following equation:

$$F_{CO2} = k \times K_0 \times (pCO_{2sea} - pCO_{2air}) \quad (1)$$

where k is the transfer coefficient based on the wind speed-dependent formulation of Nightingale et al. (2000) scaled to the temperature-dependent Schmidt number according to Wanninkhof (1992), K_0 is the CO_2 solubility at in situ temperature and salinity (Argo temperature and salinity at 30 m) after Weiss (1974),while pCO_{2sea} and pCO_{2air} are the CO_2 partial pressures of seawater and air, respectively.

The alkalinity (Alk) was calculated from Argo temperature and salinity (30 m), following the relationship for the North Atlantic developed by Lee et al. (2006). The dissolved inorganic carbon (DIC) was calculated from Alk and measured pCO_2 using the "seacarb" package (Lavigne & Gattuso 2011), developed for R (R Development Core Team, 2012), using Argo temperature and salinity (30 m) and nutrient concentrations set to zero. The chosen constants were Lueker et al. (2000) for K_1 and K_2, Perez and Fraga (1987) for K_f and the Dickson (1990) constant for K_s, as recommended by Dickson et al. (2007).

The seasonal drawdown of DIC and NO_3^- were used to quantify the NCP and new production, respectively. The gaps in the PAP time series did not allow for examination of the seasonal drawdown on an annual basis (expect for the year of 2004, as published by Körtzinger et al. (2008)). However, for most months of the year data from at least two to four different years were available, and NCP_{MLD} and $NO3_{MLD}$ was estimated two to four times for each of these months. This allowed the quantification of the average seasonal NCP_{MLD} and $NO3_{MLD}$ and variability (expressed as one standard deviation; SD) from the PAP time series. With the exception of March and April for NCP_{MLD}, when there was only data for one year (2004) and consequently SD could not be calculated (error bars missing in Fig. 3). The monthly changes in equations 3 and 4 (below) were computed in a circular manner i.e. the change in the 12th month is the difference January minus December. For $NO3_{MLD}$ there was only data for one year in December, and consequently the SD could not be calculated. For NCP_{MLD} there was data from two different years in December and three years in January, however they coincided only for 2004. Therefore, the variability could not be determined for December for either NCP_{MLD} and $NO3_{MLD}$ (error bar missing for December in Fig. 3).

A different source of uncertainty in NCP and new production estimates come from measurement uncertainty, which propagates into calculated values. However, for new production, the variability associated with measurement uncertainty is negligible compared to the natural variability. The measurement uncertainty for the NO_3^- sensor given by the manufacturer (Satlantic ISUS V3 sensor) was 2 µmolkg kg^{1}. This gives a propagated probable error in the $NO3_{MLD}$ estimates of < 0.05 mol N m^{-2} (calculated from the square root of the sum of squared errors), which is considered negligible compared to the uncertainty associated with monthly variation of ±0.14 mol N m^{-2}. Therefore we present the uncertainty related to monthly variation in $NO3_{MLD}$. Conversely, the total uncertainty associated with monthly variations in NCP_{MLD} was ±0.27 mol C m^{-2}, which is smaller than the total error associated with the calculation of DIC from estimated TA and measured fCO2 of ±0.85 mol C m^{-2}. The latter was determined by propagation using the method described in Dickson and Riley (1978), together with the errors in the estimated TA values (±6.4 µmolkg^{-1}; Lee et al. 2006) and measured pCO2 (±2 µatm; Wanninkhof et al., 2013). We have therefore chosen to present the propagated probable error as a conservative estimate of the uncertainty in our NCP estimates.

The monthly changes in DIC concentrations (ΔDIC_{obs}) can be attributed to changes caused by air-sea gas exchange (ΔDIC_{gas}), physical mixing processes (ΔDIC_{mix}) and biological production (ΔDIC_{BP}). The monthly (ΔDIC_{gas}) (in µmol kg^{-1}) can be estimated from the air-sea CO_2 flux (F_{co2}) and MLD by the following formulation:

$$\Delta DIC_{gas} = \frac{F_{co2}}{MLD} \times \frac{365}{12} \qquad (2)$$

Helene Frigstad 25.8.15 23.04
Deleted: o

Helene Frigstad 25.8.15 22.39
Formatted: Default Paragraph Font, Font:Cambria, Norwegian Bokmal

Helene Frigstad 25.8.15 18.00
Deleted:

Helene Frigstad 25.8.15 18.00
Deleted: However, for each month of the year data from at least two to four different years were available. Therefore, NCP and new production were estimated two to four times for each of the months January – November (an explanation for December to be followed shortly). This allowed the quantification of the average seasonal NCP and new production and variability (expressed as one standard deviation) from the PAP time series. The monthly changes in equations 3 and 4 (below) were computed in a circular manner i.e. the change in the 12th month is the difference January minus December. Data from three different years were available for both of these months, but they coincided only for 2004. Therefore, NCP and new production in December could be estimated only once (based on the 2004 data) and, thus, the variability could not be estimated for this month

Helene Frigstad 25.8.15 21.28
Formatted: Not Highlight

Helene Frigstad 25.8.15 17.41
Deleted: An additional source of variability in NCP and new production estimates come from measurement uncertainty, which propagates into calculated values. However, the variability associated with measurement uncertainty is negligible compared to the natural variability. For instance, the measurement uncertainty for the NO_3 sensor given by the manufacturer (Satlantic ISUS V3 sensor) was ±2 µmol kg^{-1}. This gives a propagated probable error in the $NO3_{MLD}$ estimates of < 0.001 mol N m^{-2} (calculated from the square root of the sum of squared errors), which is considered negligible compared to the uncertainty associated with monthly variation (see Fig 3). Similarly, using ±3 µmol kg^{-1} as the uncertainty in DIC and AlK values (e.g.,Millero 1995) does not include errors by using Alk calculated from salinity) gives a probable propagated error of < 0.05 mol C m^{-2}, which is small compared to the uncertainty from monthly variation in Fig. 3.

