Reply to reviewer #2 in red italic

General comments

This paper presented the recent trends in PAR, chlorophyll a, and PP. Authors also explained the PP trend by a parameter CHL/KPUR, which is different from previous studies. The PP change in the Arctic region and its controlling factor is one of the important topics to consider biogeochemical and ecological change to global climate change. Therefore, this paper is scientifically important and within the scope of Biogeosciences. However, some parts are still difficult to understand and need to provide clearer descriptions and evidences. I hope the authors to make all figures clear and larger to understand results easily.

REPLY: We would like to thank the reviewer for his/her appreciation of the manuscript. We will make sure the figures will be published in high resolution, as they were actually produced, and we will provide tables with statistics.

Specific comments

1. Details of primary production model as expressed by equation (1) should be described. Authors wrote that "Our model uses satellite derived spectral diffuse attenuation (Kd) to ...." at lines 15-19 on page 13997. However, equation (1) is not including Kd or KPUR and it is difficult to understand how the Kd or KPUR govern in the model. If you have written in previously published paper, it is probably acceptable.

REPLY: Our PP model was used in two publications (Tremblay et al, GRL (2011) and in LeFouest et al (2011)) and the PAR model was published and validated in Xie et al L&O (2009). We are preparing a specific paper on the model in which a sensitivity study will be performed.

Equation 1 was first proposed by Platt et al (1980) and modified by Arrigo and Sullivan (1994) who replaced PAR by PUR. These references will be added to the revised version.

The revised version will also provide a more detailed description of the model. Spectral Kd from satellite retrievals is used to estimate PUR from the surface to the bottom of the euphotic zone (0.1% surface light level). It was written in the text but not explicitly presented in the equations. Equation 2 will thus become:

$$PUR(z,t) = \int_{400}^{700} E^0(\lambda, 0-, t) \cdot \exp[-K_d(\lambda) \cdot z] \cdot \left(\frac{a_{ph}(\lambda)}{a_{ph}(443)} \right) d\lambda$$

A paragraph describing how K_{PUR} was calculated will be added as well. In brief, PUR(z) was propagated from 0- to the depth of 1% of PUR(0-) (i.e. PUR(z)/PUR(0-) = 0.01) and K_{PUR} is the slope of the log transformed PUR as a function of depth. Thus K_{PUR} was obtained as:

$$PUR(z) = PUR(0-) \exp[-K_{PUR} \cdot z]$$

from which,

$$K_{PUR} = -\frac{\ln\left(\frac{PUR(z)}{PUR(0-)}\right)}{z} = \frac{4.6}{z_{1\%}},$$

where PUR(z) is given by eq. 2 and z1% is the depth of the 1% light level (i.e., 1% of PUR(0-)).

2. Authors assumed the PBmax to be constant. As you wrote on page 13996, PBmax varies with temperature. Nutrients and other many environmental conditions can be a controlling factor of PBmax, too. Although, one of important results in this study is PP increase due to rising of Chl/KPUR, induction of the result by assuming of constant PBmax is anticipated.

REPLY : We avoid the use of PBmax versus SST because no such relationships have been published so far for the Arctic waters. The relationship published by Behrenfeld and Falkowski (1997) for PBopt vs. PAR does not suggest a significant relationship in the low temperature range (see also). We will also refer to Huot et al. (BGD 2013) who examined the PBmax vs. T relationship. A more appropriate parameterization for Arctic of photosynthetic parameters was proposed by Huot et al. (BGD 2013), in which PBmax varies a function of depth and phytoplankton size classes. We did not implement this new approach because it is not published yet. Our future work will examine in more details the sensitivity of the model to photosynthetic parameters (including their impacts on PP trends).

Since SST may have increase in the Arctic, the use of a relationship between PBmax and SST would probably make the PP trends very slightly more positive.

3. What is the index CHL/KPUR? Authors explained a meaning as only "biomass divided by attenuation coefficient of PUR". I tried to consider intuitive meaning for interpretation of this paper, but it is still confusing. Inverse of the index can be KPUR/CHL = KBPUR, so is it related to a*ph and photosynthetic rate? If so, it conflicts with constant PBmax.

