8.May 2015

Dear Editor,

In this document you can find the point by point response to the reviewers comments and the track change version of the manuscript. We moved all figures to the main text as requested by two of the referees. However, if you consider that the amount of figures is excessive, we can re-arrange that. A few additional editorial corrections were carried out without affecting the content of the text.

In addition, the correspondence e-mail of the leading author has been modified since the Alfred Wegener Institute (AWI) e-mail account will be disconnected in July 2015 due to a change of institute. Please send all further correspondence to mar.fdez.mendez@gmail.com or mar.fernandez.mendez@npolar.no. The affiliation for this manuscript remains as it is.

For your information, the leading author and several coauthors will not have internet access between the 18 of May and the 30th of June 2015 due to an expedition to the Central Arctic. We will happily address any further changes on the manuscript either before or after that time period.

We hope that you will consider the revised and improved version of the manuscript for publication. Thank you for your time and understanding.

Best regards,

Mar Fernandez-Mendez in behalf of all coauthors.

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Response to Anonymous Referee #1

The authors would like to thank Referee #1 for the useful comments that will definitely improve the manuscript. Below you can find the comment and our answer starting with an "A:" below it.

General Comment: I request that all figures and tables placed in the SI be included in the manuscript as they are very frequently referred to in the main text. Then the figures are necessary, not supplementary.SI is thus NOT the place for them! It is annoying to have to go to the SI to find these figures.

A: We agree and hope the editor allows for the extra space. All figures are now placed in the main text. Only Table S1 and Table S3 will remain in the supplementary since they show Pangaea dois and data that is shown in Fig. 4 anyways.

2898 L16 'light limitation in which season? Growth season? summer?

A: Light limitation in late summer (August-September). This information will be added in the text.

2899 L4 add "as a proxy for nutrient stocks" after winter mixing.

A: Added.

2900 L2-4 that's a single snapshot! one station! Anything in Olli et al 2007? Any russian pubs?

A:We added more references to this statement.

2900 L11 add Miller et al.2015 Elementa

A: Added.

2902 L4 define Atlantic inflow, maybe in station cartoon? please add the water column stations in fig 1

A: The Atlantic inflow has been defined in the text and an arrow has been added in Figure 1a to depict it. Adding the water column stations to Figure 1 would make it very crowded, but we added a note in the caption indicating that the water column was sampled along the entire transect and that the stations are depicted in Figure 2 (which will become Figure 4 when all the supplementary figures are added to the main text).

2902 L15 what size filter was used? Where did the FSW come from? were the cores shaved of their outerlayer to minimize contamination or any other such measure? what diameter corer was used?

A: 0.2 µm poresize filter was used to filter the sea water added to the melting ice cores. This water came from deep waters at previous stations. The ice cores were not shaved but immediately stored in sterile plastic bags to prevent contamination. The ice corer diameter was 9 cm. All this information will be added in the text.

2902 L24 were any tests done to determine any cell loss due to pump action? such as a comparison with a bucket or similar? or, bottle attached to ice-CTD?

A: No specific test was performed but no difference in debris (broken cells) content was observed in the flow cytometer samples from pump vs CTD collected water samples.

2903 L8 add '; ship's

A: Added.

2904 L19 please add (Table S1) after sea ice concentration

A: Added.

2905 L5 how is the lateral upscaling from single point to 10km done?

A: We rephrased this for clarity: "NPP was calculated analogous to section 2.2 for each grid point of a 10 km polar stereographic grid".

2906 L22 the community composition after 6d and 4d under melted conditions may not have been the same one as at To. Was any species composition or size fraction frequency or other descriptor done at To and Tf?

A: Yes, this is a recurrent issue when working with sea-ice samples. The shift in community composition during melting is a known issue that affects mainly flagellates. After melting, the community composition was monitored using light microscopy in a qualitative way. From this observations no major shifts in the sea-ice diatom based community could be observed. This information will be added to the manuscript.

2907 L19 Ah! but not measured at the beginning; too bad

A: Yes, also at the beginning.

2911 L23 a "measurable" increase?

A: Correct. We added "measurable" to the sentence for clarity.

2911 L23 Interesting that this was not due to micrograzers but microalgae compositionas sea ice diatoms!!

A: Indeed a few micrograzers (flagellates) were observed with the microscope and they might have contributed to nutrient uptake. This will be added to the manuscript.

2913 L9 please add as many figures from supplement into full ms! If cited (and they are cited multiple times), then the figures are necessary, not supplementary.

A: Agreed.

2913 L15 please use INPP and NPP consistently throughout the manuscript; ie, always INPP if the value represents an integration

A: INPP represents depth integration and the manuscript will be checked for consistency when using this abbreviations.

2913 L28 The value could also decrease if you take into account that bacteria also may use nutrients. But it could also be underestimated if there is nutrient replenishment by physical or biological processes

A: This is a very good point that will be added to the discussion. There are indeed some assumptions made when doing this type of calculations.

2915 L25 almost two decades earlier! Much could have changed, there is much interannual variability, and then there are so few data available for that region.

A: We agree that this difference could be due to interannual variability and highlights once more the lack of NPP data available from the Central Arctic Ocean. This has been added to the manuscript for clarity.

2916 L18 "and other Arctic ice-covered regions (Matrai & Apollonio [or the other way around] 2013)"

A: Reference added.

2917 L22 replace 'double' with 'twice' as much

A: Replaced

2918 L16 fix ref formatting

A: Rudels is single author in that paper. No reformatting is needed.

2918 L19 due to *the large seasonal* riverine input. But you have used LeFouest to support a minimal influence of river nutrients. Which one is it: min or max influence? And the river freshet will have occurred long before the summer sampling time; was there much flow still then?

A: The increased silicate concentrations in the area adjacent to the Laptev Sea could be due to riverine influence at the shelf. However, the influence of riverine nutrients in the deep Eurasian Basin is not able to maintain an increase in new production. Some lateral advection might occur but has not been quantified yet. Yes, the main river discharge occurred before the sampling time and that is probably the reason why the nitrate in that area is depleted. The surplus of silicate in summer might be due to the phytoplankton composition during the spring bloom that might have been formed by not heavy silicified diatoms or by the upwelling of deep Atlantic waters at the continental slope. This is very speculative and was therefore not included in the manuscript.

2919 L21 reword ’some nutrients left’ to ‘reduced nutrient concentrations” or similar

A:Reworded.

2919 L22-27 I believe an Apollonio reference and a Mundy reference have already expressed this notion; please acknowledge them.

A: We were not able to find those references but added one to Cota´s work in 1990.

2920 L1 replace ’able’ by ’capable’ I would be very cautious of deriving too much from a single experiment!!!

A: We agree that is a single experiment and therefore all conclusions derived from it are stated with caution.

2920 L5 replace ’is’ with ’are’

A: Replaced

2920 L6these the wrong references for zooplankton grazing on ice algae and phytoplankton. Both references are modeling studies simulating this system!

A: We agree and changed the references for two observational studies: Soreide et. al. 2006 and Hop et al. 2011.

2920 L18 how was algal C determined in the sed traps?

A: Using light microscopy counts and volumetric calculations. This is explained in the studies cited. In addition a sentence explaining this was added for clarity.

2920 L23 not ’indicate’ but ’suggest’

A: Changed.

2921 L10 NO!! it has been **predicted**! Not observed. These are PP-chl models. There are many issues affecting the derivation of NPP from ocean color models and more complex models as well. Pabi et al 2008 is also an ocean color model and the Kara Sea estimates have no ground truth data to validate them with, sadly.

A: We agree and have changed the wording consequently.

2921 L15 replace ’A’ with ’Another’ modeling study

A: Replaced.

2922 L5-10 These seas are not part of the central Arctic which is the main topic of this paper. These results don’t fit well in here, as attractive or controversial as they may be. What happened in the central Arctic? If you insist in keeping this one sentence, it is necessary to have another sentence that indicates how much of the seasonal NPP is represented by this change in an ice free sept in each of these seas, according to your model. Something like

"These increases still represent only x or as much as x% of the seasonal NPP in these regions, according to our model." Especially since most of the Greenland Sea is already ice free in Sept except for the E Greenland current and the mixed layer depths become very deep very soon once the fall storms begin.

A: The regions that we define in our study are a division of the Eurasian Basin north of 78°N. These different parts of the Central Arctic are named after the closest sea south of 78°N. To clarify this in the manuscript we added a reference to Figure S7 where the regions are depicted in the map (In the new version Figure 13). We also included a sentence indicating the percentage of seasonal NPP that September estimates account for. This puts in perspective the values discussed.

2922 L15 could be ’reduced’.

A:Modified.

2922 L18-21 All the processes listed will lead to a negative change in nutrient concentration. In other words, it may result in a decrease in NPP for the month of September.

A: From the processes listed all of them except increased winds and upwellings would lead to a decrease in nutrients and therefore in NPP. We modified the sentence as follows:

“Depending on the future role of winds and sea-ice drift vs stratification by freshening and warming, nutrient availability in the euphotic zone could change. For example, if ice formation occurs later in September and winds that cause upwelling also increase, a second productivity peak might be observed at the end of the season (Ardyna et al., 2014). On the contrary if stratification increases its strength and less nutrients are available it may result in a decrease in NPP for the month of September.”

2924 L7 replace ITPs with ’automated, autonomous systems’ since floats, gliders and other buoys may also provide such information. Just making this sentence broader than ITPs

A: Done.

2924 Section 5 Conclusions: I would make your conclusions specific to your 2012 results and modeling. Exclude grazing, nutrients. No speculation or discussion here.

A: We tried to make our conclusions as specific as possible to our results. Grazing and nutrients are included in the study and therefore we feel that they should be mentioned in the conclusions.

2924 L17 replace ’can contribute’ with ’contributed’

A:Replaced.

2924 L19 specifiy if these are ’measured’ estimates or ’model-derived’ estimates

A: They are measured estimates. This information has been added to the sentence.

2928 L30 RUBAO JI, MEIBING JIN and ØYSTEIN VARPE. Sea ice phenology and timing of primary production pulses in the Arctic Ocean. Global Change Biology (2013) 19, 734–741, doi: 10.1111/gcb.12074

A: Corrected.

2940 will the volumetric values of NPP and chl a also be available in Pangea? Please!

A: The volumetric values of NPP will be available in Pangaea. The volumetric Chla values will be published soon in another manuscript by I.Peeken.

2941 Fig 1: please indicate all stations sampled. Fig 2 has many more symbols than the 8 ice stations shown here

A: The water column was sampled throughout the entire cruise track almost constantly, therefore, including all these stations in Fig. 1 would be confusing and would make the figure too crowded. A reference to Fig. 2 (now Fig.4) will be added in the figure caption of Fig. 1 to refer to the water column stations.

2942 Fig 2: can you please circle which symbols correspond to the INPP of fig 4? Simply display a line around the symbol

A: This will be added in the final version of the figure.

2945 Fig 5: Any melt ponds or sea ice in the coastal beaufort left in sept 2012? please add the line of min sea ice extent in aug and sept or for a specific day in each month.

The coastal Beaufort Sea does not appear in the maps shown in Fig. 5 (in the latest version it will be Fig. 11). The line of average sea ice extent in August and September has been added to the maps.

Response to Anonymous Referee #2

The authors would like to thank Referee #2 for the kind words and the useful comments that will improve the manuscript. Please find below the comment followed by our answer starting with an "A:"

General comments

The manuscript presents a comprehensive view of primary production (PP) in the Central Arctic Ocean. This study provides measurement of PP during August and September 2012 for sea-ice, melt ponds and water column. The authors suggest that sub-ice algae are an important component of total PP and may represent up to 60% of the Central Arctic PP. Overall, this manuscript is of high quality, well focus and its content is scientifically truly relevant. As acknowledge by the authors the Central Arctic is one of the least-well understood regions of the world, partly due to its remote and extreme environment which made it barely inaccessible. Therefore, this manuscript, as a part of a larger scheme, is leading to a better understanding of regional and temporal this remote area.

The authors are also using complementary approaches in order to assess the impact of a decreasing ice-cover environment, but they could go further with these approaches.

I also have minor comments about the manuscript (list below). Nevertheless, I'm confident that the manuscript, after revision, will make a significant contribution to the field.

A: Yes, we would have liked to expand our model calculations to an entire season, but we decided not to do it as we are aware of the high seasonal variability of photosynthetic parameters and biomass concentrations for which no data is available. We hope to improve the model and its predictive power in the future by adding seasonal data from sea-ice algae and phytoplankton.

Specific comments

Abstract

P. 2898 L15 - What do you mean by "end of the season". Please define the "season" here or in the introduction.

A: End of the productive season in the Central Arctic refers to August-September. This has been clarified in the text.

Introduction

P. 2901 L18-20 – These approaches should be more developed throughout the manuscript.

A: We added such information where necessary to explain each approach properly.

Method

P. 2902 Section 2.1 – What were the sampling depth for the water in ice-free area? Is only one depth was sampled for PP measurement? What was the method use for the taxonomy data (or cited the study where these data where coming from)?

A: The sampling depth for the ice-free area was 2-5 m depth. The phytoplankton sampled at this depth is supposed to be representative of the phytoplankton present in the mixed layer (5-15 m during summer), so yes, only one depth was sampled and then incubated at different light intensities mimicking different depths. No real taxonomy data is presented in this study. The few descriptions of community composition are based on light microscopy as explained in 2907 L19-23.

Results

P. 2909 Section 3.1 – Is ammonia data are available from the cruise? It could be interesting to add ammonia data to the nutrient overview.

A: Unfortunately ammonia was not part of the main set of parameters measured, there are only a few values from samples of water below the ice at certain stations around 0.5, in rare cases 2 µM. Therefore, these data was not included in this manuscript. We do agree that it would be interesting to have full ammonia data for all stations and environments, but we did not have the manpower to complete them on board.

P.2910 L 1-6 – What is the criteria (concentration's threshold) used to determined nutrient depletion for nitrate and silicate?