Physical mixing processes, such as vertical entrainment, diffusion and advection, will to some degree contribute to monthly DIC changes, however are difficult to quantify without information on vertical and horizontal gradients. Following the approach by Körtzinger et al. (2008) we have performed a simplified calculation of seasonal NCP and new production for the summer period when the mixed layer is relatively stable and the biological drawdown in DIC (and NO_3^-) is strong. Therefore, the contribution of ΔDIC_{mix} was assumed negligible, and ΔDIC_{BP} was assumed to be largely determined by NCP (excluding the effect of calcification). The monthly NCP integrated over the MLD (NCP_{MLD} in mol C m^{-2}) was calculated from the monthly changes in DIC corrected for the effects of air-sea gas exchange ($\Delta DIC^{GasCorr} = \Delta DIC_{obs} + \Delta DIC_{gas}$);

$$NCP_{MLD} = (\Delta DIC_{m+1}^{GasCorr} - \Delta DIC_{m}^{GasCorr}) \times \frac{(MLD_{m+1} + MLD_m)}{2} \quad (3)$$

where $\Delta DIC_{m+1}^{GasCorr} - \Delta DIC_{m}^{GasCorr}$ is the difference in $\Delta DIC^{GasCorr}$ between two consecutive months (m and $m+1$) and the last term gives the average MLD of the two months. Positive values of NCP_{MLD}represents net autotrophy (i.e. the months where the biological drawdown of DIC exceeds the DIC released by heterotrophic processes), and the seasonal NCP_{MLD} can then be calculated as the sum of months with a positive NCP.

The same rationale can be applied to the monthly changes in NO_3^- concentrations ($\Delta NO3$), naturally without having to consider the effect of air-sea exchange. The monthly MLD-integrated NO_3^- changes ($\Delta NO3$ in mol N m^{-2}) were calculated as:

$$NO3_{MLD} = (\Delta NO3_{m+1} - \Delta NO3_{m}) \times \frac{(MLD_{m+1} + MLD_m)}{2} \quad (4)$$

Summing up the months with a net drawdown in NO_3^- gives the seasonal new production.

Net primary production (NPP) was estimated from satellite data using the Vertically Generalised Production Model (Behrenfeld & Falkowski 1997), which requires inputs of chlorophyll concentration, sea surface temperature and photosynthetically available radiation data, here taken from NASA's MODIS Aqua satellite (reprocessing R2012.0). The NPP data were downloaded from the Ocean Productivity website (see Table 1).

2.4 Particle tracking and cross-correlations

In addition to estimating the surface origin of particles sinking to the sediment trap using a simple 100 km box around the PAP observatory, we also used modelled velocity fields to determine the likely source region. The velocity field (u and v components) was taken from the NEMO model (Madec 2008) run at NOC at 5-day, ¼° resolution for the period 2002-2011. The model has 75 depth levels increasing in thickness with depth, ranging from 1 m near surface to 200 m at 6000 m depth. All particles reaching the PAP sediment trap at 3000 m depth are assumed to have a sinking speed of 100 m day^{-1}, which is chosen because it falls in the middle of the range observed for particle sinking speeds at the PAP observatory of between 60 and 180 m day^{-1} (Riley et al., 2012; Villa-Alfageme et al., 2014). Particles are tracked

Helene Frigstad 25.8.15 17.50
Deleted: T

Helene Frigstad 25.8.15 18.50
Deleted: ($\Delta DIC^{GasCorr}$)

Helene Frigstad 25.8.15 18.53
Deleted: D

Helene Frigstad 25.8.15 17.47
Deleted: and

Helene Frigstad 25.8.15 17.47
Deleted: p

backwards in time in 3 dimensions by linear interpolation of the gridded velocity field to the local position of the particle, until they reach the surface (30 days after release).

The cross-correlation between the sediment trap data and either NPP in a 100 km box around the PAP observatory or in source locations identified by particle tracking, were calculated using the ccf function in R (R Development Core Team, 2012). The cross-correlations were performed on monthly anomalies (monthly climatology – observed monthly value), to avoid possible inflation of p-values due to auto-correlation. To test for significant differences between the correlation coefficients the Fisher r-to-z transformation was used (two-tailed test, with two dependent correlations sharing one variable), from the R library "Psych" (Fisher 1915, Revelle 2012).

2. Results

Time series data from 2003 to 2012 from the PAP surface mooring and sediment trap are shown in Fig 1. The temperature and salinity (both PAP sensors and Argo 30 m) varied in the range 12-18 °C and 35.4-35.8, respectively. The mixed layer depths (MLD) were fairly consistent between years, although the winter mixed layer only extended down to ~100 m in 2010. There was a pronounced seasonal drawdown in pCO_2 (similarly for DIC), with summer values as low as 300 µatm during August 2004 and typical winter values between 360-380 µatm. Corresponding seasonal trends were seen for NO_3^-, with a winter maximum of 10 µmol kg^{-1} in March 2004 and values close to detection limit during summer. The strongest bloom was observed in June 2011 with Chl *a* concentrations between 3 and 5 µg l^{-1}, with higher than typical summer values of around 2 µg l^{-1}. The air-sea CO_2 flux was negative (i.e. oceanic uptake of CO_2) throughout the time period, with an average uptake of around 1.5 mmol m^{-2} day^{-1}. There were three years with unusually high sediment fluxes, with short bursts of high flux during summer in 2004, 2009 and 2012.

The monthly climatology (or average seasonal cycle) for temperature showed a seasonal warming of around 5 °C, with very good overlap between the temperatures measured by the PAP sensor and the Argo floats at 30 m (see monthly climatologies in Fig. 2). There was little seasonal variation in salinity, although the Argo float data is generally around 0.05 lower than the salinity measured by the sensors at the PAP observatory. The summer MLD was around 30 m (usually between May and October), and mixing extended down to 250 m depth in winter. The pCO_2 decreased by around 30 µatm from winter values to the summer minimum in August (reduction of around 35 µmol kg^{-1} for DIC), while NO_3^- decreased by around 5 µmol kg^{-1} to the summer minimum typically found in September. There was a gradual build-up of Chl *a* from February, with highest values typically found between May and July with large standard deviations reflecting the high interannual variability in Fig.1. There was no clear seasonal signal in air-sea CO_2 flux, with high variability throughout the year. The sediment fluxes had high interannual variability, however, the highest volume flux was typically found in June, while an autumn peak was often found for dry weight and POC in September or October.

The monthly MLD-integrated NO_3^- changes ($NO3_{MLD}$) were positive from February to August (Fig. 3), which means that during these months there was a net decrease in NO_3^- concentrations in the mixed layer caused by biological drawdown. Conversely, there were negative $NO3_{MLD}$ from September to February, meaning that during these months the NO_3^- concentrations increased due to remineralization and

Helene Frigstad 25.8.15 18.56
Deleted: also

entrainment of new nutrients through winter mixing. This corresponds to a MLD-integrated seasonal new production (from February to August, see 2.3 for calculation) of 0.37 ± 0.14 mol N m^{-2}. Note that all uncertainties given for production estimates in this work are due to interannual variability, as explained in section 2.3. The monthly MLD-integrated changes in NCP (NCP_{MLD}) showed the same seasonal trend, with a positive NCP_{MLD} (i.e. decrease in DIC concentrations) from February to July. In addition, there was a much higher NCP_{MLD} in March compared to the other spring/summer months. The MLD-integrated seasonal NCP (from February to July) was 4.57 ± 0.27 mol C m^{-2}.