REPLY: We should not try to interpret this quantity as physiological index of phytoplankton. The rational for the use of the ratio CHL/K_{PUR} are two-fold:

1. *Every satellite-based PP model can be generalized by the following generic equation (see also equations 1 and 2 in Cullen et al BGC 2012, and their discussion):*

   $$Pz = \frac{P_m^B B}{K_{PAR}} \cdot f(E^*_{PAR})$$

   where: Pz (mg C m^-2 h^-1) is the instantaneous, depth integrated rate of primary production; P_m^B (mg C mg Chl^-1 h^-1) is the maximum rate of photosynthesis, normalized to chlorophyll; B is the concentration of chlorophyll at the surface (mg Chl m^-3); and K_{PAR} (m^-1) is the attenuation coefficient for photosynthetically available radiation (PAR; the total irradiance between 400 nm and 700 nm), evaluated from the surface to the depth of 1% surface PAR. The dependence on surface irradiance is modeled as a function of E^*_{PAR} (dimensionless), which is scalar PAR quantum *irradiance just below the surface ($\overset{o}{E}_{PAR}$ (0-), μmol m^-2 s^-1) normalized to the PAR saturation irradiance for photosynthesis, $\overset{o}{E}_{k,PAR}$ (μmol m^-2 s^-1). For depth- and time-integrated fluxes ($P_{z,T}$), the generic equation above can be modify to account for the day length (D), such as:*

$$P_{z,T} = \frac{P_m^B \cdot B \cdot D}{K_{PAR}} \cdot f(E^*_{m,PAR}).$$

Since we used PUR rather than PAR, our model follows the same formulation but with K_{PUR} in place of K_{PAR}. This dependency can also be demonstrated mathematically by integrating eq 1 with some assumptions. Here PP is calculated using

$$PP = CHL \cdot P_m^B \int_{z=0}^{\infty} PUR(0-)\exp(-K_{PUR} \cdot z) \cdot (1 - e^{-\frac{PUR(0-)\exp(-K_{PUR} \cdot z)}{E_k}})dz$$

The factor $(1 - e^{-\frac{PUR(0-)\exp(-K_{PUR} \cdot z)}{E_k}})$ *represents the non-linearity between PP and PUR. In most situations, however, PUR is < Ek, so PP is linearly related to PUR. In these circumstances the factor* $(1 - e^{-\frac{PUR(0-)\exp(-K_{PUR} \cdot z)}{E_k}})$ *can be replaced by the factor f(PUR) for simplicity. Thus*

$$PP \approx CHL \cdot P_m^B \cdot f(PUR) \int_{z=0}^{\infty} PUR(0-)\exp(-K_{PUR} \cdot z)dz$$

or

$$PP \approx CHL \cdot P_m^B \cdot PUR(0-) \cdot f(PUR) \int_{z=0}^{\infty} \exp(-K_{PUR} \cdot z)dz$$

Integrating the equation yield:

$$PP \approx CHL \cdot P_m^B \cdot PUR(0-) f(PUR) \Big|_0^{\infty} \frac{\exp(-K_{PUR} \cdot z)}{-K_{PUR}}dz$$

$$PP \approx CHL \cdot P_m^B \cdot PUR(0-) f(PUR)(\frac{1}{K_{PUR}})$$

So if PP is normalized to PUR(0-), we obtain the

$$\frac{PP}{PUR(0-)} \approx P_m^B \cdot f(PUR)(\frac{CHL}{K_{PUR}})$$

2. *In our approach, CHL and K_{PUR} are not fully interdependent. It is true that KPUR will tend to increase when CHL increases, but not systematically. This is because Kd is not a single function of CHL as in previous models, but is estimated using the QAA. Therefore, the ratio CHL/KPUR is more strongly correlated to PP than CHL or KPUR taken separately. In other words, CHL/KPUR gives a measured of the biomass relative to all the optical constituents that contribute to light attenuation (CHL, CDOM, NAP, BBP, water). It is not a phytoplankton physiological index.*

We agree with the reviewer that the use of this index was not clearly stated. We will provide a new figure (see below) with 4 panels illustrating the relationships:

A) CHL versus KPUR,
B) CHL versus PP/PAR(0-)
C) KPUR versus PP/PAR(0-)
D) CHL/KPUR versus PP/PAR(0-)

These relationships help understanding the point we wanted to make in the paper.