A: Nutrient depletion is defined here as concentrations lower than 1 µmol L^{-1} nitrate, 0.2 µmol L^{-1} phosphate, and 1.5 µmol L^{-1} silicate.

P.2910 L 15-25 – What is the sampling depth for "under-ice" and "ice-free" water phytoplankton?

A: 2-5 m depth for both. The exact depth depended on the station and is specified in the Pangaea dataset.

P.2911 L 6 – Why a depth of 25 m was chosen for the nutrient addition experiment?

A: Because the fluorometer of the CTD during the downcast showed that the Chl a max was at that depth.

P.2914 L 21-28 – Please elaborate here. The model proposed is really interesting, but it should be more developed in this section. Is it possible to assess the contribution of melt pond, sea-ice and under water to total PP with the model? Is the change in the dynamic of the ice cover lead to significant change in the contribution of each group?

A: Yes, in the previous paragraph we discuss the contribution of melt pond and sea-ice under sea-ice. These results are shown in Fig. S8 (Fig. 12 in the revised version).

P.2914 L 21, 25 and 27 – Please add absolute data to relative data presented here.

A: Table S2 containing the absolute data is now included in the main text as Table 5.

P.2914 L 26 – I understand that the ice-free scenario represent September 2050 conditions?

A: Yes, this has been added for clarification.

Discussion

P.2916 L 5-15 – I'm getting a bit lost in here. Please rephrase in order to clarify the meaning of these three sentences.

A: The sentences have been rephrased as follows to improve clarity:

"If we assume that the sinking algae had previously contributed to NPP at the surface, and that they occurred throughout the entire Eurasian Basin north of 78°N ($1.8x10^{12}$ m^2), the average 9 g C m^{-2} (range:1-156 g C m^{-2}) of sub-ice algae found deposited at the seafloor would have contributed an additional 16 Tg C to INPP. From the nitrate annual drawdown, we calculated a total carbon uptake of 17 ± 7 Tg C yr^{-1} in the Eurasian Basin north of 78ºN. However, this calculation does not take into account lateral scavenging of nutrients by sub-ice algae such as *Melosira arctica*. Algal filaments hanging from the sea ice are transported along the Transpolar drift, from the Siberian shelves where ice is formed, to the Central Arctic Ocean. Hence they may have a better access to nutrients than phytoplankton. This lateral scavenging of nutrients by the sub-ice algae should be added to the nutrient drawdown calculated from vertical profiles. Accordingly, when adding the nutrients taken up by the sub-ice algae, the total new production could be 17 + 16 = 33 ± 7 Tg C yr^{-1} in the deep basins of the Eurasian Basin."

P.2918 L 6 – What was the depth of the phytoplankton community sampled?

A: 2-5 m depth

P.2918 L 16 – What about ammonia?

A: See answer above

P.2921 L1-8 – Palmer 2011 (Polar Biol., 34, 1915–1928) also observed that change in photosynthetic parameters can be very quick in the Arctic (within few days).

A: This is correct and has been added to the discussion.

P.2922 L 3-4 – Are you referring to the September 2050 model?

A: Yes. We made this more explicit in the text.

P.2922 L 1-17 – What about the September 1982 model? What is the response in PP to 1982 conditions? Plus, some references about effect of ice reduction on PP should be added and discussed in this section.

A: This section has been modified to add information about the 1982 model run.

"The relationship between sea ice decrease and INPP increase also arises when comparing the model results of 1982 and 2012. In this case, for the entire Eurasian Basin, a 45% decrease in the ice cover leads to a doubling in the September INPP."

Also, more references, such as Kahru et al 2011, Ardyna et al 2014 and Bhatt et al 2014, have been added and discussed.

P.2922 L 18-21 – Why is the community will shift? Some more explanation are need to this conclusion.

A: The paragraph has been modified to explain this better.

"The phytoplankton community will probably shift from diatoms towards small picoplankton due to the freshening of the upper layers (Li et al., 2009), especially in the silicate limited area of the Eurasian Basin, where small picoplankton is already present (Kilias et al., 2013) and would be more nutrient efficient at low silicate concentrations (Bhatt et al., 2014; Kilias et al., 2014; Li et al., 2009), with This shift in the phytoplankton community together with the disappearance of the sea-ice communities could have potentially detrimental consequences for the Arctic food web (Bhatt et al., 2014)."

P.2922-2923 Section 4.4 –There is also vertical variability to photosynthetic parameters in the water column. I think this should be addressed in this section. I also think that new versus regenerated production should be briefly discussed there.

A: The vertical variability of photosynthetic parameters both in the water column and in the sea ice is now mentioned in this section. A short discussion of new vs regenerated production has also been included:

"In addition, nitrate vs ammonium uptake rates should be included in such studies to estimate the importance of new versus regenerated production at each period of the productive season (Dugdale and Goering, 1967; Tremblay and Gagnon, 2009). With our approaches, the in situ measurements in late summer were probably mainly measuring regenerated production, while the annual estimates of production based on nutrient drawdown is only taking into account the new production."

Figures

Figure 1 – Please explain what the red number on figure is. The orange line is very difficult to see.

A: The explanation of the red numbers is now explained in the figure caption and the orange line has been modified by a darker colour.

Figure 5 – “Sea-ice” should be rescale in order to increase the contrast for NPP. The unit should also appear in the caption. The authors should add a note to notice the different scales with the panels.

A: All changes have been done.

Supplement

Figure S7 – Maybe try a log scale in order to increase contrast.

A: Since all other plots are in linear scale we decided to keep it consistent to avoid confusion.

Figure S8 – The different scales are confusing. Please try something else (maybe log scale) or make sure to notice the reader about it.

A: A note in the figure caption has been added.

Response to Anonymous Referee #3

The authors would like to thank Referee #3 for the kind words and the useful comments that will improve the manuscript. Please find below the comment followed by our answer starting with an “A:”

General comments

The manuscript presents results from a cruise in the Eurasian Basin of the Arctic Ocean in summer 2012. The study focuses on primary productivity, both as measured net primary production (NPP), from 14CO2 uptake, and as new production estimated from seasonal drawdown in nutrients in the mixed layer. Samples from water column, sea ice and melt ponds were analysed and summarised for their contribution to the total primary production in this part of the Arctic Ocean. From the data the authors suggest the importance of ice algae and sub-ice algae to the primary production in the Arctic Ocean. The study is interesting and focuses on an important subject, and geographical area, where we need to improve our knowledge to understand future changes. I recommend the manuscript to be published after some rather minor revision.

A: We would like to thank referee 3 for this positive comment.

The decision of the authors to put so many of the figures and tables in the Supplement is unfortunate, especially since they are referred to so frequently. I strongly recommend that all (or definitely most) of these to be included in the manuscript. (Figure S4 may be the least important.)

A: We hope the editor agrees to moving all supplementary figures to the main text.

I miss the word ‘Ocean’ (as in ‘central Arctic Ocean’) in the title, and generally throughout the manuscript. This is a more correct term, but also makes it clearer. Also, the use of ‘Central Arctic’ is a bit confusing since the study only focuses on the Eurasian Basin (and adjacent shelf seas). This should maybe be changed for clarity.

A: We added the word Ocean to the title and checked for consistency throughout the manuscript.

Specific comments

P. 2899, L 20-28: When describing the area and general circulation it would be helpful to refer to a figure, with some of these features added. Figure 1 could partly do here, but then, for example, the Eurasian Basin should be noted.

A: The Eurasian Basin is now labeled in Fig. 1 and a red arrow indicating the entrance of Atlantic water has been added.

P. 2901, L 5-9: The statement 'nutrient availability . . . is probably decreasing. . .' together with the sentence after makes me a bit confused. From the second sentence, as I read it, one could get the impression that although it has been hypothesised that nutrients may increase due to river runoff, this may not be enough to substantially increase primary production. However, could it partly counteract the potential decrease due to stronger stratification, so that the net effect may be no significant change? This should at least be clarified/rephrased. The word 'probably' (L 5) could be changed to 'possibly', or 'may', or something similar, but better is if the two sentences are rephrased.

A: The sentences have been rephrased as follows:

"On the other hand, nutrient availability in the euphotic zone of the deep Central Arctic Ocean may decrease due to the stronger stratification caused by increased freshwater storage. An increase in nutrients from river runoff has been hypothesized, but a recent study by Le Fouest et al., (2012) indicates that the contribution of these nutrients will not be enough to increase primary production in the deep Central Arctic substantially, and since they will be consumed at the shelf seas."

P. 2902, L 6-7: FYI and MYI have not yet been defined. As far as I can see this is done first at P. 2904, and in Table 1, but needs to be defined here.

A: MYI is defined in P.2900 L24. FYI will be defined here.

P. 2902, L 9-10: Data sources are important information that should not be put away in a Supplement (stresses one of the General comment above).

A: Table S1 just contains the Pangaea dois, which are also in the references mentioned each time a dataset is introduced.

P. 2907, L 7: 'Only' duplicates of all treatments do not give strong statistics. The decision may have been due to available resources, but should possibly be commented on.

A: We agree that duplicates are not enough to do any kind of statistics. This is now clearly stated here.

P. 2907, L 10-11 (and throughout): To me the use of 'negative control' (when no nutrients are added) is confusing, since no nutrients are removed. Why not simply use the term 'control (C)', since this is what it is?

A: We agree and the term has been modified throughout the manuscript.

P. 2908, L 14: What depth/layer is used as 'surface'?

A: This sentence has been improved for clarity: "We then derived the uptake since last winter by calculating the difference between the integrated nutrient profile at the end of the productive season (August-September) and the nutrient value at the temperature minimum depth, which represents the initial nutrient concentration available in winter in the mixed layer."

P. 2908, L 21: I'm missing a reference to Dugdale and Goering (1967).

A: Added.

P. 2909, 3.1: To me much of this section feels like 'Method' material. It may be fine in the Results, but may be better placed earlier, to 'set the scene'.

A: The paragraph is at the beginning of the results to set the scene.

P. 2912, L 17: The reference to Table 3 must be wrong. That table shows nutrient inventories. Should be Table 4/Table TS3. The different values presented on L 14-16, are they presented in any table/figure (I don't seem to find them)? There is also a very large uncertainty in the average value for the lNPP in ice-covered waters. Any comment that could be added to this?

A: Yes, the reference should be to Table S3 (TableS2 in the revised manuscript). The values in L14-16 are presented in Figure 2 (Figure 4 in the revised manuscript). The average value for INPP in ice-covered waters is putting together a large area with high spatial variability.

P. 2913, L 20-23: These stations do also show the shallowest depth of the Euphotic zone, which could be worth mentioning/discussing.

A: We agree that this should be mentioned.

P. 2914, L 13-14: If only comparing two periods one cannot use the term 'trend'. Should be rephrased.

A: Has been substituted by "We observed a decrease.."

P. 2916, L 7-13: Is there any estimated uncertainty in the lNPP from sedimentation of sub-ice algae? The potential total new production mentioned on line 12 does not have any extra uncertainty from this addition, but certainly this may be very large.

A: The range of estimated values for sub-ice algal sedimentation range from 1-156 g C m-2 d-1. Since the aim of this calculations was to discuss the possible contribution of sub-ice algae to total new production, we used the mean. This information has been now included in the manuscript.

P. 2916, L 28-29 – P. 2917, L 1-2: These two sentences need some rephrasing. Suggestion:'. . ., they have their peak in production, and thus seem to adapt to higher light conditions. This would already have. . .'

A: Rephrased as suggested.

P. 2917, L 8-9: Sentence stands a bit disconnected. Could be rephrased and mergedwith next sentence: Our nutrient addition experiment suggests. . . their biomass, which is in agreement with previous findings that sea-ice diatoms can store. . . (Kamp et al.,. . .).

A: Rephrased as suggested.

P. 2917, L 23: The word 'normal' may not be the best choice, and would need to be explained. Maybe 'typical', or something related (during the last. . . time frame).

A: We substituted "normal" by "typical (previous to the current trend of sea-ice extent decrease)"

P. 2919, L 17-18: Are there any estimated uncertainty in these numbers?

A: Yes, Table 4 includes the information of the minimum and maximum values.

P. 2919, 27-28 + P. 2920, L1-2: This is a repeat of what was said on page 2917.

A: We agree that the information is repeated, but the context and aim of mentioning it here is different. We rephrased it to avoid being repetitive.

"This, together with the capability of ice algae to store nutrients (Kamp et al., 2011) might provide them with an advantage against phytoplankton."

P. 2920, L 17-19: This sentence is not very clear to me, but then the sentence after says the same thing, much better. Thus remove the first one, or do some merge.

A: The first sentence was removed and the second one modified as follows: "However, the carbon flux was mainly composed of debris and the few algae observed in the sediment traps using light microscopy were flagellates."

P. 2921, L 21-27: One should be careful when comparing only two years. Was the same method used to estimate NPP in these two studies? Did they cover the same area? Also, as far as I can see the Vetrov and Romankevich did not present any uncertainty estimate of their average, making it more difficult to compare. In addition, their average value for the period does not tell whether there was some trend during these years. It comes down to a question of the significance of the difference, which is hard to evaluate.

A: When comparing the Grossmann and Gleitz study with ours we made sure that the method and the area sampled were the same. The lack of estimate uncertainty in the Vetrov and Romankevich study makes assessing the significance of any difference complicated. This has been now explicitely acknowledged in the text.

P. 2924, L 24-27 + P. 2925, L 1: These sentences/statements are not very clear to me. In 'earlier sea-ice based NPP' you mean the timing? Some rephrasing could make this clearer.

A: Yes, we were referring to timing. The sentence has been modified to improve clarity.

Technical comments

A: All technical comments have been implemented as suggested.

Overall: typically citations in text should be arranged chronologically, not alphabetically as is done consistently in this manuscript.

A: Thanks for the hint. There was a problem with the citation software.