Tracking of the particles arriving at the sediment trap at 3000 m at the PAP observatory (see Sect. 2.4), revealed that the source locations of particles could vary substantially between years, and also on an annual time scale (Fig. 4). The satellite NPP in these source regions also varied markedly, and the highest NPP of around 210 mmol C m^{-2} day^{-1} was found in 2009.

There was a high cross-correlation between the seasonal anomalies of NPP in source locations identified by the particle tracking and the volume flux in the sediment trap (+0.62; Fig. 5) at lag = 0 months. The corresponding cross-correlation for NPP averaged over a 100 km box around the PAP observatory and volume flux was considerably lower (+0.48; Fig 5), however the difference between the two cross-correlations was not significant (Fisher transformation, n = 111, z = 1.58, p = 0.11). The correlation coefficients between either dry weight or POC and the two different NPP estimates were lower, and similarly showed no significant difference between either using the NPP identified by particle tracking or a 100 km box. The highest cross-correlations between NPP and dry weight was found at lag = -1 month (i.e. dry weight lagged NPP by one month), while it was at lag = -3 months for NPP and POC. We also tested the cross-correlations using the NPP at the exact latitude and longitude of the PAP observatory (49°N 16°W) and extending the box to 200 km around the observatory, but there were no significant differences in cross-correlations using these instead of the mean of a 100 km box around the PAP observatory as above (results not shown).

Helene Frigstad 25.8.15 18.19
Deleted: 2500

Helene Frigstad 25.8.15 18.19
Deleted: g

3. Discussion

4.1 Estimates of surface productivity

The seasonal cycles of carbon (pCO_2/DIC) and NO_3^- at the PAP observatory are characteristic of highly productive sub-polar regions, where cooling, convection and remineralization cause a winter maximum, while drawdown from biological production during spring and summer causes a minimum during late summer (Takahashi et al. 2002). This is true also for pCO_2, because the decreasing effect of production is stronger than the opposing effect of warming. The same seasonal effects are seen in the MLD integrated changes in NO_3^- and DIC concentrations used to calculate new production and NCP (i.e. Fig 3). There were positive monthly changes in $NO3_{MLD}$ and NCP_{MLD} during spring/summer, due to decreasing concentrations related to biological production within a shallowing or fairly stable mixed layer. During winter the combined effects of cooling, deep mixing and remineralization caused negative $NO3_{MLD}$ and NCP_{MLD} (i.e. increasing NO_3^- and DIC concentrations).

The MLD-integrated seasonal NCP (from February to July) was 4.57 ± 0.27 mol C m^{-2}, which is comparable to, but lower than, the NCP calculated for the PAP observatory by Körtzinger et al. (2008) for 2004 of 6.4 ± 1.1 mol C m^{-2} from March to early August. This is natural given that Körtzinger et al. (2008) integrated over a much deeper fixed mixed layer (238 m) from March until mid May, while here we used the mean MLD between consecutive months. As can be seen in Fig. 2, the MLD shallows rapidly from around 250 m in March to 50 m in May, and we believe using the actual depth of the mixed layer gives a more realistic estimate of NCP during this period of rapid stratification. From May to August the MLD is slightly shallower than the depth of the sensors at 30m, which could influence our estimates of NCP and new production. This uncertainty is impossible to quantify without measurements from within the mixed layer, although the effect is believed to be minor. It could potentially overestimate biological production due to more readily available nutrients at 30m than within the mixed layer, or lead to an underestimate due to additional drawdown within the mixed layer. Consistent with Körtzinger et al. (2008), we find that the strongest NCP occurs before the onset of shallow stratification in summer, with a NCP maximum in March. The MLD-integrated seasonal new production (from February to August) was 0.37 ± 0.14 mol N m^{-2}. This is within the range of new production estimates, using different approaches, from 0.23 - 1.1 mol N m^{-2} from the northeast Atlantic Ocean and Icelandic Sea (Fernández I et al. 2005, Hartman et al. 2010, Jeansson et al. 2014).

Converting the new production in terms of nitrogen to carbon units using the Redfield ratio of 6.6 (Redfield 1958), gives a value of 2.5 mol C m^{-2}, which is substantially smaller than the NCP calculated from DIC changes. However, there is not necessarily any basis for assuming that new production and NCP should be equal, even in a steady state system (cf. Laws 1991). This would imply that carbon is assimilated and recycled by heterotrophs (as respiration is included in NCP) in the same ratio as nitrogen is assimilated by autotrophs during new production, which need not be the case (i.e. variable stoichiometry, see review by Sterner and Elser (2002)). The fact that the production calculated from carbon is higher than the production calculated from nitrogen, is referred to as carbon overconsumption (Toggweiler 1993), and has been demonstrated repeatedly in the North Atlantic (Sambrotto et al. 1993, Körtzinger et al. 2001, Koeve 2006). It has also been shown specifically for the PAP observatory (Körtzinger et al. 2008, Painter et al. 2010). The seasonal C:N ratio for the PAP observatory from this study (i.e. NCP/new production) would be ≈12, which is greatly exceeding the Redfield ratio, although within the range of C:N ratios previously found in this region (Koeve 2006, Körtzinger et al. 2008, Painter et al. 2010).

Studies have found N_2 fixation to be low or zero at latitudes >40°N (PAP observatory is at 49°N) in the North Atlantic (Moore et al. 2009, Reynolds et al. 2007), therefore N_2 fixation is not thought to be an important factor for C overconsumption. Therefore the C overconsumption must be sustained by preferential remineralization of nutrients, either in slowly sinking detritus (Sambrotto et al. 1993, Thomas et al. 1999, Körtzinger et al. 2001) or a build up of C-rich (and N-poor) DOM in the euphotic zone (Williams 1995, Kähler & Koeve 2001, Falck & Anderson 2005). Additionally transparent exopolymer particles (TEP; Alldredge et al. 1993), which have been shown to have high C:N ratios (Engel & Passow 2001) could represent a route for the C overconsumed in the euphotic zone to reach the deep ocean (Koeve 2005). The regenerated nutrients can fuel additional production in the euphotic zone, and consequently estimates of new production based on nitrate might

Helene Frigstad 25.8.15 22.21
Deleted: o

Helene Frigstad 25.8.15 22.21
Deleted: o

Helene Frigstad 25.8.15 22.22
Deleted: o

Helene Frigstad 25.8.15 23.04
Deleted: o

Helene Frigstad 25.8.15 23.04
Deleted: o

Helene Frigstad 25.8.15 23.05
Deleted: o

Helene Frigstad 25.8.15 20.22
Deleted: I

Helene Frigstad 25.8.15 20.22
Deleted: n regions where N_2 fixation is not thought to be an important factor,

Helene Frigstad 25.8.15 23.05
Deleted: o

Helene Frigstad 25.8.15 23.07
Deleted: a

underestimate production rates (Thomas et al. 1999).