The panel A) shows the dependence of K_{PUR} on CHL and compares it to the relationship predicted by the Morel and Maritorena (2001) model built for the clear oceanic waters. In July 2007, for example, 82% of the variance in K_{PUR} in the circum-Arctic was explained by CHL. The remaining variance (18%) was due to other optically significant constituents, or phytoplankton pigments characteristics. It also shows that the K_{PUR} for a given value of CHL is much higher than the value predicted the case-1 water model published by Morel and Maritorena (2001). The differences are more pronounced in the low chlorophyll-a concentration range and tend to diminish as CHL increases. When PP is normalized to the incident irradiance (PAR(0-), PP, a strong positive relationship is obtained with CHL (r^2=0.92; panel B). Note that PAR(0-) alone explained 18% of the variance in PP (not shown). Similarly, PP* was also positively correlated to K_{PUR} due to its dependence on CHL (r^2=0.58; panel C). Panel D shows the strong relationship existing between PP* and the ratio of CHL/ K_{PUR} (r^2=0.98). The remaining variability may be attributed to the non-linearity of the P vs I relationship (i.e. f(PUR)).*

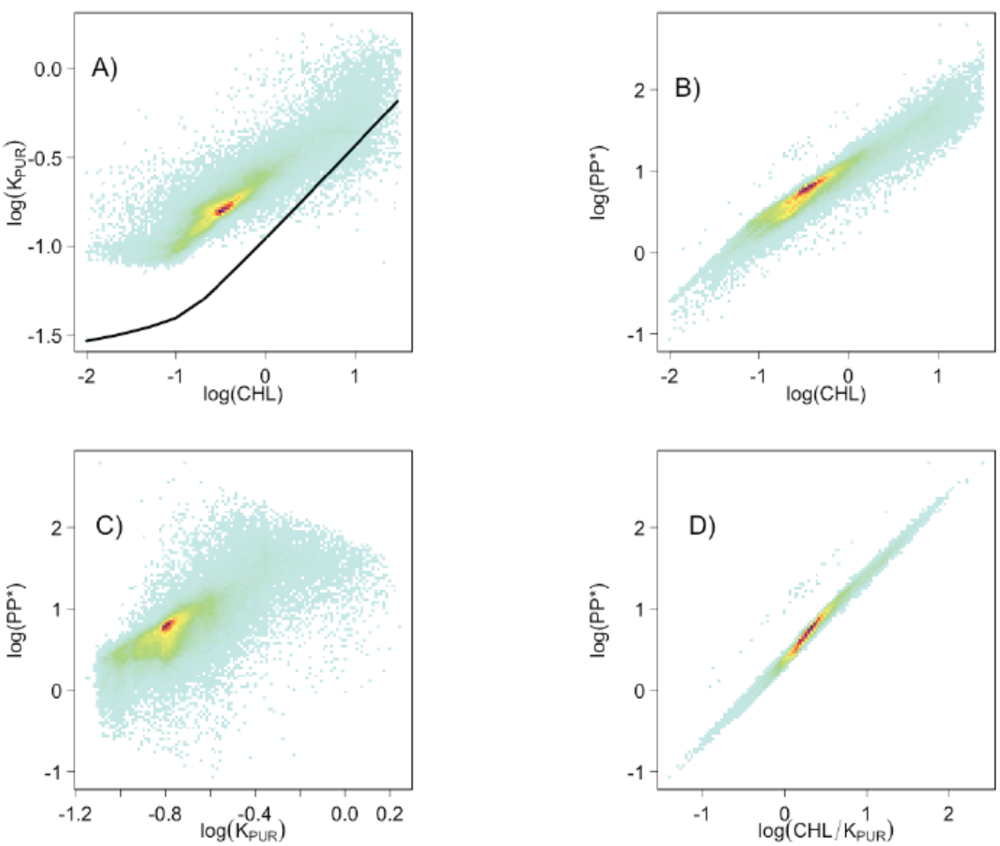


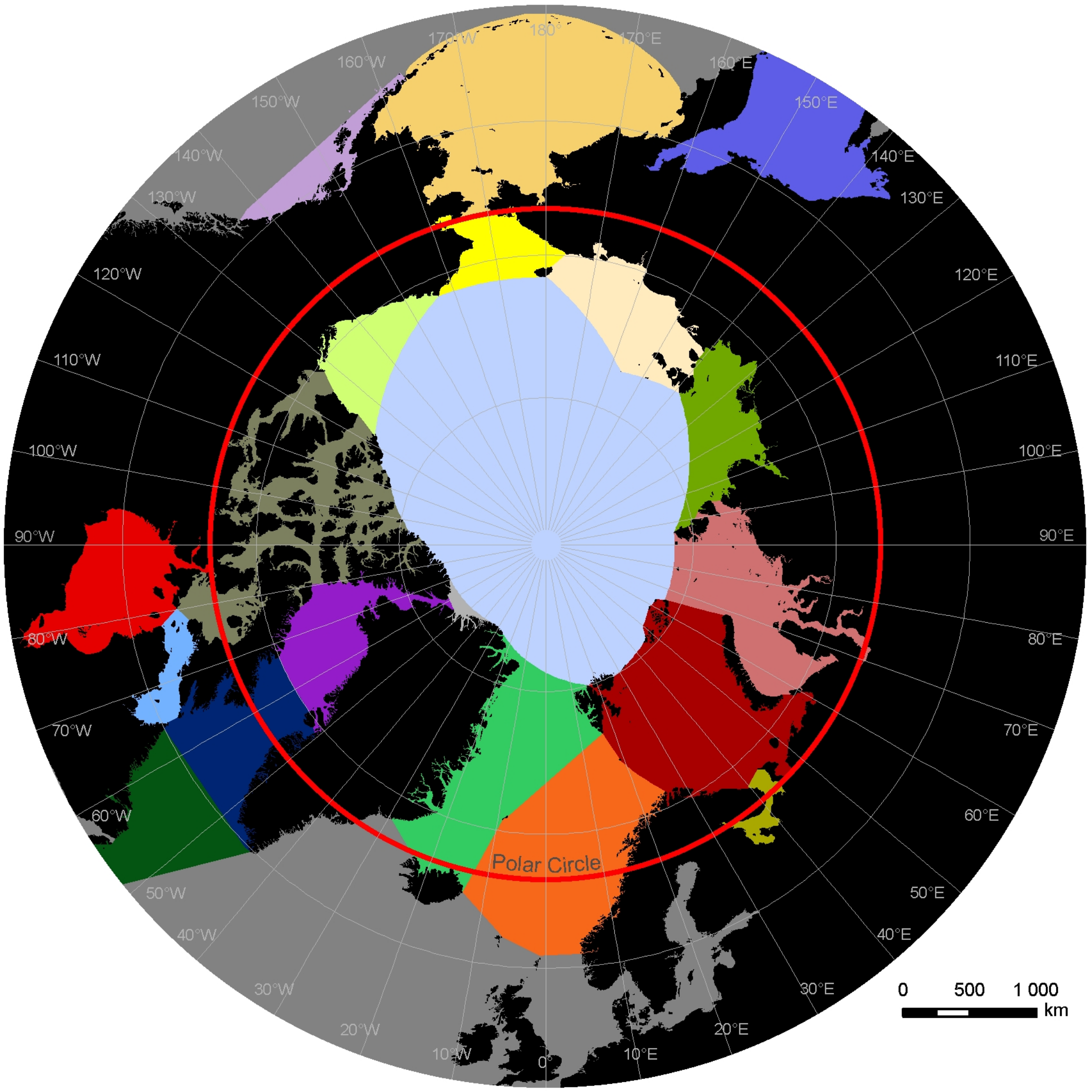
