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Interactive comment on "Warmer winters causes an increase of chlorophyll-a concentration in deeper layers: the opposite role of convection and self-shading on the example of the Black Sea" *by* Elena A. Kubryakova and Arseny A. Kubryakov

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Nicolas Mayot, we would like to thank You for comments and valuable and constructive suggestions for improving the paper.

Please note that this response to the review is accompanied by corrected figures (Fig. 2-4, 6, 8). These figures are given here according to the numbering in the revised manuscript. Figures R1-R4 will not be inserted in the article. They are provided here to explain the answers.

General comments (GC)

GC1: "Authors wrote several times in the manuscript that in the Black Sea, as in other oligotrophic basins, the nitracline is closely connected to an isopycnal (for examples, see lines 80, 156, 161 and 287). When looking at figure 2 c-d, we can clearly see that isopynals between 1014 kg/m3 and 1014.4 kg/m3 (associated with the nitracline, see line 158 and figure S1) are shallower in summer 2017 than in summer 2016. Therefore, in summer 2017 the nitracline (or nutricline) is shallower than in summer 2016. The low chlorophyll-a concentration in 2017 between 40-60 m is probably due to a change in in the depth of isopycnals and not to a "rise of light attenuation", as argued by authors (line 387).

Answer GC1. In fact, the concentrations of nitrates and phosphates rise gradually with depth reaching their subsurface maximum at 1015.5 kg/m3 (see Fig. R1 below). Nutricline defines the area of the highest gradients of nutrients concentration but not the position of their maximum. Therefore, at deeper isopycnal layers (1014.6-1015.5 kg/m3), the concentration of nutrients is even larger than at 1014-1014.4 kg/m3. According to Your assumption, the Chl should have been higher in the deeper layers in 2017, when the isopycnals were raised. However, according to the Bio-Argo measurements, Chl was lower in deep layers in 2017 (see Fig. 3-5 in the manuscript).

In the manuscript, it was written: "For example, the concentration of nitrates begins to gradually increase below the isopycnal of 1014 kg/m3 (see Supplementary Fig. S1), and rises more sharply below the isopycnal of 1014.4 kg/m3 where the upper part of the nutricline is located (Konovalov & Murray, 2001)". To avoid misunderstanding, we have rewritten this phrase as "The concentration of nitrates begins to gradually increase below the isopycnal of 1014 kg/m3, and reach its maximum at $\sigma\sim$=15.5 kg/m3 (Konovalov & Murray, 2001)".

To answer Your question, we have added to the paper the variability of the Chl in density coordinates (see revised Fig. 4c, d below). As it is seen, there is no correlation between Chl and density. For example, in March-May at σ=1014.5 kg/m3, Chl in 2017 was higher than in 2016, while at the summer period Chl in 2016 was higher than in 2017. This indicates that Chl variability is not directly related to isopycnals' position, which is related to the crucial role of light penetration, which depends on the bio-optical properties of the water in upper layers and defines the isopycnal layers, where phytoplankton can grow.

We have revised the Fig. 4 and its description to the paper.

GC2: Line 343 – "The closeness of DCM and nutricline increases the nutrient fluxes in the summer of the years with warm winter, which compensates for their decrease in winter caused by weak convective entrainment." Such a statement is false because the authors did not discuss differences in the depth of the nutricline between summer 2016 and summer 2017.

Answer GC2. We agree that this statement was inaccurate. So we have rewritten it as "The closeness of DCM and deep isopycnal layers with high amount of nutrients increases the nutrient fluxes in the summer of the years with warm winter, which compensates for their decrease in winter caused by weak convective entrainment."

To demonstrate this fact, we have added the diagrams of the seasonal variations of Chl in density coordinates in 2016 and 2017 (Fig. 4c, d) to the paper. As You can see, in the warm period of 2016, higher values of Chl was detected in deeper isopycnal layers (reaching 1014.7 kg/m3), which contain higher concentrations of nutrients. That is why we conclude that the DCM was closer to the nutricline in the summer of warm 2016.

We have added this information to the text: "The same features are seen in the Fig. 4c, d, which demonstrates the variability of Chl in σ-coordinates, where σ is potential density. Chl in 2017 was higher in upper isopycnal layers. However, in 2016 relatively large values of Chl were observed in the deepest isopycnal layers. Particularly in 2016, in summer months, Chl at σ=1014.5-1014.7 kg/m3 exceeded 0.2 mg/m3, whereas, in 2017, it was near zero. These values of density 1014.5-1014.7 kg/m3 were higher than that density of waters entrained to the surface in winter (revised Fig. 2c below), which was less than 1014.2 kg/m3".