The degree to which the C overconsumed in the surface waters reaches the deep ocean, and thus is sequestered on long time scales is important, because it represents a potential negative feedback on atmospheric CO_2. Studies have shown an increasing C:N of sinking material due to preferential remineralization of nutrients (Schneider et al. 2003, Lee & Cronin 1984), and the potential feedback of a depth dependent C:N ratio may influence atmospheric CO_2 concentrations by about 20 ppm (Schneider et al. 2004). However, the deep ocean remineralization ratio of C:N has been shown to be close to the Redfield ratio (Anderson & Sarmiento 1994), and if the C overconsumption is mainly during summer (Koeve 2004, Jiang et al. 2013) and remineralized above the depth of the winter mixed layer, it could be questioned whether the "extra-Redfield" C is sequestered in the deeper ocean, and can therefore influence the oceanic C-budget on longer time scales (Koeve 2006). However, the deep ocean remineralization rates of Anderson and Sarmiento (1994) did not include the Atlantic Ocean. A study on the remineralization ratios in the North Atlantic Ocean specifically showed higher than Redfield C:nutrient ratios in the remineralized material in the deeper waters, and thereby a higher C drawdown by the biological carbon pump than would be expected from applying Redfield ratios in the formation of organic matter (Thomas 2002).

The export flux of POC around the PAP observatory has been quantified in several studies using different techniques (see overview in Fig. 4 in Riley et al. (2012)). The average POC flux in the upper 170 m obtained from PELAGRA drifting sediment trap deployments for short periods of time (3-5 days) between 2003 and 2005 was 72 mg C m^{-2} d^{-1} (Lampitt et al. 2008). During a cruise in August 2009 the flux was found to be 84 and 146 mg C m^{-2} d^{-1} at 50 m, using PELAGRA and a marine snow catcher, respectively (Riley et al. 2012). Using the ^{234}Th technique the flux of POC at 100 m in the vicinity of the PAP observatory was determined to be in the range between 64 and 207 mg C m^{-2} d^{-} (based on measurements from a single cruise and long-time trap data; Lampitt et al. 2008, Thomalla et al. 2008). The export ratio describes the efficiency of nutrient utilization in the euphotic zone, and is often calculated as the POC flux at the base of the euphotic zone or a fixed depth (typically 100 m), divided by the NPP (Dugdale & Goering (1967). Using an average of the above values for POC flux out of the surface layer of 115 ± 61 mg C m^{-2} d^{-1} and the March-July average NPP in the 100 km box around the PAP observatory of 772 mg C m^{-2} d^{-1} gives an export ratio of 0.15. This is identical to the estimate by Lampitt et al. (2008) for the PAP observatory during post-bloom conditions from 2003-2005, and consistent with the estimate by Henson et al. (2011) of between 10 and 30% for temperate and sub-polar waters, respectively.

4.2 Links between surface production and deep ocean flux of POC

Using particle tracking to identify the source location of material arriving in the sediment trap at 3000 meters at the PAP observatory showed that the particles could originate up to 140 km away (in 2007; Fig. 4). There was large variation in the source location of particles between years, depending on the prevailing current conditions in the given year. There was also large variation within individual years, but the satellite NPP generally increased during spring and decreased during autumn along the trajectory of the particles reflecting the seasonal cycle. Mesoscale variability will also contribute to the variability in source location of particles, both between and within years. The highest NPP was found in 2009 (around 210 mmol C m^{-2} day^{-1}), which

Helene Frigstad 25.8.15 19.26
Deleted: Compilation of existing data sets

Helene Frigstad 25.8.15 19.28
Deleted: can

Helene Frigstad 25.8.15 19.29
Deleted: parts per million

Helene Frigstad 25.8.15 19.30
Deleted: , because this basin was too complex for the chosen method

Helene Frigstad 25.8.15 22.46
Formatted: Default Paragraph Font, Font:Cambria, Norwegian Bokmal, Check spelling and grammar

Helene Frigstad 25.8.15 19.31
Deleted: Comparing our estimates of NCP and new production with satellite-derived estimates of NPP could shed some light on the balance between autotrophy and heterotrophy in this region. Summing the average monthly satellite NPP in a 100 km box around the PAP observatory from the period March to July gives ~10 mol C m^{-2}, which is about double the estimated seasonal NCP at the PAP observatory. This would imply approximately equal contributions from NCP and heterotrophic respiration to NPP (as NCP = NPP – heterotrophic respiration). However, it is questionable whether estimates of surface productivity (as given in this study) can be directly compared with satellite NPP. The NCP and new production are estimated based on changes in bulk properties over fairly long timescales, and are integrated over the mixed layer (assuming that the measurements made at ~30 m depth are representative for the entire mixed layer). While the satellite-derived estimates of NPP are often based on shorter timescales and different depth profiles, and therefore the two estimates of surface productivity can involve fundamentally different timescales (cf. Platt et al. 1989). An additional complicating factor is that NCP theoretically includes all the carbon contained in organic material, both the particulate ... [1]

Helene Frigstad 25.8.15 19.33
Deleted: determined to be 64 and 207 mg C m^{-2} d^{-1}

Helene Frigstad 25.8.15 21.56
Deleted: (

Helene Frigstad 25.8.15 23.17
Deleted:

Helene Frigstad 25.8.15 23.17
Deleted: (De La Rocha & Passow 2012, Henson et al. 2012)

Helene Frigstad 25.8.15 18.20
Deleted: >

Helene Frigstad 25.8.15 18.21
Deleted: 000

Helene Frigstad 25.8.15 18.21
Deleted: g

corresponds to very high fluxes in both volume flux and dry weight in the sediment trap at the PAP observatory (Fig. 1). Interestingly, there was not a strong bloom at the PAP observatory according to the in situ Chl *a* observations at 30 m depth (sensor data available from May to late July; Fig. 1), while the satellite NPP showed high correlations with the volume flux and dry weight in the sediment trap. The correlations were highest between the NPP in source locations as identified by particle tracking, compared to the mean NPP in a fixed 100 km box around the PAP observatory. However, the differences in correlation coefficients were not statistically different, and more observations (n = 111 in present analysis) would be needed to determine if using a particle tracking approach when examining the origin of particles in sediment traps indeed gives higher correlations.