Fig. 4. Examples of relationships between (**A**) CHL and K_{PUR}, (**B**) CHL and PP normalized by surface PAR (PP*), (**C**) K_{PUR} and PP*, and (**D**) CHL/K_{PUR} and PP* for the month of July 2007. The black line on panel (**A**) is K_{PUR} predicted from CHL using the empirical model of Morel and Maritorena (2001) for K_d and Matsuoka et al. (2011) for a_{ph}.

4. Analysis of trends such as relationship among PP, CHL, CHL/KPUR is lacking statistic results. Most of the trend analysis showed only each increase/decrease rate or comparison of patterns on satellite images. Authors should show the results statistically.

REPLY: As also requested be reviewer #1, we will provide four new tables for the monthly regional average and trends in PAR(0+), PAR(0-), PP and CHL/ K_{PUR}. The region limits are the ones provided by the IHO (see figure below).). The significance of each trend was tested using the non-parametric Mann-Kendall test. Here is an example of table for PAR(0+)

Table 1. Regionally averaged daily flux of PAR above the sea (ice) surface (PAR(0+) in $molphotonm^{-2}d^{-1}$) and its relative trends computed for the 1998 to 2009 period (in parenthesis, in % y^{-1}). Significant trends are in bold text with superscript indicating the level of significance: (a) $0.05 < p < 0.1$, (b) $0.01 < p < 0.05$, and (c) $p < 0.01$
table