P. 2902, L 16: Remove ‘only’.

P. 2902, L 22: Change ‘the’ to ‘a’ (CTD system).

P. 2903, L 5, and P. 2906, L 20: Chl a. . .

P. 2903, L 27: ‘. . . the amount of labelled. . .’

P. 2905, L 3: ‘. . .those where. . .’

P. 2905, L 4: NPP is already defined, on page 2903, so don’t need to be written out here.

P. 2905, L 23-26: lNPP has not been defined yet, and first comes on P. 2912 and Table 4 (as far as I can see).

P. 2912, L 8: (18 and 30, respectively).

P. 2912, L 26-27: Remove ‘. . . sampled with the peristaltic pump from the ice floe, . . .’ since this is described in the Methods.

P. 2914, L 10-28: I don’t find a reference to Fig. S7. This would fit in the last paragraph on the page, but then figures from S7 and onwards need to be renumbered.

P. 2914, L 24: ‘. . . in 1982 as in 2012.’

P. 2920, L14-17: Many ‘However’ here, the first one could probably be removed.

P. 2924, L 27: ‘. . .Central Arctic Ocean Basins. . .’

Figures:

Fig. 2, Caption: Remove ‘nitrate’ after ‘> 3 μM’.

Fig. 5: ‘Central Arctic Ocean’. Add a notation about the different scales. Also, if this is the expected size of the figure in the printed version the text/values on the colour bar must be much larger. Now it’s almost impossible to read them.

Supplement (which I hope will be moved to the manuscript):

Table S2: Neither lNPP nor MYI is explained/defined. It is of course in the manuscript, but would be helpful here. In addition the five geographical sections are the ones shown in Fig. S7, right? It could be helpful to refer to that here.

Fig. S6: Change ‘nitrogen (A)’ to ‘nitrate (A)’.

Fig. S7: It would be helpful to see the sea-ice extent in 1982 depicted in (A).

A: We tested this but since almost the entire area shown was ice covered, the few discontinuous lines depicting the ice extent were rather confusing.

Fig. S8: Make a note about the different scales for the Melt ponds panels.

Photosynthetic production in the Central Arctic Ocean during the record sea-ice minimum in 2012

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Abstract

The ice-covered Central Arctic Ocean is characterized by low primary productivity due to light and nutrient limitations. The recent reduction in ice cover has the potential to substantially increase phytoplankton primary production, but little is yet known about the fate of the ice-associated primary production and of the nutrient supply with increasing warming. This study presents results from the Central Arctic Ocean collected during summer 2012, when sea-ice reached a minimum extent since the onset of satellite observations. Net primary productivity (NPP) was measured in the water column, sea ice and melt ponds by $^{14}CO_2$ uptake at different irradiances. Photosynthesis vs. irradiance (PI) curves were established in laboratory experiments and used to upscale measured NPP to the deep Eurasian Basin (north of 78°N) using the irradiance-based Central Arctic Ocean Primary Productivity (CAOPP) model. In addition, new annual production was calculated from the seasonal nutrient drawdown in the mixed layer since last winter. Results show that ice algae can contribute up to 60% to primary production in the Central Arctic Ocean at the end of the productive season (August-September). The ice-covered water column has lower NPP rates than open water due to light limitation in late summer. As indicated by the nutrient ratios in the euphotic zone, nitrate was limiting primary production in the deep Eurasian Basin close to the Laptev Sea area, while silicate was the main limiting nutrient at the ice margin near the Atlantic inflow. Although sea-ice cover was substantially reduced in 2012, total annual new production in the Eurasian Basin was 17 ± 7 Tg C yr^{-1}, which is within the range of estimates of previous years. However, when adding the contribution by sub-ice algae, the annual production for the deep Eurasian Basin (north of 78°N) could double previous estimates for that area with a surplus of 16 Tg C yr^{-1}. Our data suggest that sub-ice algae are an important component of the productivity in the ice-covered Eurasian Basin of the Central Arctic Ocean ~~productivity~~. It remains an important question if

their contribution to productivity is on the rise with thinning ice, or if it will decline due to overall sea-ice retreat and be replaced by phytoplankton.

Keywords: Primary production, Arctic, phytoplankton, sea-ice algae, melt ponds, nutrient limitation, photosynthesis-irradiance curves, carbon cycle.

1 Introduction

Estimates of annual primary production (PP) in the ice-covered Central Arctic Basins are among the lowest of all oceans worldwide (Sakshaug et al., 2004). On an annual base, the total incoming irradiance and the depth of the winter mixing as a proxy for nutrient stocks are the two main factors that constrain Arctic primary production (Ardyna et al., 2011; Popova et al., 2010). Available irradiance is generally sparse due to the low angle of the sun around the North Pole, and the attenuation effect of sea ice (Sakshaug and Slagstad, 1991). When enough light becomes available for PP between May and September (Arndt and Nicolaus, 2014; Leu et al., 2011), Arctic phototrophs grow in the water column (phytoplankton), in and below sea ice (sea-ice algae), and in melt ponds (melt-pond algae). Light is the main limiting factor for the phytoplankton below thick ice at the beginning of the productive season (Sherr et al., 2003). However, during the summer months the total incoming irradiance increases since daylight is available during 24h, and sea ice is melting away. North of 78°N latitude, the productive season is shorter (June to September) than in southern Arctic regions, since it is restricted by the amount of light penetrating through the dense sea-ice cover (Leu et al., 2011). Nutrients become limiting as the season advances (Tremblay and Gagnon, 2009), due to strong vertical stratification and reduced wind-driven mixing affected by sea ice (Carmack et al., 2006).

The Central Arctic Ocean is divided into two deep basins separated by the Lomonosov Ridge: the Eurasian and the Amerasian basins (Fig.1). These central basins cover 40% of the Arctic Ocean, but due to their inaccessibility, data for both regions are scarce (Matrai et al., 2013). The two central basins differ in the inflow of waters. Low salinity, phosphate rich and nitrate depleted Pacific waters enter the Amerasian Basin through the Bering Strait. Warm, high salinity Atlantic waters with a higher N:P ratio ~~enter~~ reach the Eurasian Basin through the Fram Strait, but remain submerged under a layer of fresher Arctic surface water for ~5 years before upwelling (Jones et al., 1998). Since most of the studies regarding nutrient limitation in Arctic waters come from the Amerasian Basin, nitrate is considered the main limiting nutrient for primary production in the Central Arctic~~-~~ Ocean (Tremblay and Gagnon, 2009; Tremblay et al., 2012). However, nutrient ratios in the Eurasian Basin are very different to the Amerasian pointing towards silicate limitation rather than nitrate in some regions (Codispoti et al., 2013; Sakshaug et al., 2004; Wheeler et al., 1997). In late summer, mostly regenerated production based on ammonium takes place (Martin et al., 2012). Grazing pressure and the microbial loop also play an important role controlling recycling of nutrients vs export (Boetius et al., 2013; Olli et al., 2007; Yager et al., 2011), but remain understudied in the Central Arctic Ocean.

Sparse sampling, high spatial and temporal variability and the use of~~The~~ different methodologies to estimate PP in and under the ice, as well as in ice-free regions ~~together with the high spatial and temporal variability~~ result in poorly constrained PP values for the Central Arctic Basins (Miller et al., 2015). These range from 1 Tg C yr^{-1}, assuming no production in ice covered areas (Hill et al., 2013), to 119 Tg C yr^{-1} when taking into account the total amount of nutrients used for PP from the mixed layer (Codispoti et al., 2013). The annual areal NPP estimates for the Eurasian Basin, including sea-ice algae, range between 10-15 g C m^{-2} yr^{-1}, twice as much as in the Amerasian Basin (Codispoti et al., 2013; Gosselin et al., 1997; Sakshaug et al., 2004; Ulfsbo et al., 2014; Wheeler et al., 1996). In the Central Arctic Ocean sea-ice algae can contribute up to 57% of the NPP in summer (Gosselin et al., 1997), but their patchy distribution, the technological challenges in sampling them, and the difficulties to obtain in situ estimates of their PP, cause a high uncertainty in the overall estimates (Fernández-Méndez et al., 2014; Katlein et al., 2014a).

Recent evidence suggests that the rapid Arctic warming and sea-ice retreat are changing key factors governing primary productivity, especially in the Central Arctic Basins. The percentage of thick multi-year ice (MYI) is decreasing rapidly (Laxon et al., 2013; Maslanik et al., 2007; Stroeve et al., 2012), reducing the ~~average~~annual mean ice thickness from ~~xx–xx m~~3.6 to 1.2 m ~~in the past decade~~since 1975 (Lindsay and Schweiger, 2015). A summerly ice-free Arctic has been predicted to occur around 2050 (Wang and Overland, 2012). The lowest sea-ice extent since the beginning of recorded observations was reached in September 2012 (National Snow and Ice Data Center (NSIDC), 2012) leaving 45% of the Eurasian Basin north of 78ºN ice-free (<15% ice cover). Furthermore, an increase in melt-pond covered sea ice has been observed (Rösel and Kaleschke, 2012), enlarging the habitat of phytoplankton and sea-ice algae (Kramer and Kiko, 2011; Lee et al., 2011). All of these changes combined lead to an increase in the amount of irradiance reaching the water column in the Central Arctic- Ocean (Nicolaus et al., 2012). On the other hand, nutrient availability in the euphotic zone of the deep Central Arctic Ocean ~~is probably decreasing~~may decrease due to the stronger stratification caused by increased freshwater storage. An increase in nutrients from river ~~origin~~ runoff has been hypothesized, but a recent study by Le Fouest et al., (2012) indicates that ~~the contribution of~~ these nutrients will not be enough to increase primary production in the deep Central Arctic substantially, ~~and~~ since ~~any effect may be constrained to the~~they will be consumed at the shelf seas. Furthermore, changes in light conditions and nutrient availability might affect the timing of sea ice and water column blooms and the composition of the autotrophic biomass, this will have implications for timing and food quality available for grazers (Leu et al., 2010; Slagstad et al., 2011) and for total export to the deep sea (Lalande et al., 2013).

This study assesses primary productivity in the Eurasian Basin of the Central Arctic Ocean at the time of the sea-ice minimum extent in summer 2012, in comparison to previous estimates. It aims to quantify the relative contribution of sea ice, melt ponds and water column to total NPP, both in situ and for the entire Eurasian Basin, with a focus on the bottom up limiting factors of NPP (light and nutrients) at different time scales. Using complementary approaches we test the hypothesis that primary productivity – including that of under-ice algae - could increase with decreasing ice-cover in the Central Arctic Ocean.

2 Methods

2.1 Study site and sampling

Sea ice, melt ponds and water column were sampled during the RV Polarstern expedition ARK-XXVII/3 to the Eurasian Basin of the Central Arctic Ocean during summer 2012. The expedition started in early August visiting the ice margin and heading towards the Laptev Sea (Fig. ~~1A~~1a). At the beginning of September the ice-free shelf edge of the Laptev Sea (77-80°N, 118-133°E) was sampled (Fig. ~~1B~~1b) and at the end of the month the Central Arctic was reached (85-88°N. 52-123°E) (Fig. ~~1C~~1c). The expedition covered a large portion of the Eurasian Basin and included 33 water stations in Atlantic~~waters near the Atlantic inflow~~ -influenced waters entering the Arctic through Fram Strait (Atlantic inflow as described in ~~(~~Rudels, 2012), ~~and~~ as well as 8 ice stations expanding through different nutrient regimes, ice coverage (from ice free waters to 100% ice cover) and ice types according to age, thickness, pond and snow cover and topography~~: ~~. ~~f~~First year ice (FYI) ~~is~~ was rather flat with a high coverage of melt ponds and MYI is thicker and has more snow on top (Table 1).

Sea-ice concentration and melt-pond coverage were assessed during the entire cruise by observations from the bridge (Hendricks et al., 2012) (Table S1). Sea-ice thickness was additionally measured with an air-borne electromagnetic (EM) Bird as described in Haas et al. (2009). Sea ice was sampled using an ice corer (9 cm diameter) (Kovacs Enterprise, Roseburg, USA). Ice cores were cut into two equal sections (top and bottom) for primary productivity measurements and in 10 cm sections for biomass and nutrient measurements. Ice cores were melted in the dark at 4°C for 24 h on a shaker (Mikkelsen et al., 2008; Rintala et al., 2014). ~~Filtered s~~Seawater from 50-100 m depth from a nearby ~~the previous~~ station filtered through a

0.2 µm filter (200 ml per cm of ice) was only added to the ice sections used for pigment analysis (Thomas and Dieckmann, 2010).

Melt pond water samples were obtained with a hand pump (Model 6132-0010, Nalgene, Penfield, NY, USA) and melt pond depth, temperature and salinity were measured in situ using a hand-held conductivity meter (315i with TetraCon electrode cell, WTW GmbH, Weilheim in Oberbayern, Germany). Water column profiles of temperature and salinity were obtained using the a Conductivity Temperature Depth (CTD) system with a Carousel Water Sampler (Sea-Bird Electronics Inc., Washington, USA). Water below the ice was sampled using a peristaltic pump (Masterflex® E/S™ portable sampler, 115 VAC, Oldham, UK), while water samples in ice-free areas were collected at 2-5 m depth during the upcast of the CTD Rosette sampler. Flow cytometer samples obtained using both approaches showed no evident difference duein relation to theeither sampling method used. To exclude the effect of propeller mixing in the upper 20 m of CTD profiles, additional vertical profiles of under ice salinity, temperature and fluorescence were obtained by manually lowering a CTD probe through holes in the ice floes sampled (‘ice-CTD’; Sea and Sun Technology CTD75M, Trappenkamp, Germany). Fluorescence in the water column was measured with two fluorometers (Turner Cyclops, California, USA) attached to the ship CTD and the ice-CTD, respectively. Fluorescence values were calibrated *a posteriori* with chlorophyll *a* (Chl *a*) concentrations from water samples using high-performance liquid chromatography (HPLC) as described in Tran et al., (2013) and David et al., (2014). Chl *a* in the ice and melt ponds was measured using the same HPLC method.