The transfer efficiency is a useful metric to describe the long-term removal of carbon (> 100 years) from the atmosphere (cf. De La Rocha & Passow 2012). Using the same average POC flux of the surface layer (0-170 m) as in the calculation of the export flux above and the average flux between March and July of POC at 3000 m from the sediment trap at the PAP observatory (5.1 mg C m^{-2} d^{-1}), the transfer efficiency was calculated to be 4%. This corresponds well with the transfer efficiency between 5 and 10% found for the 50°N region by Henson et al. (2012b), indicative of regions where the available nitrate is not fully consumed and with strong seasonal mixing. The fairly high export ratio (15%) and low transfer efficiency (4%) fits the description of the general trends in high latitude ecosystems in the above-cited study well. This dichotomy in efficiencies implies that although a large proportion of the primary production is exported below the euphotic zone, this material is relatively labile and is efficiently remineralized in the mesopelagic zone, so that only a very small fraction of the exported organic matter reaches the deep ocean and is stored on long time scales.

The PAP observatory currently sits near the boundary between the sub-polar and sub-tropical gyres of the North Atlantic. Seasonably variable areas, like the sub-polar region, are thought to export a higher fraction of labile material than sub-tropical regions (Lutz et al. 2007). As climate change is predicted to result in the oligotrophic gyres expanding over the next century (Sarmiento et al. 2004), the PAP observatory will likely transition into more sub-tropical conditions. This could result in more refractory material being exported at the PAP observatory, potentially reversing the pattern we report here with a high export ratio and low transfer efficiency. In addition, a more strongly positive NAO index is predicted due to climate change (Gillett 2003), which is expected to increase diatom abundance at the PAP observatory, and result in reduced organic carbon flux to the deep ocean (Henson et al., 2012a). Although the precise response of the biological carbon pump to climate change is as yet unclear, transition-zone regions between gyres (such as the PAP observatory), could be among the systems that are most strongly affected by climate change (Henson et al. 2013).

5. Conclusions

The PAP observatory is characterized by strong interannual variability in hydrography, biogeochemistry, and especially sediment fluxes. The seasonal cycles of carbon and nitrogen show a winter maximum and summer minimum, characteristic of highly productive sub-polar regions. The MLD-integrated seasonal NCP (from February to July) was 4.57 ± 0.27 mol C m^{-2}, which is consistent, with but slightly lower than the estimate by Körtzinger et al. (2008) for 2004. The MLD-integrated

Helene Frigstad 25.8.15 20.25
Deleted: is used to describe the efficiency of the biological carbon pump, and

Helene Frigstad 25.8.15 20.28
Deleted: is

Helene Frigstad 25.8.15 20.28
Deleted:

Helene Frigstad 25.8.15 20.28
Deleted: at or close to the boundary between the sub-polar and sub-tropical gyres of the North Atlantic, and will likely transition into more sub-tropical conditions as the gyres expand over the next century (Sarmiento et al. 2004). It has been shown that seasonably variable areas, like the sub-polar region, export a higher fraction of labile material than sub-tropical regions (Lutz et al. 2007), which could imply that the current export regime of the PAP observatory is likely to change as a result of climate change.

Helene Frigstad 25.8.15 23.05
Deleted: o

seasonal new production (from February to August) was 0.37 ± 0.14 mol N m^{-2}, which gives a Redfield ratio (NCP/new production) of 12, corroborating other reports of carbon overconsumption for the North Atlantic (Sambrotto et al. 1993, Körtzinger et al. 2001, Koeve 2006) and the PAP observatory specifically (Körtzinger et al. 2008, Painter et al. 2010).

The export ratio was 15%, while the transfer efficiency was 4%, which is typical of high latitude ecosystems where, although a large proportion of the primary production is exported out of the euphotic zone, this material is relatively labile and therefore remineralized before it reaches the deep ocean. It is hypothesized that the export regime at the PAP observatory could change with climate change, as the region will probably transition into more sub-tropical conditions over the next century (Sarmiento et al. 2004, Lutz et al. 2007).

Using particle tracking to identify the source regions of material reaching the sediment trap at the PAP observatory, revealed higher correlations between NPP in the identified source regions and export flux than other methods. However, more observations are needed to establish if a particle-tracking approach indeed gives added value in sediment trap analyses.

Helene Frigstad 25.8.15 22.50
Moved (insertion) [1]

Unknown
Field Code Changed

Helene Frigstad 25.8.15 23.05
Deleted: o

Helene Frigstad 25.8.15 22.50
Moved up [1]: (Sambrotto et al. 1993, Kortzinger et al. 2001, Koeve 2006)

Helene Frigstad 25.8.15 22.51
Deleted: ;

Acknowledgements

We would like to acknowledge the various ship crew, engineers and scientists involved in preparation, deployment and recovery of the PAP sustained observatory moorings, especially Jon Campbell and Mark Hartman. We wish to thank Maureen Pagnani, Athanos Gkritzalis-Papadopoulos, Zong-Pei Jiang and Andres Cianca for compilation, quality control and calibration of PAP data. Mooring data and support for this research was provided by the European research projects ANIMATE (Atlantic Network of Interdisciplinary Moorings and Time- Series for Europe), MERSEA (Marine Environment and Security for the European Sea), EUR- OCEANS (European Network of Excellence for Ocean Ecosystems Analysis) and EuroSITES grant agreement EU 202955. The work was also supported through the Natural Environment Research Council (NERC), UK, project Oceans 2025 and National Capability. H. F. was supported by EU FP7, through projects MEECE (212085), EURO-BASIN (264933) and GreenSeas (265294).