Region	May	June	July	August	September
Greenland Sea	29.0 (**-0.90**)^a	38.6 (**-1.07**)^c	34.6 (-0.52)	22.4 (**-0.98**)^c	14.8 (-0.37)
Norwegian Sea	33.3 (-0.20)	37.8 (-0.42)	33.5 (**-1.16**)^c	24.2 (-0.71)	12.8 (**-0.88**)^c
Barents Sea	28.0 (**-1.06**)^b	37.1 (**-1.86**)^c	33.9 (-0.83)	21.0 (**-0.93**)^b	13.3 (**-1.15**)^c
Kara Sea	24.6 (-0.64)	35.6 (**-0.94**)^b	35.3 (-0.67)	22.2 (**-1.41**)^c	17.4 (**-1.35**)^b
Laptev Sea	26.3 (-0.44)	35.7 (**-1.54**)^b	35.8 (**-1.29**)^b	22.7 (**-0.95**)^b	17.6 (**-0.85**)^c
East Siberian Sea	28.0 (**-1.53**)^a	41.2 (-0.72)	39.8 (**-0.98**)^b	25.1 (**-0.79**)^a	17.3 (**-0.84**)^b
Chukchi Sea	33.0 (-0.72)	46.0 (-0.93)	40.9 (-0.98)	26.3 (0.12)	12.8 (-0.51)
Beaufort Sea	29.9 (**-1.86**)^b	44.9 (-0.40)	42.2 (-0.02)	27.5 (-0.20)	18.6 (-0.52)
Arctic Ocean	26.1 (-0.85)	36.9 (-0.92)	38.2 (-0.45)	23.5 (-0.21)	21.1 (0.24)
Northwestern Passages	29.5 (-0.63)	40.8 (-0.34)	40.8 (-0.38)	25.9 (-0.32)	14.8 (-0.26)
Baffin Bay	29.2 (-0.41)	40.0 (**-0.95**)^b	37.8 (0.39)	23.2 (0.24)	11.0 (-0.21)
Hudson Bay	34.2 (**-1.65**)^c	46.0 (**-0.64**)^a	46.1 (-0.28)	33.3 (-0.53)	18.8 (-0.26)
Hudson Strait	31.9 (-0.87)	41.8 (-0.03)	43.9 (-0.35)	30.4 (-0.34)	17.6 (-0.69)
Davis Strait	33.4 (**-0.68**)^c	41.1 (-0.44)	40.7 (-0.03)	28.1 (**-0.70**)^b	15.8 (-0.88)
Labrador Sea	36.5 (-0.47)	40.3 (-0.23)	39.5 (-0.22)	31.1 (**-0.65**)^b	20.7 (-0.18)
Sea of Okhotsk	37.9 (**-0.60**)^b	43.0 (0.27)	39.9 (-1.03)	31.2 (-0.62)	22.3 (-0.14)
Bering Sea	34.6 (**-0.99**)^b	37.0 (**-1.0**)^c	34.5 (**-0.98**)^b	27.1 (-0.79)	18.7 (**-0.87**)^c
Gulf of Alaska	38.5 (**-1.06**)^b	41.3 (-0.39)	37.6 (-0.67)	31.2 (**-1.15**)^a	19.7 (-0.74)
Arctic + sub-Arctic Seas	33.0 (**-0.86**)^b	39.6 (**-0.71**)^c	37.4 (**-0.84**)^c	26.0 (**-0.57**)^c	17.1 (**-0.67**)^c
Circum Arctic	29.2 (-0.71)	38.7 (**-1.11**)^b	36.4 (-0.63)	23.3 (-0.31)	15.6 (**-0.48**)^b



Arctic and Sub-Arctic Seas

Arctic Ocean (5 039 101 km²)	East Siberian Sea (605 858 km²)	Laptev Sea (521 130 km²)
Baffin Bay (519 139 km²)	Greenland Sea (1 136 905 km²)	Lincoln Sea (35 171 km²)
Barentsz Sea (1 360 155 km²)	Gulf of Alaska (258 519 km²)	Northwestern Passages (993 128 km²)
Beaufort Sea (416 185 km²)	Hudson Bay (723 931 km²)	Norwegian Sea (1 391 805 km²)
Bering Sea (2 046 593 km²)	Hudson Strait (172 740 km²)	Sea of Okhotsk (1 316 602 km²)
Chukchi Sea (328 609 km²)	Kara Sea (859 913 km²)	White Sea (81 569 km²)
Davis Strait (663 856 km²)	Labrador Sea (694 735 km²)	Others seas

Sources
Seas : International Hydrographic Organization, 1953
Realisation : Marie-Andrée Roy, UQAR, juin 2011

Technical corrections

Line 13, page 13988: "+8%" Is this "-8%"?

REPLY : Yes, that one was confusing. +8% has been replaced by -8%. Thank you.

Line 9 and 10, page 13997: "< +0.5" and "< -0.3" Is this ">+0.5" and ">-0.3"?

REPLY : the “<” have been removed.

"mol photons" is better than "Einstein" as a SI unit.

REPLY : Yes, that’s right. Einstein has been replaced by “mol photons”.