For the nutrient addition experiments, 20 L of seawater were collected at station 3 at the depth of the maximum Chl *a* concentration (25 m) using the ship´s CTD sampler, and a piece of sea ice of 40 cm x 40 cm was cut with an ice saw at station 8 and melted in the dark in 0.2 µm filtered seawater from the same location (Rozanska et al., 2009; Thomas and Dieckmann, 2010).

2.2 In situ Net Primary Production

Net Primary Production (NPP) was measured using the ^{14}C uptake method (Steemann Nielsen, 1952) with minor modifications. Melted sea ice, seawater, and melt pond samples were spiked with 0.1 µCi mL^{-1} of ^{14}C labelled sodium bicarbonate (Moravek Biochemicals, Brea, USA) and distributed in 10 clear bottles (20 mL each). Subsequently they were incubated for 12 h at -1.3°C under different scalar irradiances (0–420 µmol photons m^{-2} s^{-1}) measured with a spherical sensor (Spherical Micro Quantum Sensor US-SQS/L, Heinz Walz, Effeltrich, Germany). At the end of the incubation, samples were filtered onto 0.2 µm nitrocellulose filters and the particulate radioactive carbon uptake was determined by liquid scintillation counting using Filter count scintillation cocktail (Perkin Elmer, Waltham, USA). The carbon uptake values in the dark were subtracted from the carbon uptake values measured in the light incubations.

Dissolved inorganic carbon (DIC) was measured for each sample using the flow injection system (Hall and Aller, 1992). The DIC concentration was taken into account to calculate the amount of labelled bicarbonate incorporated into the cell. Carbon fixation rates were normalized volumetrically and by Chl *a* (doi:10.1594/PANGAEA.834221). Photosynthesis-irradiance curves (PI curves) were fitted using MATLAB® according to the equation proposed by Platt et al. (1980) including a photoinhibition parameter (β) and providing the main photosynthetic parameters: maximum Chl *a* normalized carbon fixation rate if there were no photoinhibition (P^b) and the initial slope of the saturation curve (α). The derived parameters: light intensity at which photosynthesis is maximal (I_m), the carbon fixation rate at that maximal irradiance (P^b_m) and the adaptation parameter or photoacclimation index (I_k) were calculated according to Platt et al. (1982) (Table 2).

Depth-integrated in situ rates were calculated for each environment as a function of the available photosynthetically active radiation (PAR). Irradiance profiles were calculated for each environment (sea ice, melt pond, water under the ice and open water) from the daily average incoming solar shortwave irradiance measured by a pyranometer (Kipp & Zonen, Delft, Netherland) mounted on the ship. We used light attenuation coefficients of 10 m^{-1} for snow, 1.5 m^{-1} for sea ice (Perovich, 1996) and 0.1 m^{-1} for Atlantic-influenced Arctic seawater, based on literature values and observations during the cruise. Planar irradiance was transformed to scalar irradiance according to Ehn and Mundy (2013) and Katlein et al., (2014). Water column production was integrated over the euphotic zone (1% of incoming irradiance) and sea-ice production over the ice thickness. Melt-pond coverage and sea-ice concentration (Table ~~2~~1) were taken into account when calculating the total primary production per area.

2.3 Central Arctic Ocean Primary Productivity model

We developed the Central Arctic Ocean Primary Productivity (CAOPP) model as an irradiance-based model to ~~provide~~ obtain estimates of sea ice, melt pond and water column NPP in the Central Arctic (north of 78°N). This model is based on the photosynthesis equation from Platt et al. (1980) and the under-ice light parameterization of Arndt and Nicolaus (2014). Average Chl *a* profiles and average PI curves were calculated for each environment (~~Fig. S1~~Fig. 2): melt ponds (MP), multi-year ice (MYI), first-year ice (FYI), water under the ice (WUI), and open water (OW). Key parameters for photosynthetic activity (Table 2) were calculated from the measured PI curves during summer 2012, excluding those were the coefficient of determination of the fit (R^2) was smaller than 0.5. ~~Net Primary Production (~~NPP~~)~~ was calculated ~~analogous to~~as described in section 2.2 for each grid point ~~in~~ of a 10 km polar stereographic grid, ~~as~~ and a vertical integration with a resolution of 10 cm in the ice and 1 m in the water column. Downwelling solar irradiances at the surface (PAR) were calculated from the European Centre for Medium-Range Weather Forecast (ECMWF) Era Interim re-analyses (Dee et al., 2011). Downwelling transmitted irradiances underneath the sea-ice were calculated using the light parameterization of Arndt and Nicolaus, (2014a) based on sea ice data from OSI SAF (Andersen et al., 2007). Light extinction in all media was assumed to follow an exponential decay. For water and sea ice we used the same light extinction coefficients as presented above. NPP was calculated as a function of PAR for every depth multiplied with the according Chl *a* concentration and integrated over the euphotic zone (1% incoming PAR). For pixels with a sea-ice concentration >15%, the WUI average PI curve was used, while for pixels with < 15% sea-ice concentration the OW average PI curve was used. Note that the OW average PI curve is based on data obtained close to the Laptev Sea area. For melt ponds, an average depth of 0.4 m was used based on observations during the expedition (Hendricks et al., 2012). Since satellite-based melt pond cover data were not available for summer 2012, a constant melt pond concentration was used for FYI: 26% and for MYI: 29% following Arndt and Nicolaus (2014) and Rösel and Kaleschke (2012). These values are similar to the average melt pond coverage observed during our cruise (30 ± 15 %) (Hendricks et al., 2012). Total depth integrated NPP (INPP) was calculated as an average of the three compartments “open water”, “water covered by sea ice” and “water covered by sea ice with melt ponds” weighted with the respective areal fraction. To estimate the total range of INPP we ran the CAOPP model three times using the average, the minimum and the maximum photosynthetic parameters.

To investigate differences in NPP in different sectors of the deep Eurasian Basin due to changes in the sea-ice conditions, we ran the model under two different scenarios: one with sea-ice conditions previous to the rapid sea-ice decline in the 80s, and another one with no sea-ice cover in summer. For the first scenario we chose 1982 as a representative year previous to the long term trend of sea-ice decline (Fig. 1C). For the second scenario we chose a summer ice-free scenario that has been predicted to occur around 2050 (Wang and Overland, 2012). For the 1982 scenario, the sea-ice coverage information was retrieved from OSI SAF (Andersen et al., 2007) and the incoming irradiance from data re-analysis (Arndt and Nicolaus, 2014). For the ice-free scenario, the ice cover was removed from the model and all other parameters, including incoming irradiance were kept as in 2012. Both scenarios assume no changes in the photosynthetic parameters, and the nutrient concentrations ~~compared~~ were set as observed in~~to~~ 2012. The mean results for September 1982, 2012 and 2050 are compared in ~~Table S2~~Table 5 to detect the increasing or decreasing trend in NPP.

2.4 Nutrient addition experiments

Two nutrient addition experiments were performed during the cruise at ice stations 3 and 8 (Fig. 1). For the first one, seawater from the depth of the Chl *a* maximum (25 m) was collected, and for the second one, MYI with a brown coloration due to the high content of sea-ice algae, was melted in filtered seawater taken at the same spot. Both samples were pre-filtered through a 100 µm mesh to remove grazers and kept at 0 ºC and 65 µmol photons m^{-2} s^{-1} in 25 L transparent bottles until the start of the experiment. Chl *a* was monitored every day with a Turner Trilogy Fluorometer (model 7200-000) (Turner, California, USA) to identify the end of a possible lag effect. Once Chl *a* reached a stable concentration (6 days for seawater and 4 days for sea ice) the sample was mixed and distributed in 10 transparent 5L-Nalgene bottles (2L in each). The initial biomass concentration in the samples was estimated by measuring Chl *a* and particulate organic matter. A sub-sample (0.5 L) was filtered through a pre-combusted glass fiber filter (GF/F) (0.7 µm poresize, Whatman, Kent, United Kingdom) and analyzed with an elemental analyser (EA3024-IRMS, EuroVetorSpA, Milan, Italy) to quantify particulate organic carbon (POC) and nitrogen (PON). For Chl *a* quantification a sub-sample (0.5 L) was filtered through a GF/F filter and the pigments were extracted with 90% acetone during 24 h (Parsons et al., 1984). The fluorescence was then measured with a Turner Fluorometer (Turner, California, USA).

Nutrient concentrations (nitrate, phosphate and silicate) were measured with a standard photometric method using a Technicon TRAACS 800 continuous flow auto analyzer (Technicon Corporation) according to established methods (Boetius et al., 2013). Five different treatments in duplicate were incubated at 75 µmol photons m^{-2} s^{-1}. This irradiance is slightly higher than the average irradiance below the ice at the end of the productive season to avoid light limitation and prevent photoinhibition. The five treatments consisted on a ~~negative~~ control with no nutrient addition (C-), a positive control with the three nutrients added (C+) and three treatments with one nutrient added in each (N+, P+ and Si+). In each treatment, the added nutrient concentration resembled the concentration of that nutrient in deep waters (>100 m) at the same ice station. Biomass (Chl *a*, POC and PON) and nutrients were measured in each treatment after 2 days and compared to the initial value. In parallel a sub-set of four samples

(20 mL each) from each treatment were spiked with ^{14}C bicarbonate to estimate NPP as described above. Three samples were incubated under light conditions (75 µmol photons m^{-2} s^{-1}) and one in the dark for 24 h. Previous to incubation and a~~A~~t the end of the experiments the qualitative algal composition from each treatment was studied with a plankton chamber (Hydro-Bios, Altenholz, Germany) and an inverted light microscope with phase contrast optics (Axiovert 40C, Carl Zeiss, Jena, Germany) with integrated camera (AxioCamMRc, Carl Zeiss, Jena, Germany). No qualitative shifts in the community composition were observed before and after the incubation.

2.5 Annual New Production

We determined the mixed layer depth during the previous winter from temperature in our summer CTD profiles of the upper Arctic Ocean, following Rudels (1995) and Korhonen et al. (2013). In the temperature profiles during the Arctic Ocean melting season, the winter mixed layer depth is indicated by a temperature minimum above the lower halocline. Any conservative property, such as salinity, observed at the depth of this temperature minimum, represents the conditions of the mixed layer during the previous winter. An estimate of the change from the previous winter is given by the difference between a conservative property in summer and its reference value at the depth of the temperature minimum. The vertical integral of these differences represents the addition or removal of a quantity or substance, for example nitrate, since the previous winter. All oceanographic data used in this study are available from the Earth system data base PANGAEA (Rabe et al., 2012) (Table S1).

Nutrients (phosphate, silicate, and nitrate) in the water column were measured at discrete depths (2, 10, 20, 30, 50, 75 and 100 m) as described above (Bakker, 2014) (Table S1). Subsequently we interpolated total inorganic nitrogen (TIN = NO^-_3+NO^-_2), phosphate and silicate to the vertical resolution of the continuous temperature profiles (Reiniger et al., 1968), to calculate the nutrient inventory in the layer above the temperature minimum. We then derived the uptake since last winter by calculating the difference between the integrated ~~surface~~ nutrient profile at the end of the productive season (August-September) and the nutrient value at the temperature minimum depth, which represents the initial nutrient concentration available in winter in the mixed layer. This approach is similar to the one used by Codispoti et al., (2013) with the main difference that they used the few available winter surface nutrient concentrations. The annual TIN, phosphate and silicate uptake were then transformed to carbon units using the Redfield ratio 106C:16N:15Si:1P (Brzezinski, 1985; Codispoti et al., 2013; Cota et al., 1996; Harrison et al., 1977; Smith et al., 1997) giving annual new production estimates for sea ice and water column during the Arctic productive season. Since the description of new production refers to production based on nitrate, most of the annual new production estimates are based on nitrogen draw-down (Dugdale and Goering, 1967). Higher than Redfield C:N ratios (7.3-8.3) seem to be common in Arctic phytoplankton and sinking material (Frigstad et al., 2013; Tamelander et al., 2013; Tremblay et al., 2008). Using these ratios would result in a ~10% increase in the new production estimates, but to be able to compare our results with previous estimates we chose the commonly used Redfield ratio. Silicate can also be used to estimate diatom-based new production (Yool et al., 2007). Both, higher and lower N:Si ratios have been reported for Arctic diatoms (Simpson et al., 2013; Spilling et al., 2010) depending on the time of the year and the amount of detritus material present. To be consistent with the nitrogen-based estimates, we used Redfield ratios for silicate as well. To calculate an average daily rate, we assumed a productive season of 120 days (Gradinger et al., 1999). This method assumes that lateral input of nutrients from rivers or shelves is negligible which should be the case in the deep part of the Central Arctic Ocean north of 78°N (Le Fouest et al., 2013).

3 Results

3.1 Environmental conditions

Sea ice, melt ponds, and water column environments were sampled in the Eurasian Basin in August and September 2012 at the end of the productive season, including completely and partially ice-covered areas above the abyssal basins as well as open waters on the Eurasian shelf. From the eight ice stations sampled, stations 1, 2 and 3 represent the ice margin (Nansen Basin) in early August (Fig. ~~1A~~1a); 4, 5 and 6 represent the degraded ice cover (average 1 m thickness) above the continental slope of the Eurasian margin (Fig. ~~1B~~1b), and 7 and 8 represent MYI (average 1.8 m thickness) in the Central Arctic Ocean (Amundsen Basin) in late September (Fig. ~~1C~~1c). In September, a thin snow cover of 0.02 and 0.06 m thickness was observed. Melt pond cover varied between 10 and 50%, and from mid-September most of the melt ponds were frozen over (<0.1 m ice thickness). Salinity in the ice (0-4) and the water column (30-34) were in typical ranges for these environments, while steep gradients were found in melt ponds (vertical gradients of 0.4 at the surface to 32 at the bottom) and also between different melt ponds, depending if they were open to the seawater below or closed. The daily mean incoming irradiance showed a strong temporal decrease from a 24 h average of 250 µmol photons m^{-2} s^{-1} in early August to 13 µmol photons m^{-2} s^{-1} in late September. In the water column directly below the ice, photosynthetically active radiation (PAR) decreased from 40 µmol photons m^{-2} s^{-1} in early August to 1 µmol photons m^{-2} s^{-1} in late September.