References

Alldredge AL, Passow U, Logan BE (1993) The Abundance and Significance of a Class of Large, Transparent Organic Particles in the Ocean. Deep-Sea Res Pt I 40:1131-1140

Anderson LA, Sarmiento JL (1994) Redfield Ratios of Remineralization Determined by Nutrient Data-Analysis. Global Biogeochem Cy 8:65-80

Behrenfeld MJ, Falkowski PG (1997) Photosynthetic rates derived from satellite-based chlorophyll concentration. Limnol Oceanogr 42:1-20

Berelson WM (2001) The flux of partuculate organic carbon into the ocean interior: A comparison of four U.S. JGOFS regional studies. Oceanography 14:59-67

De La Rocha CL, Passow U (eds) (2012) The biological pump, Vol 6. Elsevier, Oxford

Dickson AG, Riley JP (1978). The effect of analytical error on the evaluation of the components of the aquatic carbon-dioxide system. Mar Chem 6:77-85

Dickson AG (1990) Standard Potential of the Reaction - Agcl(S)+1/2h-2(G)=Ag(S)+Hcl(Aq) and the Standard Acidity Constant of the Ion Hso4- in Synthetic Sea-Water from 273.15-K to 318.15-K. J Chem Thermodyn 22:113-127

Dickson AG, Sabine CL, Chrsitian JR (2007) Guide to best practices for ocean CO2 measurements. PICES Special Publication, Book 3

Dugdale RC, Goering JJ (1967) Uptake of New and Regenerated Forms of Nitrogen in Primary Productivity. Limnol Oceanogr 12:196-&

Engel A, Passow U (2001) Carbon and nitrogen content of transparent exopolymer particles (TEP) in relation to their Alcian Blue adsorption. Mar Ecol-Prog Ser 219:1-10

Eppley RW, Peterson BJ (1979) Particulate Organic-Matter Flux and Planktonic New Production in the Deep Ocean. Nature 282:677-680

Falck E, Anderson LG (2005) The dynamics of the carbon cycle in the surface water of the Norwegian Sea. Mar Chem 94:43-53

Falkowski PG, Barber RT, Smetacek V (1998) Biogeochemical controls and feedbacks on ocean primary production. Science 281:200-206

Fernández I C, Raimbault P, Garcia N, Rimmelin P, Caniaux G (2005) An estimation of annual new production and carbon fluxes in the northeast Atlantic Ocean during 2001. Journal of Geophysical Research: Oceans 110:C07S13

Fisher RA (1915) Frequency distribution of the values of the correlation coefficient in samples of an indefinitely large population. Biometrika 10:507-521

Francois R, Honjo S, Krishfield R, Manganini S (2002) Factors controlling the flux of organic carbon to the bathypelagic zone of the ocean. Global Biogeochem Cy 16

Gaillard F, Autret E, Thierry V, Galaup P, Coatanoan C, Loubrieu T (2009) Quality Control of Large Argo Datasets. J Atmos Ocean Technol 26:337-351

GLOBALVIEW-CO2 (2012) Cooperative Atmospheric Data Integration Project – Carbon Dioxide. NOAA ESRL, Boulder, Colorado [Available at http://www.esrl.noaa.gov/gmd/ccgg/globalview/%5D.

Gruber N (2008) The marine nitrogen cycle: Overview and challenges. In: Capone DG, Bronk DA, Mulholland MR, Carpenter EJ (eds) Nitrogen in the Marine Environment, Book 2. Elsevier, Amsterdam

Gaarder T, Gran HH (1927) Investigation of the production of phytoplankton in the Oslo Fjord. Rapp PV Cons Int Explor Mer 42:1-48

Hartman SE, Lampitt RS, Larkin KE, Pagnani M, Campbell J, Gkritzalis T, Jiang ZP, Pebody CA, Ruhl HA, Gooday AJ, Bett BJ, Billett DSM, Provost P, McLachlan R, Turton JD, Lankester S (2012) The Porcupine Abyssal Plain fixed-point sustained observatory (PAP-SO): variations and trends from the Northeast Atlantic fixed-point time-series. Ices J Mar Sci 69:776-783

Hartman SE, Larkin KE, Lampitt RS, Lankhorst M, Hydes DJ (2010) Seasonal and inter-annual biogeochemical variations in the Porcupine Abyssal Plain 2003-2005 associated with winter mixing and surface circulation. Deep-Sea Res Pt Ii 57:1303-1312

Henson SA, Dunne JP, Sarmiento JL (2009) Decadal variability in North Atlantic phytoplankton blooms. J Geophys Res-Oceans 114

Henson SA, Sanders R, Madsen E, Morris PJ, Le Moigne F, Quartly GD (2011) A reduced estimate of the strength of the ocean's biological carbon pump. Geophys Res Lett 38

Henson S, Lampitt R, Johns D (2012a) Variability in phytoplankton community structure in response to the North Atlantic Oscillation and implications for organic carbon flux, Limnol Oceanogr 57:1591-1601

Henson SA, Sanders R, Madsen E (2012b) Global patterns in efficiency of particulate organic carbon export and transfer to the deep ocean. Global Biogeochem Cy 26

Henson S, Cole H, Beaulieu C, Yool, A (2013) The impact of global warming on seasonality of ocean primary production, Biogeosciences 10: 4357-4369

Holte J, Talley L (2009) A New Algorithm for Finding Mixed Layer Depths with Applications to Argo Data and Subantarctic Mode Water Formation. J Atmos Ocean Tech 26:1920-1939

Jeansson E, Bellerby RGJ, Skjelvan I, Frigstad H, Ólafsdóttir SR, Ólafsson J (2014) Fluxes of carbon and nutrients to the Iceland Sea surface layer and inferred primary productivity and stoichiometry Biogeosciences In review

Jiang Z-P, Hydes DJ, Tyrrell T, Hartman SE, Hartman MC, Dumousseaud C, Padin XA, Skjelvan I, González-Pola C (2013) Key controls on the seasonal and interannual variations of the carbonate system and air-sea CO2 flux in the Northeast Atlantic (Bay of Biscay). Journal of Geophysical Research: Oceans 118:785-800

Kähler P, Koeve W (2001) Marine dissolved organic matter: can its C : N ratio explain carbon overconsumption? Deep-Sea Res Pt I 48:49-62

Koeve W (2004) Spring bloom carbon to nitrogen ratio of net community production in the temperate N. Atlantic. Deep-Sea Res Pt I 51:1579-1600

Koeve W (2005) Magnitude of excess carbon sequestration into the deep ocean and the possible role of TEP. Mar Ecol-Prog Ser 291:53-64

Koeve W (2006) C : N stoichiometry of the biological pump in the North Atlantic: Constraints from climatological data. Global Biogeochem Cy 20

Körtzinger A, Koeve W, Kähler P, Mintrop L (2001) C : N ratios in the mixed layer during the productive season in the northeast Atlantic Ocean. Deep-Sea Res Pt I 48:661-688

Körtzinger A, Send U, Lampitt RS, Hartman S, Wallace DWR, Karstensen J, Villagarcia MG, Llinas O, DeGrandpre MD (2008) The seasonal pCO(2) cycle at 49 degrees N/16.5 degrees W in the northeastern Atlantic Ocean and what it tells us about biological productivity. J Geophys Res-Oceans 113

Lampitt RS, Achterberg EP, Anderson TR, Hughes JA, Iglesias-Rodriguez MD, Kelly-Gerreyn BA, Lucas M, Popova EE, Sanders R, Shepherd JG, Smythe-