Integrated nutrient inventories were very low in all environments in accordance with the time of the year (Table 3). Nutrient distributions in the euphotic zone of the water column were reflected in the N:P and N:Si ratios (~~Fig. S2~~Fig. 3) leading to the characterization of three distinct nutrient regimes in the Eurasian Basin during the cruise: (1) silicate-depleted ice margin in early August, (2) nitrate-depleted Laptev Sea margin, and (3) all nutrients depleted high Central Arctic Ocean (north of 85ºN) in late September (~~Fig. 2~~Fig. 4, Table 3). Nutrient depletion is defined here as concentrations lower than 1 µmol L^{-1} nitrate, 0.2 µmol L^{-1} phosphate, and ~~2~~1.5 µmol L^{-1} silicate.

3.2 Photosynthesis and irradiance

Despite the high spatial and temporal variability present in our data set, certain patterns emerged when comparing the photosynthetic parameters of sea-ice algae, melt pond phototrophs and water column phytoplankton (Table 2). A general decrease in all photosynthetic parameters was detected between August and September. However, the low number of samples and the wide area sampled makes it difficult to further differentiate the photosynthetic parameters. Sea-ice algae showed the best adaptation to low light (initial slope of the PI curve α). Photoinhibition (β) was lower in sea-ice algae than in melt pond phototrophs and under-ice phytoplankton, but higher than for phytoplankton in ice-free waters (Table 2). In late summer (August and September), sea-ice algae were adapted to light intensities between 20 and 100 µmol photons m^{-2} s^{-1}, similar to the under-ice phytoplankton (14-80 µmol photons m^{-2} s^{-1}). These irradiances were generally higher than the average irradiance available under the ice (0.2-20 µmol photons m^{-2} s^{-1}, Table 2). Phytoplankton showed higher photoinhibition below the ice than in ice-free waters. Furthermore, in September under-ice phytoplankton showed a higher range of light intensities at which photosynthesis is maximal (I_m) than phytoplankton in open waters. Melt-pond phototrophs and phytoplankton in open waters close to the ice margin in early August reached the highest carbon fixation rates ($P^b{}_m$). However, they also showed the highest photoinhibition rates at high irradiances (Table 2), despite being adapted to higher irradiances (I_k: 50-290 µmol photons m^{-2} s^{-1}) than sea-ice algae and phytoplankton. In general, the light intensity to which the sea-ice and melt-pond communities were adapted (I_k) and the light intensity at which photosynthesis is maximal (I_m) were similar to what they received (I) at the time of sampling. In contrast, phytoplankton below the ice and in open waters, generally received less light than what they would need to perform optimally.

3.3 Nutrient addition experiments

For the first nutrient addition experiment, seawater was collected from the Chl *a* max depth (25 m) ~~depth~~ at ice station 3. It had low nitrate (1.3 µmol L^{-1}), phosphate (0.1 µmol L^{-1}) and silicate (1.2 µmol L^{-1}) concentrations, and a Chl *a* concentration of 1.6 µg L^{-1}. Four days after the addition of 13 µmol L^{-1} NO_3^-, 0.8 µmol L^{-1} PO_4^{3-}, and 10 µmol L^{-1} SiO_4^{3-}, to reach concentrations as below the mixed layer, NPP increased in the silica (Si+) treatment and in the positive control with all nutrients (C+) (~~Fig. 3~~Fig. 5A). POC, PON and Chl *a* only increased significantly when all nutrients were added (~~Fig. S3~~Fig. 6A). The increase in NPP corresponded to a carbon yield of 1.3 mg C L^{-1} d^{-1}, matching the POC increase of 1.6 mg C L^{-1} d^{-1} and the increase in PON (0.15 mg N L^{-1} d^{-1}). The C:N ratio in the Si+ and C+ treatments increased compared to the other treatments from 10 to 14. Silicate uptake increased significantly in the Si+ and C+ treatments (1.7 and 1.9 µmol L^{-1} d^{-1}) compared to the control with no nutrient addition (0.2 µmol L^{-1} d^{-1}, Fig. 3B). This would correspond to a silicate yield of 0.07 mg Si L^{-1} d^{-1}. The organism responsible for the response was the chain forming diatom *Chaetoceros socialis* (~~Fig. S4~~Fig. 7A).

The sea ice sampled at station 8 was depleted in nutrients with very low nitrate (0.2 µmol L^{-1}), phosphate (0.1 µmol L^{-1}) and silicate (1 µmol L^{-1}) concentrations. In this case, the addition of nutrients resulted in measurable nutrient uptake, but neither in a~~n~~ measurable increase in biomass nor in NPP (~~Fig. 3~~Fig. 5C, D and S3B). Nitrate yield in the N+ treatment was 0.019 mg N L^{-1} d^{-1}, twice as much as the PON increase (0.008 mg N L^{-1} d^{-1}), indicating nitrate storage in the cells. The community composition of this sample was formed by typical sea-ice diatoms in a healthy state (with visible chloroplasts): *Nitzschia sp.*, *Pseudonitzschia sp.*, *Fragilariopsis sp*. and *Entomoneis sp.* (~~Fig. S4~~Fig. 7B). A few micrograzers (flagellates) were observed with the microscope and they might have contributed to nutrient uptake.

3.4 Net primary production in sea ice, melt ponds and water column

Integrated over the depth of the euphotic zone, ~~Phytoplankton~~ phytoplankton constituted most of the ~~integrated~~ phototrophic biomass, expressed in Chl *a* units, in all FYI stations (70-98%), while sea-ice algae accounted for 68-86% of the biomass in the two MYI stations (Table 1). MYI contained almost one order of magnitude more Chl *a* than FYI. Melt-pond water, excluding algal aggregates located at the bottom (Fernández-Méndez et al., 2014), contributed the least to integrated biomass (0.1-6%). The two melt ponds with the highest Chl *a* values (~0.3 mg m^{-2}) had the highest salinity (18 and 30 respectively).

~~NPP~~ Net primary production of the water column was also integrated over the depth of the euphotic zone, which varied spatially. In open waters north of Svalbard and the Laptev Sea margin, the euphotic zone depth was 45 m. In the partially ice-covered areas of the ice margin it ranged between 24 and 33 m, and below thicker ice, north of 85ºN in late September, it was between 7 and 15 m deep (~~Fig. S5~~Fig. 8A). Water column integrated NPP (INPP) measured from samples collected with the ship´s CTD varied from 18 to 308 mg C m^{-2} d^{-1} (Average 95 ± 78, n=11) in ice-free waters of the Central Arctic Ocean in summer 2012, and from 0.1 to 232 mg C m^{-2} d^{-1} (Average 33 ± 50, n=22) in ice-covered waters (Fig .2, ~~Table S3~~Table S2). The large uncertainties in these values derive from averaging all stations, which are spatially and temporarily diverse. The highest INPP rates occurred at stations close to the shelves at the beginning of August, in a water mass that was not yet nutrient depleted (~~Fig. 2~~Fig. 4). The area adjacent to the Laptev Sea, which showed nitrate depletion, had INPP rates ~100 mg C m^{-2} d^{-1}. The lowest INPP rates of <1 mg C m^{-2} d^{-1} were measured in nutrient-depleted ice-covered waters north of 85ºN in late September where PAR below the ice was 0.2-12 μmol photons m^{-2} s^{-1} (~~Fig. 2~~Fig. 4).

Total INPP rates including water below the ice, sea ice and melt ponds (0.8-60 mg C m^{-2} d^{-1}, n=8), also showed highest values along the ice edge and lowest in the northernmost stations, decreasing from late summer to early fall~~ (Table S3)~~. INPP in the water under the ice (0.1-60 mg C m^{-2} d^{-1}), ~~sampled with the peristaltic pump from the ice floe, ~~contributed 63-99 % to total INPP at ice margin stations (Ice stations 1 to 6), while sea ice, in an advanced melting stage, contributed 0.1-33% (0.2-13 mg C m^{-2} d^{-1}; ~~Table S3~~Table S2 and ~~Fig. 4~~Fig. 9). Melt ponds INPP ranged between 0.01 and 4 mg C m^{-2} d^{-1}, and their contribution to total INPP was highly variable (0.05-34%). They contributed significantly to INPP at stations 3, 7 and 8 (24-34%). Sea-ice algae contributed significantly (50-62%) to total INPP at stations 7 and 8, despite their low total INPP rates (1.5 and 0.5 mg C m^{-2} d^{-1} respectively), because the water column production was very low (~~Fig. 4~~Fig. 9).

3.5 Annual new primary production

The depth of the temperature minimum associated with haline convection during last winter had a mean of 55 m but ranged from 15 to 93 m depth (~~Fig. S5~~Fig. 8B). The depth of the winter haline convection sets the total amount of nutrients available at the surface for annual production. These nutrients will be used in the euphotic zone as the productive season evolves. Therefore, in situ production is integrated until the euphotic zone depth while annual production based on nutrient uptake is integrated until the winter haline convection depth. Stations north of 85°N covered by MYI showed the deepest values. According to the nutrient profiles at the end of the productive season, the total inorganic nitrogen (NO^{-}_3+NO^{-}_2) consumption was 119 ± 46 mmol m^{-2}. Using the Redfield ratio (106C:16N), we estimated the carbon used up for annual new production from nitrogen consumption to be between 0.6 and 17 g C m^{-2} yr^{-1} (Average: 9.4 ± 3.6 g C m^{-2} yr^{-1}, ~~Fig. S6~~Fig. 10). Assuming a productive season of 120 days (Gradinger, 2009), the average INPP rate for the Eurasian Basin was 78 ± 30 mg C m^{-2} d^{-1}, which is in the upper range of our in situ measurements in late summer including sea-ice INPP. This value decreases if we increase the length of the productive period. Indeed, due to earlier sea-ice retreat it might be that the productive season in the Central Arctic Ocean was longer in 2012. Annual new production is homogenously distributed through the Eurasian basin. Only the most northern stations show higher annual INPP (13-17 g C m^{-2} yr^{-1}), corresponding to the shallowest euphotic zone as well as the~~a~~ ~~deeper~~ deepest winter haline convection depth (70-80 m) ~~and therefore,~~causing a higher nutrient availability and draw-down.

New production based on phosphate drawdown using Redfield gives a similar range (1-16 g C m^{-2} yr^{-1}). Using silicate draw-down in the ratio typical for diatoms (7 C:Si) gives an annual carbon uptake range of 0.01-7 g C m^{-2} yr^{-1} , meaning that around 10-50% of the annual carbon uptake based on nitrate was performed by this group of phytoplankton (~~Fig. S6~~Fig. 10). Sea-ice algae sampled in August-September showed an C:Si ratio average of 9. Using this higher C:Si ratio, and assuming that sea-ice algae are the main consumer of silicate during the growth season, this would yield annual carbon uptake values 20-30% higher. However, sea-ice algae may have a C:Si ratio closer to Redfield during the growing season when new production occurs. The new production value would decrease if nutrient uptake by heterotrophs would be taken into account, and increase if nutrient replenishment by physical advection or biological remineralization would ~~be accounted for~~take place.~~–~~ Unfortunately ~~there are no accurate measurements of~~we could not assess these processes ~~available~~during the mission.

3.6 Arctic primary production model: CAOPP estimates

Average PI curves and Chl *a* profiles were calculated for each environment from summer 2012 measurements. ~~and~~ They were used to calculate NPP as a function of available PAR for the Eurasian Basin of the Arctic Ocean (78-90º N, 135º E - 45º W) using the CAOPP model. We ~~will~~ present here the results calculated with average parameters, ~~but~~ and the minimum and maximum values are available in Table 4. The average total INPP for the Eurasian Basin was 54 mg C m^{-2} d^{-1} in August and 34 mg C m^{-2} d^{-1} in September 2012. We observed a ~~decreasing~~ decrease ~~temporal trend~~ in total INPP from August to September, in parallel with a decrease in incoming irradiance (~~Fig. 5~~Fig. 11). On average at a basin scale, in late summer/early autumn, sea-ice algae contributed 6% to total INPP in the Eurasian Basin, while NPP in melt ponds ~~were~~

was almost negligible (1%) (~~Fig. S8~~Fig. 12). Algal aggregates trapped in melt ponds were not taken into account due to their patchiness and difficulty to upscale their contribution to NPP (Fernández-Méndez et al., 2014). Ice covered waters contributed significantly less (36%) to total NPP per month than open water (57%) north of 78º N.

When running the CAOPP model with the sea-ice conditions of September 1982 (Fig. 13) (mainly >2 m thick MYI), the INPP in the Eurasian Basin was half the NPP in September 2012 (~~Table S2~~Table 5) assuming that the nutrient concentrations in surface waters and the percentage of melt pond cover were the same in 1982 ~~than~~ as in 2012, since no data was available for 1982. In general, the reduction of both MYI and FYI from 1982 to 2012 has lead to a ~20% decrease in the contribution of sea-ice production to total INPP and an increase in water column contribution to total INPP. The fraction of MYI has been reduced the most in the Laptev Sea, where the total INPP has increased 53% according to our model. In a potential scenario in which the Arctic would be completely ice-free in September (2050) and nutrients and the mixed layer depth would remain as in 2012, INPP could increase 60% on average in the Eurasian Basin north of 78ºN with the biggest increases occurring in the Barents and Greenland sectors due to the reduction in MYI fraction and the consequent increase in euphotic zone depth from 6-25 m to ~50 m (~~Table S2~~Table 5).

4 Discussion

4.1 Importance of sea-ice productivity in the Central Arctic Ocean

The role of sea-ice algae varies regionally and seasonally in the Arctic Ocean (Dupont, 2012; Legendre et al., 1992). In agreement with previous data by Gosselin et al., (1997) for August 1994, sea-ice algae contributed up to 60% to total NPP in those parts of the Central Arctic Ocean covered by MYI at the end of the productive season in 2012. However, our contribution estimate is conservative, since the sub-ice algal aggregates formed by *Melosira arctica* that we observed at all stations can contribute up to 90% of total NPP at a local scale (Fernández-Méndez et al., 2014). Due to their patchy distribution and the difficulties in upscaling sub-ice algal aggregates contribution to NPP (Katlein et al., 2014a), they were not included in the sea-ice NPP estimates presented in this study, although they were observed at all stations.

In areas covered by FYI, sea-ice productivity contributed only 1-30% to total INPP (~~Fig. S8~~Fig. 12). MYI has different physical properties than FYI (Lange et al., 2014; Spindler, 1994) and generally hosts higher algal biomass concentration (Werner et al., 2007). In total, MYI and FYI together fixed 0.31 Tg C during August and September 2012, without taking the patchily distributed under-ice and melt-pond algal aggregates into account (Fernández-Méndez et al., 2014). This corresponds to 6 % of the total carbon fixed in the Eurasian Basin north of 78ºN in summer. This estimate is in agreement with annual estimates from a biophysical model where sea-ice primary production contributes 7.5% to total annual PP for the whole Arctic (Dupont, 2012).

However, our sea-ice INPP measurements (0.1-13 mg C m^{-2} d^{-1}) in August and September fell in the lower end of the range of previously reported values from two decades earlier in the same area (0.5-310 mg C m^{-2} d^{-1}, Gosselin et al., 1997). This difference could be due to interannual variability, or to the loss of MYI, ~~and~~ highlightsing ~~once more the lack of~~the need for more NPP data ~~available~~ from the Central Arctic Ocean. The higher end of the range in that study (AOS expedition, 1994) refers to sub-ice algal communities formed by sub-ice diatoms like *Melosira arctica*. This diatom was also found to comprise much of the total algal biomass during our expedition at station 7, showing an INPP of 13-40 mg C m^{-2} d^{-1}, similar to the AOS expedition estimates (Fernández-Méndez et al., 2014), and even more to total export flux. The rapid sea-ice melt in July/August 2012 lead to major sinking of fresh algal biomass to the seafloor of the Arctic basins (Boetius et al., 2013). If we assume that the sinking algae had previously contributed to NPP at the surface, and that they occurred throughout the entire Eurasian Basin north of 78°N ($1.8x10^{12}$ m^2), the~~An estimated~~ average ~~NPP of~~ 9 g C m^{-2} (range:1-156 g C m^{-2}) ~~by~~ of sub-ice algae found deposited ~~in the deep sea~~at the seafloor ~~sedimented during July and August~~ would ~~result in an~~have contributed an additional ~~INPP of~~ 16 Tg C to INPP.~~, if upscaled to the Eurasian Basin north of 78°N ($1.8x10^{12}$ m^2).~~ From ~~our~~ the nitrate annual drawdown, we calculated a total carbon uptake of 17 ± 7 Tg C yr^{-1} in the Eurasian Basin north of 78ºN. However, this calculation does not take into account lateral scavenging of nutrients by sub-ice algae such as *Melosira arctica*. ~~Considering that sub-ice algae~~ Algal filaments hanging from the sea ice ~~drift following~~are transported along the Transpolar drift, ~~together with the sea ice~~from the Siberian shelves~~,~~ where ice is formed, to the Central Arctic Ocean. ~~and therefore~~Hence they may ~~have access to constant~~ ~~a broader pool of~~have a better access to nutrients than phytoplankton. ~~replenishment during their drift~~This lateral ~~transport of~~scavenging of nutrients by the sub-ice algae should be added to the nutrient drawdown calculated from vertical profiles. ~~W~~Accordingly, when adding the nutrients taken up by the sub-ice algae~~,~~ the total new production could be 17 + 16 = 33 ± 7 Tg C yr^{-1} in the deep basins of the Eurasian Basin. The overall contribution of sea-ice productivity would be 50%. When including sub-ice algal aggregations such as *Melosira arctica* filaments, the average total production of 33 Tg C yr^{-1} in the Eurasian Basin of the Central Arctic Ocean is higher than previously estimated (22 Tg C yr^{-1}, Codispoti et al., 2013). Therefore, studies that do not include sea-ice productivity and sub-ice algal aggregations may substantially underestimate annual NPP in the Central Basins and other ice--covered regions (Matrai and Apollonio, 2013).

Melt ponds contributed up to 4% to total INPP, which is in the range of previously reported estimates (<1 to 10%, Arrigo, 2014; Lee et al., 2012). Some melt ponds also contain significant accumulations of algal biomass (Fernández-Méndez et al. 2014), and hence might also become more important for total Arctic PP as their coverage continues to increase (Lee et al., 2011; Rösel and Kaleschke, 2012). Some of the sea-ice algae trapped in melt ponds can rapidly adapt to the changing conditions, as we observed in their high Chl *a* normalized maximum photosynthetic rates compared to all other environments. Sea-ice algae are low light adapted (Table 2; Cota, 1985) and show lower photoinhibition in late summer (Michel et al., 1988; Mundy et al., 2011). However, in June-July when they receive 90% of the annual light flux (Arndt and Nicolaus, 2014), they have their peak in production and thus seem ~~are probably able~~ to adapt to higher light conditions ~~and have their peak in production~~. This would have already been exported to the deep sea when we did our sampling in August-September.

An important question concerns the ability of sea-ice algae to deal with nutrient limitations. Integrated over the ice thickness ~~Inside the sea-ice~~ and ~~in~~ melt pond depths, nutrient concentrations ~~integrated over the ice thickness~~, were significantly lower than in the water column. N:P molar ratios in sea-ice were in general below Redfield (16:1) indicating prior production by ice algae limited by nitrate (Maestrini et al., 1986; Smith et al., 1997). Melt pond nutrient ratios were very variable (Table 3) highlighting the high spatial heterogeneity of this environment. Very high N:Si ratios (> 3) at some stations point towards silicate limitation as well. ~~Sea-ice diatoms can store nutrients in their cytoplasma (Kamp et al., 2011; Needoba and Harrison, 2004)~~. Our nutrient addition experiment (Fig. 3D) suggests that sea-ice algal communities can take up nutrients without increasing their biomass, which is in agreement with previous findings that s~~S~~ea-ice diatoms can store nutrients in their cytoplasma (Kamp et al., 2011; Needoba and Harrison, 2004). This may be an ~~other useful~~important physiological ~~advantage~~ trait ~~for~~ of sea-ice algae ~~in~~ to cope with the oligotrophic conditions of the deep Central Arctic Ocean.

4.2 Light and nutrients as limiting factors

Seasonal light availability in the Central Arctic Ocean limits photosynthesis (Leu et al., 2011; Wassmann and Reigstad, 2011). Our in situ measurements and upscaling results using the CAOPP model clearly show the strong effect of sea-ice cover and season on NPP (~~Fig. 2~~Fig. 4 and 5). The comparison between ice-free and ice-covered waters of the Eurasian Basin reveals the indirect effect of sea-ice through light attenuation, limiting phytoplankton productivity in ice-covered waters. This is noticeable at the end of the productive season (mid-September), north of 87°N, below MYI, where the euphotic zone is reduced to the upper 7-15 m (~~Fig. S5~~Fig. 8A). Hence, years with an extensive ice melt as in 2012 host ~~double~~ twice as much NPP in the Eurasian Basin as years with ~~normal~~ typical (previous to the current trend of sea-ice extent decrease) sea-ice cover such as 1982 (~~Table S2~~Table 5).

Sea-ice algae are adapted to low light but can profit from increased light availability in thin ice in late summer (I_k range from sea ice and melt ponds 17-290 µmol photons m^{-2} s^{-1}; Table 2).

However, lack of snow covering the ice at the beginning of the growth season can also be detrimental for the sea-ice community due to photoinhibition and ice bottom ablation (Juhl and Krembs, 2010; Lund-Hansen et al., 2014; Mundy et al., 2011). In our study, evidence for photoinhibition was mainly recorded in August on sea-ice algae trapped at the ice surface of melt ponds where the irradiance was maximal (up to 279 µmol photons m^{-2} s^{-1}, ~~Fig. S1~~Fig. 2, Table 3). However, the highest irradiance fluxes in 2012 occurred in June (Arndt and Nicolaus, 2014) so the potential for photoinhibition was higher in the earlier summer months, especially if no snow was covering the ice. Phytoplankton sampled at 2-5 m depth on the contrary showed almost no photoinhibition under irradiances up to 420 µmol photons m^{-2} s^{-1}, allowing them to potentially benefit even more from an increase in irradiance reaching the water column.

Besides constraining the total amount of carbon that can be converted into biomass during the productive season (Codispoti et al., 2013), nutrients also play an important role since they determine algal photoadaptation (Sakshaug and Slagstad, 1991). During our cruise we identified three different nutrient regimes from integrated molar ratios over the euphotic zone at the end of the productive season (~~Fig. S2~~Fig. 3, Table 3). Along the ice margin in the Nansen Basin in August, silicate was the most depleted nutrient with N:Si ratios as high as 3 (~~Fig. S2~~Fig. 3), which were also reported for the year 1994 by (Gosselin et al., 1997). This may be due to nitrate input from Atlantic waters (Rudels, 2012), but little is known about upward nutrient mixing rates. In the area adjacent to the Laptev Sea, silicate concentrations were higher, probably due to the large seasonal riverine input (Le Fouest et al., 2013), with N:Si ratios below 1 and N:P ratios (1-9) below Redfield (16), indicating nitrate depletion. In late September north of 85°N, all depth integrated nutrient concentrations were low (Table 3). This indicates a general nutrient and light depletion typical of the end of the season (Wheeler et al., 1997), partly due to the reduced depth of the euphotic zone (7-15 m).

When calculating the annual new production from nutrient drawdown for the Eurasian Basin in 2012, estimates derived from nitrogen and phosphate yield similar results (1-17 g C m^{-2} yr^{-1}), which are in accordance with the latest maximum net community production estimate for this region (14 g C m^{-2} yr^{-1}, n=6, Codispoti et al., 2013). Estimates derived from silicate, using a C:Si ratio of 7 (Brzezinski, 1985; Harrison et al., 1977), yield annual NPP rates half of the estimates derived from nitrogen or phosphate, suggesting that diatom production makes up for about 50% of annual new production, as biogenic silica is the main component of diatom frustules (Martin-Jézéquel et al., 2000). Assuming that sea-ice algae would contribute the most to silicate uptake during the growth season and that they have a higher C:Si ratio as measured at the end of the season, the contribution of diatoms to annual production would increase up to 70%. However, diatoms typically have close to Redfield carbon to nutrient ratios during the growing season when nutrients are available. The observed N:Si ratios (~~Fig. S2~~Fig. 3) suggest that nitrate was limiting NPP in the Amundsen Basin (from the Laptev Sea slope to the North Pole), but silicate was limiting NPP in the Nansen Basin (close to the ice margin in the Kara and Barents sectors) of the Eurasian Basin, that is influenced by Atlantic waters. Thus, diatoms are probably limited in the Nansen Basin as soon as the first spring bloom has consumed all the silicate in the mixed layer. Indeed, the increase in NPP and biomass of the diatom *Chaetoceros socialis* in a sample from the water below the ice at the ice margin, after silicate addition, supports this idea (~~Fig. 3~~Fig. 5A,B, ~~Fig. S3~~Fig. 6A, ~~Fig. S4~~Fig. 7A).

Taking into account the export of sub-ice algae earlier in the season 2012 (Average 9 g C m^{-2}, Boetius et al., 2013) and the C:Si molar ratio of diatoms (7), an average of 107 mmol Si m^{-2} had already been removed from surface waters before August. Since sea-ice algal production starts earlier than phytoplankton productivity (Søreide et al., 2006), sea-ice algae might contribute to nutrient removal in surface waters at the beginning of the season leaving ~~only some nutrients left~~reduced nutrient concentrations for the phytoplankton bloom. However, since most of the sea ice in the Central Arctic Ocean originates in the shelf areas of the Eurasian Basin and is then transported by the transpolar drift (Pfirman et al., 1997), the sub-ice algae growing attached to the bottom of the ice might have access to the nutrients mixed up on the shelves, upwelled at the shelf-edge or ice-edge earlier in the season and to the surface nutrients of a wider area while they drift with the ice (Carmack et al., 2006; Cota et al., 1990; Fernández-Méndez et al., 2014; Syvertsen, 1991). ~~Our nutrient addition experiment performed on a typical ice-algal community, indicates that sea-ice diatoms might be capable of nutrient storage~~This, together with the capability of ice algae to store nutrients (Kamp et al., 2011) might~~,~~ ~~providing~~ provide them with an advantage ~~against~~ over phytoplankton ~~(Fig. 3C,D, Fig. S3B)~~.

Besides the bottom-up control of primary production, there are other factors limiting the amount of biomass present in the ice or the water column, such as grazing. Arctic zooplankton and under-ice fauna ~~is~~ are known to feed on sea-ice algae and phytoplankton (Hop et al., 2011; Søreide et al., 2006), transferring the fixed carbon to higher trophic levels. In the Central Arctic Ocean grazing has been reported to consume 15% of NPP (Olli et al 2007). At the time of sampling, the theoretical carbon demand of the dominant zooplankton and under-ice grazers (*Calanus spp*. and the ice amphipod *Apherusa glacialis*) was on average 19 mg C m^{-2} d^{-1} in the Eurasian Basin calculated from all stations investigated in this study (David et al., 2015). This would correspond to more than 80 % of the mean daily NPP measured in ice covered areas, indicating that algal biomass could periodically be significantly controlled by grazers in the Central Arctic Ocean, especially at the end of the productive season. However, the The total POC export fluxes measured in August/September with short-time sediment traps was 31 mg C m^{-2} d^{-1} on average (Lalande et al., 2014), which is higher than the average INPP measured in situ (24 mg C m^{-2} d^{-1}). However, this flux includes algae and debris, and the amount of algal carbon exported in August/September was very low. tThe carbon flux was mainly composed of debris and the few algae found observed in the sediment traps using light microscopy were flagellates. According to seafloor observations in 2012 in the same area, the largest amount of algal carbon export had occurred already in June/July in 2012 during the main melting event, and was due to the productivity of sub-ice algal communities (Boetius et al., 2013). These results indicate suggest that the system was predominantly heterotrophic and that most of the productivity is consumed before sinking in late summerat the time of sampling.