Helene Frigstad 25.8.15 23.08
Deleted: a

Wright D, Yool A (2008a) Ocean fertilization: a potential means of geoengineering? Phil. Trans. R. Soc. A 366: 3919-3945

Lampitt RS, Boorman B, Brown L, Lucas M, Salter I, Sanders R, Saw K, Seeyave S, Thomalla SJ, Turnewitsch R (2008b) Particle export from the euphotic zone: Estimates using a novel drifting sediment trap, Th-234 and new production. Deep-Sea Res Pt I 55:1484-1502

Lampitt RS, Salter I, de Cuevas BA, Hartman S, Larkin KE, Pebody CA (2010) Long-term variability of downward particle flux in the deep northeast Atlantic: Causes and trends. Deep-Sea Res Pt Ii 57:1346-1361

Lavigne H, Gattuso J-P (2011) Seacarb: seawater carbonate chemistry with R. R package version 2.4. http://CRAN.R-project.org/package=seacarb.

Laws EA (1991) Photosynthetic Quotients, New Production and Net Community Production in the Open Ocean. Deep-Sea Res 38:143-167

Laws EA, Falkowski PG, Smith WO, Ducklow H, McCarthy JJ (2000) Temperature effects on export production in the open ocean. Global Biogeochem Cy 14:1231-1246

Lee C, Cronin C (1984) Particulate amino acids in the sea: effects of primary productivity and biological decomposition. J. Mar. Res 42:1075–1097.

Lee K (2001) Global net community production estimated from the annual cycle of surface water total dissolved inorganic carbon. Limnol Oceanogr 46:1287-1297

Lee K, Tong LT, Millero FJ, Sabine CL, Dickson AG, Goyet C, Park G-H, Wanninkhof R, Feely RA, Key RM (2006) Global relationships of total alkalinity with salinity and temperature in surface waters of the world's oceans. Geophys Res Lett 33

Long MC, Dunbar RB, Tortell PD, Smith WO, Mucciarone DA, DiTullio GR (2011) Vertical structure, seasonal drawdown, and net community production in the Ross Sea, Antarctica. J Geophys Res-Oceans 116

Lueker TJ, Dickson AG, Keeling CD (2000) Ocean pCO(2) calculated from dissolved inorganic carbon, alkalinity, and equations for K-1 and K-2: validation based on laboratory measurements of CO2 in gas and seawater at equilibrium. Mar Chem 70:105-119

Lutz MJ, Caldeira K, Dunbar RB, Behrenfeld MJ (2007) Seasonal rhythms of net primary production and particulate organic carbon flux to depth describe the efficiency of biological pump in the global ocean. Journal of Geophysical Research: Oceans 112:C10011

Madec G (2008) NEMO ocean engine. Note du Pole de modélisation, Institut Pierre-Simon Laplace (IPSL), France, No 27 ISSN No 1288-1619

Martin JH, Knauer GA, Karl DM, Broenkow WW (1987) Vertex - Carbon Cycling in the Northeast Pacific. Deep-Sea Res 34:267-285

Millero FJ (1995) The thermodynamics of the carbonic acid system in the oceans. Geochimica et Cosmochimica Acta 59:661-667

Moore C, Mills M, Matthew M, Achterberg EP, Geider RJ, LaRoche J, Lucas MI, McDonagh EL, Pan X, Poulton AJ, Rijkenberg, MJA, Suggett, DJ, Ussher SJ, Woodward E, Malcolm S (2009) Large-scale distribution of Atlantic nitrogen fixation controlled by iron availability.Nature *Geoscience* 2:867-871.

Nevison CD, Keeling RF, Kahru M, Manizza M, Mitchell BG, Cassar N (2012) Estimating net community production in the Southern Ocean based on atmospheric potential oxygen and satellite ocean color data. Global Biogeochem Cy 26

Nightingale PD, Malin G, Law CS, Watson AJ, Liss PS, Liddicoat MI, Boutin J, Upstill-Goddard RC (2000) In situ evaluation of air-sea gas exchange parameterizations using novel conservative and volatile tracers. Global Biogeochem Cy 14:373-387

Painter SC, Lucas MI, Stinchcombe MC, Bibby TS, Poulton AJ (2010) Summertime trends in pelagic biogeochemistry at the Porcupine Abyssal Plain study site in the northeast Atlantic. Deep-Sea Res Pt Ii 57:1313-1323

Passow U, Carlson CA (2012) The biological pump in a high CO2 world. Mar Ecol Prog Ser 470:249-271

Perez FF, Fraga F (1987) Association Constant of Fluoride and Hydrogen-Ions in Seawater. Mar Chem 21:161-168

Platt T, Harrison WG, Lewis MR, Li WKW, Sathyendranath S, Smith RE, Vezina AF (1989) Biological Production of the Oceans - the Case for a Consensus. Mar Ecol Prog Ser 52:77-88

Quay PD, Peacock C, Bjorkman K, Karl DM (2010) Measuring primary production rates in the ocean: Enigmatic results between incubation and non-incubation methods at Station ALOHA. Global Biogeochem Cy 24

Redfield AC (1958) The Biological Control of Chemical Factors in the Environment. Am Sci 46:205-221

Revelle W (2012) Psych: Procedures for Personality and Psychological Research Northwestern University, Evanston, http://personality-project.org/r/psych.manual.pdf, 1.2.1.

Reynolds, SE, Mather RL, Wolff GA, Williams RG, Landolfi A, Sanders R, Woodward EMS (2007) How widespread and important is N2 fixation in the North Atlantic Ocean?, Global Biogeochem Cy 21

Riley JS, Sanders R, Marsay C, Le Moigne FAC, Achterberg EP, Poulton AJ (2012) The relative contribution of fast and slow sinking particles to ocean carbon export. Global Biogeochem Cy 26

Sabine CL, Feely RA, Gruber N, Key RM, Lee K, Bullister JL, Wanninkhof R, Wong CS, Wallace DWR, Tilbrook B, Millero FJ, Peng TH, Kozyr A, Ono T, Rios AF (2004) The oceanic sink for anthropogenic CO2. Science 305:367-371

Sambrotto RN, Savidge G, Robinson C, Boyd P, Takahashi T, Karl DM, Langdon C, Chipman D, Marra J, Codispoti L (1993) Elevated Consumption of Carbon Relative to Nitrogen in the Surface Ocean. Nature 363:248-250

Sarmiento JL, Gruber N (2006) Ocean Biogeochemical Dyamics. Princeton University Press, Princeton, New Jersey, USA