Using the CAOPP model and according to the light fluxes calculated by Arndt and Nicolaus, (2014), we estimate that 88% of the annual PP occurs between May-July, and only 12% in August and September, using late summer NPP rates and biomass measurements to extrapolate to the earlier part of the season. The CAOPP model estimate matches very well with our estimates based on in situ NPP in August and September, and with the annual new production estimate based on nitrate drawdown, where we estimate that 15% of the annual PP occurs in late summer and the rest earlier in the season. A more elaborate model taking into consideration quick changes in photosynthetic parameters, grazing and seasonal shifts in standing stock and nutrient availability , such as (Palmer et al., (2014) would be necessary to improve these estimates and to more accurately predict simulate primary productivity under different scenarios~~,~~. ~~but~~ However, a better understanding of the future of productivity in the Central Arctic Ocean foremost depends on better biological ground truth data for the entire season ~~in the Central Arctic Ocean are still needed~~.

4.3 Effects of sea-ice reduction on primary production in the Central Arctic Ocean

An increase in open water NPP due to sea-ice retreat has already been ~~observed~~ predicted by satellite derived and in situ data in the Eurasian Arctic (Arrigo and van Dijken, 2011; Vetrov and Romankevich, 2014), especially in the Kara and Barents Seas (Pabi et al., 2008). However, changes in productivity in sea-ice and in water under the ice cannot be detected by satellites. In September 2012, during our cruise, sea-ice extent reached its minimum ever recorded (Parkinson and Comiso, 2013). Another model study predicted enhanced productivity in the East Siberian and Laptev Seas due to the great summer cyclone (Zhang et al., 2013). By comparing our results with previous estimates from the Eurasian Basin and recent syntheses of all PP data available (Codispoti et al., 2013; Hill et al., 2013; Matrai et al., 2013), we tried to assess the impact of sea-ice retreat on NPP. The sea-ice retreat in 2012 in the Eurasian Basin increased the open water area in August-September by 45% compared to earlier years. The INPP rates measured in the open waters of the Laptev region (84 ± 38 mg C m^{-2} d^{-1}) are higher than INPP measurements from the same area using the same method in August 1995, when most of the Laptev Sea area was ice covered (21 ± 8 mg C m^{-2} d^{-1}, Grossmann and Gleitz, unpublished measurements from Polarstern expedition ARK XI/1). The average from satellite data from 2003 to 2012 for open waters of this region (71 mg C m^{-2} d^{-1}, Vetrov and Romankevich, 2014) is also slightly lower than our measurements during the sea-ice record minimum~~ (71 mg C m^{-2} d^{-1}, Vetrov and Romankevich, 2014)~~. No ~~uncertainty~~error ranges w~~as~~ere provided for these earlier observations, ~~making the~~hence it remains uncertain if they indicate significant temporal changes.~~ significance of these differences complicated to evaluate~~.

As retreating sea-ice leaves behind more open water areas in summer, different Arctic regions are expected to react differently to the increase in irradiance received (Arrigo et al., 2008). To test this, we removed the ice cover in our forcing input data from our CAOPP model – mimicking predicted sea ice conditions for 2050 - and compared the results from September with our 2012 results (~~Table S2~~Table 5, Fig. 11 and 13). Based on the changes in light penetrating through the ice and assuming no change in nutrient availability, total INPP for September would increase by 292% in the Greenland sector, 56% in the Barents, 38% in the Laptev and 23% in the Kara sector of the -Central Arctic Ocean north of 78°N (Fig. 13, ~~Table S2~~Table 5). These increases ~~still~~ represent only 10-15% of the seasonal NPP in these regions according to our model and directly represent the higher INPP ~~increase~~ in open waters~~ that host higher INPP~~. The relationship between sea ice decrease and INPP increase also arises when comparing the model results of 1982 and 2012. In this case, for the entire Eurasian Basin, a 45% decrease in the ice cover leads to a doubling in the September INPP. In the Amerasian Basin, similar increases in phytoplankton annual production have been predicted mainly due to earlier sea ice retreat (Arrigo et al., 2008; Kahru et al., 2011).~~-~~However, the loss of ice-attached biomass, such as sub-ice algal aggregates which are not taken into account in these calculations, might counteract the increase in water column PP as sea-ice disappears. The regional variability of changes is due to different sea-ice coverage of the different areas. However, sea-ice retreat will not only affect light transmission, but also water column stratification that might hinder nutrient upwelling (Codispoti et al., 2013). Depending on the future role of winds and sea-ice drift vs stratification by freshening and warming, nutrient availability in the euphotic zone could change. For example, if ice formation occurs later in September, and if winds ~~that cause upwelling~~ would also increase and cause upwelling, a second productivity peak might be observed at the end of the season (Ardyna et al., 2014). ~~On the contrary~~In contrast, if stratification -increases,~~s~~ ~~its strength and~~ less nutrients ~~a~~would be~~re~~ available, ~~it may~~ resulting in a decrease in NPP for the month of September. ~~Most likely, s~~Sea-ice algal productivity ~~will~~ would likely increase and shift to earlier periods of the year, and their rapid export from the melting of their habitat in July and August will decrease nutrient availability (Boetius et al., 2013; Lalande et al., 2009). The phytoplankton community will probably shift from diatoms towards small picoplankton due to the freshening of the upper layers (Li et al., 2009), especially in the silicate limited area of the Eurasian Basin, where small picoplankton is already present (Kilias et al., 2013), and would be more nutrient efficient at low silicate concentrations. ~~(Bhatt et al., 2014; Kilias et al., 2014; Li et al., 2009), with~~ This shift in the phytoplankton community together with the disappearance of the sea-ice communities could have potentially detrimental consequences for the Arctic food web (Bhatt et al., 2014).

4.4 Limitations and uncertainties of Arctic NPP estimates

The Central Arctic Ocean remains one of the most challenging environments to sample due to its remoteness and the year-round ice cover on top of its deep basins. The majority of Arctic NPP estimates are from seasonally ice-free waters, mainly shelves, sampled during the spring or summer months (Hill et al., 2013; Matrai et al., 2013). Ice-associated NPP has been widely neglected in previous Arctic PP estimates, because it can not be assessed remotely via satellite-borne sensors (Arrigo and van Dijken, 2011), and also due to methodological and logistical problems to measure it in the field (Matrai et al., 2013). Two orders of magnitude uncertainties in NPP estimates for the Central Arctic Ocean reflect the high spatial and temporal variability characteristic for this environment (Tremblay et al., 2012). Thus, it remains difficult to establish regionally representative baselines in Arctic NPP, to be able to detect significant changes in productivity related to the on-going sea-ice retreat.

This study provides summer in situ NPP data from the under-sampled Eurasian Basin including water column, sea-ice and melt pond that can be used to validate ocean general circulation models predicting changes in Arctic PP (Ferland et al., 2011; Tremblay et al., 2012). Photosynthetic parameters derived from PI curves under realistic conditions are important for modelling primary productivity (Popova et al., 2012; Vancoppenolle et al., 2013). A combination of in situ obtained photosynthetic parameters and a light parameterization for light transmittance of sea-ice (CAOPP model) enabled us to estimate INPP for the entire Eurasian Basin, including ice-covered areas (Fig. 11). Although the CAOPP model does not include nutrient information, the PI curves were measured at the end of the season in nutrient limited waters. Hence, using the same parameters to model PP earlier in the season, when more nutrients are available, will underestimate productivity. Photosynthetic parameters vary locally, ~~and~~ seasonally, and vertically as well as horizontally in the water column and in the sea ice (Behrenfeld and Falkowski, 1997; Duarte et al., 2015; Palmer et al., 2014). Therefore, the photosynthetic parameters cover a wide range (Table 2) and are not well constrained. This leads to two orders of magnitude difference between the minimum and the maximum NPP calculated with the model. To constrain the results further, more in situ measurements are needed to capture the regional and temporal variability in photosynthetic parameters.

In addition, nitrate vs ammonium uptake rates should be included in such studies to estimate the importance of new versus regenerated production at each period of the productive season (Dugdale and Goering, 1967; Tremblay and Gagnon, 2009). With our approaches, the in situ measurements in late summer were probably mainly measuring regenerated production, while the annual estimates of production based on nutrient drawdown is only taking into account the new production.

Another limitation of our upscaling using the CAOPP model is that the light parameterization assumes a constant extinction coefficient in the water column and is not spectrally resolved (Manes and Gradinger, 2009; Palmer et al., 2011; Sakshaug and Slagstad, 1991). This could lead to NPP overestimation in open water coastal areas (Alver et al., 2014). A recent INPP estimate for the Arctic Ocean Basin including the Amerasian Basin ~~where they measured~~based on NPP measurements only in ice-free waters (0.4 Tg C month^{-1} (Arrigo et al., 2011; Bélanger et al., 2012) is at the lower end of our estimated range for the water under the ice in the Eurasian Basin in August (0.2-6.8 Tg C month^{-1}), but suggests that our model can give realistic estimates. Seasonality remains a critical issue in the Central Arctic Ocean since there are still no measurements of early spring photosynthetic parameters from communities thriving in and under the ice. Assessing the algal biomass below the ice using automated autonomous systems such as Ice Tethered Profiles (ITPs) that drift with the ice during an entire year might be an ~~great~~ important step forward to improve our understanding of the annual cycle of primary production in the central basins (Laney et al., 2014).

Conclusions

The Central Arctic Ocean basins have been generally regarded as low productivity areas. Due to their inaccessibility they have remained largely under-sampled leading to a lack of baseline data to assess current changes. This study provides measurements of primary production during the record sea-ice minimum in the Eurasian Basin in 2012, and new estimates for all environments where phototrophs thrive: sea-ice, melt ponds and water column. Sea-ice algae ~~can~~ contributed up to 60% to the total INPP in the Central Arctic Ocean at the end of the productive season. Comparing our ~~results~~ measured estimates from 2012 with previous estimates of NPP in the Central Arctic Ocean, we conclude that an overall change in NPP magnitude would be foremost related to a change in the role of the ice-algal production and export of sub-ice algal aggregates. INPP in m~~M~~elt ponds can contribute up to 34% locally, but at a larger scale their contribution to INPP is <4 %, excluding local aggregations of sea-ice algae. Ice-covered waters sustain lower NPP than open waters in the late summer season, indicating light limitation. However, over the annual productive period, the role of sub-ice algae may be increasing with the overall thinning of sea-ice. Therefore, an increase in irradiance transmitted through the ice will probably lead to an increase in both ice and water column NPP in the Central Basins and a shift in timing towards earlier sea-ice ~~based~~ NPP. These shifts in the timing and location of ice-algal blooms are likely to impact life cycle strategies and community composition of zooplankton and under-ice fauna, with unknown consequences for the under ice food-web and export fluxes. However, nutrients will still constrain the annual budget of new production both for sea-ice algae and phytoplankton. In the Eurasian Basin, nitrate limits NPP in the Amundsen Basin and silicate limits diatom-based NPP at the ice margin near the Atlantic water inflow (Nansen Basin) at the end of the productive season. Better understanding of the overall development of Arctic productivity will need year-round long-term observations of nutrient supplies and light availability, as well as of mixing processes and grazer populations.

Author contribution

M.F.M. and A.B. designed the experiments, C.K. and M.N. carried out the modeling, K.B., I.P. and H.F. provided data. M.F.M. wrote the manuscript with input from AB and all coauthors.

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Table 1. Physical parameters and autotrophic biomass of the eight ice stations sampled during the expedition ARKXXVII/3 to the Eurasian basin of the Central Arctic during August-September 2012.

Station Number	1	2	3	4	5	6	7	8
Station ID	PS80/3_224	PS80/3_237	PS80/3_255	PS80/3_277	PS80/3_323	PS80/3_335	PS80/3_349	PS80/3_360
Date (dd/mm/yyyy)	09/08/2012	14/08/2012	20/08/2012	25/08/2012	04/09/2012	07/09/2012	18/09/2012	22/09/2012
Latitude	84° 3.03' N	83° 59.19' N	82° 40.24' N	82° 52.95' N	81° 55.53' N	85° 6.11' N	87° 56.01' N	88° 49.66' N
Longitude	31° 6.83' E	78° 6.20' E	109° 35.37' E	130° 7.77' E	131° 7.72' E	122° 14.72' E	61° 13.04' E	58° 51.81' E
Incoming PAR (μmol photons m^{-2} s^{-1})	249 ± 90	174 ± 90	104 ± 71	101 ± 57	81 ± 63	49 ± 43	25 ± 15	13 ± 7
Ice cover	80%	80%	70%	80%	60%	50%	100%	100%
Ice thickness (m)	1.2	1.2	0.9	0.9	0.8	1.4	1.9	1.8
Ice type (FYI/MYI)	FYI	FYI	FYI	FYI	FYI	FYI	MYI	MYI
Melt Pond coverage (%)	40%	20%	40%	50%	10%	30%	20%	20%
Melt Pond depth (m)	0.6	0.2	0.3	0.4	0.3	0.2	0.3	0.3
Melt Pond Salinity	18	1	0.5	2	14	0.4	30	12
Euphotic zone depth (m)	24	29	30	29	33	29	15	7
Euphotic zone Chl*a* (mg m^{-2})	3.2	17	8	8	11	17	3	1.2
Sea ice Chl *a* (mg m^{-2})	1.2	1.7	0.6	0.4	0.3	0.4	8	8
Melt ponds Chl *a* (mg m^{-2})	0.3	0.02	0.1	0.02	0.1	0.02	0.3	0.04

Ice was classified in two types: first year (FYI) and multiyear (MYI) according to its structure and physical properties.

The euphotic zone depth is a weighted average of the euphotic zone depth below bare ice, ponded ice and open water at each station.

Chlorophyll a (Chl *a*) was integrated for the melt pond depth, the sea ice thickness and the euphotic zone depth. A C:Chl *a* conversion factor of ~600could be applied to obtain carbon units (Laney et al., 2014).

Table 2. Photosynthetic parameters and incoming irradiance of the different environments in the Central Arctic divided in August and September.

Environment (n PI curves)	Photosynthetic parameters						
	P^b	P^b_m	α	β	I_m	I_k	I
	(mg C (mg Chl*a*)$^{-1}$ h^{-1})		(mg C (mg Chl*a*)$^{-1}$ (µmol photons m^{-2} s^{-1})$^{-1}$ h^{-1})		(µmol photons m^{-2} s^{-1})		(µmol photons m^{-2} s^{-1})
	Mean (Min-Max)						
	August						
Melt Pond (n=4)	2036 (65–6670)	2.8 (0.4–8)	0.05 (0.002–0.15)	13.6 (0.08–50)	379 (135–785)	139 (50–290)	145 (102–279)
Sea Ice (n=7)	105 (0.08–377)	0.3 (0.07–0.7)	0.005 (0.001–0.01)	0.6 (0–2.3)	326 (166–876)	64 (34–98)	53 (24–229)
Water under the ice (n=4)	300 (0.2–1160)	0.6 (0.2–1.4)	0.01 (0.003–0.02)	1.9 (0–7.3)	331 (158–787)	56 (29–80)	3 (0.7–22)
Open water (n=2)	1290 (391–2187)	3.5 (2.2–4.7)	0.05 (0.004–0.08)	7.7 (0.2–15)	797 (143–1450)	293 (52–533)	32 (1.3–140)
	September						
Melt Pond (n=4)	1.8 (1.3–2.5)	1.2 (0.4–2.3)	0.03 (0.004–0.07)	0.003 (0.001–0.004)	187 (144–252)	58 (32–290)	29 (13–91)
Sea Ice (n=6)	0.07 (0.03–99)	0.06 (0.04–0.2)	0.002 (0.001–0.004)	0 (0–0.5)	127 (96–402)	26 (17–64)	4 (1–38)
Water under the ice (n=4)	0.5 (0.2–0.8)	0.4 (0.2–0.7)	0.02 (0.01–0.02)	0.001 (0–0.002)	319 (102–599)	26 (14–38)	0.7 (0.2–6)
Open water (n=7)	0.5 (0.4–0.9)	0.5 (0.3–0.9)	0.03 (0.02–0.05)	0 (0–0.001)	85 (59–734)	15 (9–26)	16 (1.3–240)

P_b is the maximum Chl*a* normalized carbon fixation rate if there was no photoinhibition; α is the initial slope of the saturation curve; β is the photoinhibition parameter; P^b_m is the carbon fixation rate at maximal irradiance; I_m is the light intensity at which photosynthesis is maximal; I_k is the adaptation parameter or photoacclimation index. I is the average daily irradiance received in each environment from the surface to the bottom of the pond, the ice or the euphotic zone in the water column.

[*] Open waters in September correspond to the Laptev Sea region.

Table 3. Nutrient inventories and molar ratios in each environment during summer 2012 separated into the three nutrient regimes observed.

	Nutrients				
	Nitrate	Phosphate	Silicate	N:P	N:Si
	(mmol m-2)			mol:mol	
	Ice margin (6–18 August 2012)				
Melt pond (n=2)	0.1–0.8	0–0.12	0.01–1.6	6.8–85	0.5–9
Sea ice (n=2)	0.3–0.8	0.03–1.3	0.2–0.5	0.6–11	0.6–4
Sea water (n=9)	76–157	7–16	27–77	9–11	1.7–2.8
	Laptev Sea (20 August–10 September 2012)				
Melt pond (n=4)	0.2–0.4	0–0.15	0.1–0.8	2–114	0.4–5
Sea ice (n=4)	0.2–0.7	0.01–0.06	0.1–0.4	5.2–15	0.6–4
Sea water (n=17)	8–126	4.5–19	35–220	1.2–8.6	0.1–1
	North of 85ºN (18–27 September 2012)				
Melt pond (n=2)	0.06–0.2	0.01–0.06	0.1–0.9	1–18.3	0.2–0.5
Sea ice (n=2)	0.2–1.7	0.04–0.1	0.1–0.2	4.7–17	1–16
Sea water (n=6)	4–31.0	1.5–3.5	12–23	3–9	0.3–1.7

Nutrient concentrations in mol L^{-1} are available in PANGAEA (doi in Table S1). Nutrient concentrations were integrated for melt pond depth, sea-ice thickness and water column euphotic zone (1% incoming PAR).

Table 4. Integrated Net Primary Production in the Central Arctic at different times and spatial scales. The number of daily measurements is given in Table 2. The contribution by sub-ice algal aggregates is not included in any of the values presented in this table.

	Integrated Net Primary Production (INPP)					
	Daily	Monthly				Annual
	In situ	August		September		2012
	Mean ± STDEV	Mean (Min-Max)				Mean ± STDEV
INPP in the Eurasian Basin	mg C m^{-2} d^{-1}	mg C m^{-2} d^{-1}				g C m^{-2} yr^{-1}
Total	24± 19	54	(21-180)	34	(21-65)	9.4 ± 3.6
Sea Ice	2.2 ± 4.1	5.8	(0.06-42)	2.6	(0.02-20)	
Melt Ponds	0.9 ± 1.3	0.5	(0.2-1.7)	0.7	(0.06-3)	
Water under the ice	20 ± 20	31	(4.5-116)	12	(3-50)	
Open water	84± 38	97	(62-115)	56	(43-50)	
	Mean*Area	Sum				Sum
INPP in the Central Arctic (78° N)	Tg C d^{-1}	Tg C $month^{-1}$				Tg C yr^{-1}
Total	0.09 ± 0.07	5.7	(1.7-24)	3.4	(1.78-8.45)	36
INPP in the Eurasian Basin	Tg C d^{-1}	Tg C $month^{-1}$				Tg C yr^{-1}
Total	0.04 ± 0.03	3.1	(1.2-10)	1.9	(1.1-3.6)	17.4±6.7
Sea Ice	0.004 ± 0.007	0.2	(0.002-1.7)	0.08	(0.0008-0.6)	
FYI	0.004 ± 0.009	0.05	(0.002-0.4)	0.008	(0.0004-0.06)	
MYI	0.002 ± 0.001	0.2	(0.0003-1.2)	0.07	(0.0002-0.5)	
Melt Ponds	0.002 ± 0.002	0.02	(0.007-0.07)	0.02	(0.002-0.09)	
Water under the ice	0.04 ± 0.04	1.3	(0.2-6.8)	0.4	(0.1-1.6)	
Open water	0.16 ± 0.071	1.5	(1-1.8)	1.4	(1-1.3)	

Table 5. Comparison of three runs of the CAOPP model using the photosynthetic parameters measured in situ in summer 2012. Sea-ice extent, multiyear ice fraction, incoming irradiance and mean INPP in Tg C month^{-1} are presented for the month of September in 1982, 2012 and 2050. Since the purpose is a magnitude comparison between different scenarios in the different sectors of the Eurasian Basin (depicted in Fig. 13), only the mean is shown. Min and Max values would deviate from the mean as presented in Table 4 for 2012.

	CAOPP results for September north of 78ºN			
	September ice extent	MYI fraction	Incoming irradiance	INPP September
	Mean	Mean	Mean (Min-Max)	Mean
	Mio. Km^{-2}	%	µmol photons m-2 s-1	Tg C month^{-1}
		1982 (7.17 Mi. Km^{2})		
Eurasian Basin (78-90N, 45 W-135 E)	1.78	71	59 (28-122)	0.93
Laptev (78-90 N, 90-135 E)	0.53	92	54 (28-84)	0.26
Kara (78-90 N, 45-90 E)	0.50	85	59 (31-75)	0.27
Barents (78-90 N, 0-45 E)	0.44	88	64 (30-104)	0.26
Greenland (78-90 N, 45 W-0 E)	0.31	82	63 (29-122)	0.13
		2012 (3.42 Mio.km^{2})		
Eurasian Basin (78-90 N, 45 W-135 E)	1.01	51	45 (23-102)	1.88
Laptev (78-90 N, 90-135 E)	0.29	12	47 (24-84)	0.63
Kara (78-90 N, 45-90 E)	0.16	30	42 (25-76)	0.66
Barents (78-90 N, 0-45 E)	0.25	50	42 (25-69)	0.46
Greenland (78-90 N, 45 W-0 E)	0.30	77	52 (24-102)	0.13
		2050 (No ice) ¥		
Eurasian Basin (78-90N, 45 W-135 E)	0	0	45 (23-102)	2.91

Laptev (78-90 N, 90-135 E)	0	0	47 (24-84)	0.87
Kara (78-90 N, 45-90 E)	0	0	42 (25-76)	0.81
Barents (78-90 N, 0-45 E)	0	0	42 (25-69)	0.72
Greenland (78-90 N, 45 W-0 E)	0	0	52 (24-102)	0.51

Figure captions

Figure 1. Cruise track and stations sampled in the Eurasian Basin during summer 2012. The different panels show the sea ice concentration at the time of sampling the first ice station in early August (A), the fifth station at the beginning of September (B), and the last ice station in early autumn (C). The dates and numbers of those~~the~~ stations A-C ~~sampled that date is~~are marked in red. The sea-ice extent minimum record was reached in early September 2012 and refreezing started two weeks later. For comparison purposes, the mean sea-ice extent for September 1982 is depicted in orange. Water column was sampled every 1 or 2 days during the entire cruise. The exact location of these stations can be seen in Figure 4.

Figure 2. Average photosynthesis versus irradiance curves (PI curve) for each environment. The average fitted curve and the photosynthetic parameters derived from it, were used to calculate the in situ primary production in each environment during August and September for the Eurasian Basin using the irradiance-based CAOPP model. The dots represent the experimental measurements, the black solid line is the fitted curve, the dashed lines are the minimum and the maximum, and the grey shaded area is the standard deviation. Average PI parameters are represented on the top left corner.

Figure 3. N:Si and N:P molar ratios in the euphotic zone of the water column during summer 2012. In panel A, the light blue-green range represents N:Si ratios optimal for diatom growth, red marks an excess of N, blue-purple represents depletion. In panel B, all values are below the N:P Redfield ratio of 16 indicating a general nitrate depletion with respect to phosphate.

Figure ~~2~~4. Integrated Net Primary Productivity (INPP) in the water column of the Central Arctic Eurasian Basin in August-September 2012. The 8 ice stations are ~~mark~~circled with a black ~~out~~line. The three boxes indicate different nutrient regimes characterized by the concentrations of nitrate (N), phosphate (P), and silicate (Si) in the water column. The superscripts on each nutrient indicate if there was high (+), medium (~) or low (-) amounts of that nutrient in the euphotic zone. High is defined as concentrations of nitrate >3 µM ~~nitrate~~, phosphate >0.3 µM, and silicate >3 µM. Low or depleted is defined as concentrations of nitrate < 1 µM, phosphate < 0.2 µM, and silicate < 1.5 µM.

Figure ~~3~~5. Nutrient addition experiments on sea water from Ice station 3 (A and B) and sea ice from Ice station 8 (C and D). Panels A and C show the NPP rate of each treatment after 24 h of nutrient addition. Panels B and D show the nutrient uptake in each treatment after nutrient addition. C^- ~~negative~~ control, N^+ nitrate, P^+ phosphate, Si^+ silicate, C^+ all nutrients added.

Figure 6. Biomass changes in nutrient addition experiments. (A) Nutrient addition experiment with seawater from the Chl *a* max depth at station 3. (B) Nutrient addition experiment with sea ice from station 8. Duplicates of each treatment were incubated for 2 days after nutrient addition.

Figure 7. Microscopy images of the community composition of the two nutrient experiments: (A) sea water phytoplankton and (B) sea-ice algae.

Figure 8. Euphotic zone depth (1% PAR) weighted average (A), and winter mixed layer depth (B) estimated from summer temperature profiles. Average and standard deviations: Euphotic zone depth 34 ± 6 m; Winter mixed layer depth 54 ± 15 m.

Figure 49. Depth Integrated Net Primary Productivity (INPP) and the contribution of sea ice, melt ponds and water at eight ice stations in the Eurasian Basin during summer 2012. The size of the pie chart represents the magnitude of INPP in mg C m^{-2} d^{-1}. The values are depicted next to each pie chart.

Figure 10. New production in the Eurasian Basin during 2012. Carbon uptake since last winter estimated from nitrate (A), phosphate (B) and silicate (C) drawdown in the mixed layer. Redfield ratio C:N:Si:P of 106:16:15:1 was used to convert nutrient uptake into annual new production.

Figure 511. Total mean INPP in mg C m^{-2} d^{-1} and in each environment: melt ponds, sea ice and water in the Central Arctic Ocean during August and September 2012 as modeled with the CAOPP model. The grey line depicts the average sea ice extent for each month. Note the different scales in the different panels.

Figure 12. Fraction contribution of NPP in each environment (melt ponds, sea ice and water column) to total NPP in the Central Arctic during August and September 2012 according to the upscaling performed using the CAOPP model. The assumptions for key factors governing NPP are explained in the materials and method section. Note the different scales of the panels.

Figure 13. September mean total INPP for two runs of the CAOPP model under contrasting sea-ice conditions: (A) sea-ice cover and incoming irradiance as in 1982, (B) no-ice cover as predicted for 2050. Nutrient concentrations and photosynthetic parameters as in September 2012.