Sarmiento JL, Slater R, Barber R, Bopp L, Doney SC, Hirst AC, Kleypas J, Matear R, Mikolajewicz U, Monfray P, Soldatov V, Spall SA, Stouffer R (2004) Response of ocean ecosystems to climate warming. Global Biogeochem Cy 18:GB3003

Schneider B, Engel A, Schlitzer R (2004) Effects of depth- and CO2-dependent C : N ratios of particulate organic matter (POM) on the marine carbon cycle. Global Biogeochem Cy 18

Schneider B, Schlitzer R, Fischer G, Nothig EM (2003) Depth-dependent elemental compositions of particulate organic matter (POM) in the ocean. Global Biogeochem Cy 17

Steinberg DK, Cope JS, Wilson SE, Kobari T (2008) A comparison of mesopelagic mesozooplankton community structure in the subtropical and subarctic North Pacific Ocean. Deep-Sea Res Pt Ii 55:1615-1635

Sterner RW, Elser JJ (2002) Ecological Stoichiometry: the biology of elements from molecules to the biosphere. Princeton University Press, Princeton, New Jersey

Takahashi T, Sutherland SC, Sweeney C, Poisson A, Metzl N, Tilbrook B, Bates N, Wanninkhof R, Feely RA, Sabine C, Olafsson J, Nojiri Y (2002) Global sea-air CO2 flux based on climatological surface ocean pCO(2), and seasonal biological and temperature effects. Deep-Sea Res Pt Ii 49:1601-1622

Team RDC (2012) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria

Thomalla SJ, Poulton AJ, Sanders R, Turnewitsch R, Holligan PM, Lucas MI (2008) Variable export fluxes and efficiencies for calcite, opal, and organic carbon in the Atlantic Ocean: A ballast effect in action? Global Biogeochem Cy 22

Thomas H (2002) Remineralization ratios of carbon, nutrients, and oxygen in the North Atlantic Ocean: A field databased assessment. Global Biogeochem Cy 16

Thomas H, Ittekkot V, Osterroht C, Schneider B (1999) Preferential recycling of nutrients - the ocean's way to increase new production and to pass nutrient limitation? Limnol Oceanogr 44:1999-2004

Toggweiler JR (1993) Oceanography - Carbon Overconsumption. Nature 363:210-211

Villa-Alfageme M, De Soto Borrero F, Le Moigne F, Giering SL, Sanders R (2014) Observations and modeling of slow sinking particles in the Twilight Zone. Global Biogeochem Cy 28:1327-1342

Wanninkhof R (1992) Relationship between Wind-Speed and Gas-Exchange over the Ocean. J Geophys Res-Oceans 97:7373-7382

Wanninkhof R, D Bakker, N Bates, A Olsen, T Steinhoff, A Sutton (2013) Incorporation of Alternative Sensors in the SOCAT Database and Adjustments to Dataset Quality Control Flags. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tennessee.

Weiss RF (1974) Carbon dioxide in water and seawater: The solubility of a non-ideal gas. Mar Chem 2:203-215

Williams PJL (1995) Evidence for the Seasonal Accumulation of Carbon-Rich Dissolved Organic Material, Its Scale in Comparison with Changes in Particulate Material and the Consequential Effect on Net C/N Assimilation Ratios. Mar Chem 51:17-29

1 **Tables**

2

3 Table 1. Overview of ancillary data

Parameter	Source
ARGO Temperature and salinity	Temperature and salinity fields: 1° by 1°, monthly temporal resolution. Depth in profiles had resolution of 5 metres between 10 and 100m and 10m between 100 and 800m. Available through Coriolis project; http://www.coriolis.eu.org/
Atmospheric CO_2	Mace Head land station in Ireland (53.33N 9.90W) from the Cooperative Atmospheric Data Integration Projects (GLOBALVIEW-CO2 2012); http://www.esrl.noaa.gov/gmd/ccgg/globalview/co2/co2_download.html
Sea Level Pressure (SLP)	FNMOC 1° by 1°, 6-hourly; http://las.pfeg.noaa.gov/las6_5/servlets/constrain?var=6
Wind speed	FNMOC 1° by 1°, 6-hourly at 10 m height; http://las.pfeg.noaa.gov/las6_5/servlets/constrain?var=82
Net primary production (NPP)	Vertically Generalised Production Model; http://www.science.oregonstate.edu/ocean.productivity/index.php

4

Figure captions

Figure 1. Time series of available data from PAP surface mooring and sediment trap with ± 1 SD (vertical bars). Temperature and salinity calculated from the Argo float data (grey dots in first two panels) is also shown, along with derived mixed layer depth estimates. Negative CO_2 flux values indicate flux from the atmosphere to the ocean.

Figure 2. Monthly climatology (black dots) with ± 1 SD (vertical bars) of available data from PAP surface mooring (30 m) and sediment trap. Temperature and salinity calculated from the Argo float data (grey dots in first two panels) is also shown, along with derived mixed layer depth estimates.

Figure 3. Monthly changes in MLD integrated NO_3^- (top) and NCP (bottom) with ± 1 SD (vertical bars). The shaded grey area indicates the months over which the seasonal new production (0.37 ± 0.14 mol N m^{-2}) and NCP (4.57 ± 0.27 mol C m^{-2}) were calculated. For NCP_{MLD} no SD could be calculated in March and April, and SD is also lacking for December for both NCP_{MLD} and $NO3_{MLD}$ (see Sect. 2.3 for calculations).

Figure 4. Satellite NPP (mmol C m^{-2} d^{-1}) in the source regions for the sediment trap as identified by particle tracking. The star shows the position of the PAP mooring and unfilled circles indicate that no NPP estimate was available from satellite data (most often during January and February). The start and end dates of the data for each year are indicated in the panels.

Figure 5. Cross-correlations between sediment trap data (top: volume flux, middle: dry weight, bottom: POC) and NPP in the source regions defined by particle tracking (left) or in a 100 km box around the PAP observatory (right). The dashed lines show the 95% confidence intervals. The unit of the lags is months.

Helene Frigstad 25.8.15 18.01
Deleted: Monthly changes in MLD integrated NO_3 (top) and NCP (bottom). The shaded grey area indicates the months over which the seasonal new production ($NO3_{MLD}$: 0.37 ± 0.14 mol N m^{-2}) and seasonal NCP (NCP_{MLD} :4.57 ± 0.27 mol C m^{-2}) were calculated. See Sect. 2.3 for calculations.

Helene Frigstad 25.8.15 18.18
Deleted: g

Helene Frigstad 25.8.15 20.32
Deleted: and sediment fluxes