"Particularly, in the considered case in warm 2016, large values of PAR (more than 3 μmol photons m-2 s-1) reached 40-60 m depth (Fig. 4b), corresponding to σ=1014.5-1015 kg/m3 (Fig. 4d). In these isopycnal layers, the concentration of nitrates sharply increases (Konovalov& Murray, 2001; TuÄ§rul et al., 2015). These values were significantly higher than that density of waters entrained to the surface in winter (Fig. 2c), which was less than 1014.2 kg/m3. Therefore, Fig. 4d evidence that in the summer of 2016, the penetration of light induces the rise of Chl directly in the nutricline waters, which were not affected by winter convective mixing."

We would like to thank You for this comment, because it helps us to demonstrate our results more clearly.

GC3: In addition, when looking at figures 4a-b, chlorophyll-a concentration at the DCM is higher in 2017 than in 2016. Considering that isopycnals were shallower in 2017 than in 2016, and based on figures 4e-f, one could argue that the light level at the nutricline is higher in 2017 than in 2016. A higher light level at the nutricline could induce a higher phytoplankton production and biomass in the DCM, as observed in 2017. Such mechanism, clearly explained in the comprehensive review of Cullen (2015), is crucial and need to be discussed".

Answer GC3. We agree that Chl at DCM was higher in 2017 and 2016. However, in 2016, DCM was wider and occupied a larger layer, as in depth-coordinates (Fig. 4a, b, 5 (in the manuscript)), as in density-coordinates (revised Fig. 4c, d).

The rise of the phytoplankton depends on the absolute values of nutrients concentration, not on their gradients (defining nutricline). It is important to note that the maximum of nutrient concentrations in the Black Sea and other ocean areas is located far below the euphotic layer (see answer on GC1, GC2). Therefore, when light penetrates to deeper isopycnal layers (as in 2016, see revised Fig. 4c, d), Chl values should be larger. That is why, as we show in revised Fig. 3b, in fact, the integral concentration of Chl was higher in the summer of 2016 than in the summer of 2017.

GC4: "When studying DCM, it is important to know if the DCM is also a subsurface phytoplankton biomass maximum. Because, changes in chlorophyll-a concentration at a DCM could be induced by variations in intracellular chlorophyll-a concentration or by changes in phytoplankton biomass. In the current version of the manuscript, this point is not discussed".

Answer GC4. We agree and have extended the Discussion on this topic: "It should also be mentioned that the vertical distribution of phytoplankton biomass often does not coincide with the distribution of Chl (Finenko et al., 2002, 2005; Krivenko, 2010; Churilova et al., 2017). Particularly, in the summer period, the peak of the phytoplankton biomass is usually located above the maximum of Chla (Finenko et al., 2005; Krivenko, 2010; Stelmakh & Babich, 2006). At this time, large diatoms such as Pseudosolenia calcaravis and Proboscia alata with high biomass and low cellular Chl prevailed in phytoplankton layers (Mikaelyan et al., 2018; Silkin et al., 2019). At the same time, the deepest phytoplankton in summer mainly consists of small flagellates and unicellular cyanobacteria (Rat'kova, 1989; Churilova et al., 2019; Mikaelyan et al., 2020), which have very high specific cellular pigment content. As a result, the biomass may be low, whereas the Chl is rather high. The phytoplankton after cold and warm winter grows at different depths, and, therefore, the environmental (light and nutrients) conditions change significantly. Deepening of the euphotic layer may promote the growth of species adapted to low light with low biomass and high Chl content (Falkowski & La Roshe, 1991; MacIntyre et al., 2002; Latasa et al., 2017), which may have an advantage in the years with warm winters".

GC5: "When using data from biogeochemical-Argo floats equipped with an ECO Triplet (as here, line 110), measurements of particulate backscattering coefficient (bbp), a proxy of the particulate organic carbon, are available. These measurements have been used in a paper published by one of the authors (Kubryakov et al., 2019). The manuscript will be more comprehensive if those measurements could be added to the current analysis".

Answer GC5. Thank You for this advice. We agree and have added the diagram of the bbp difference in the revised version of the manuscript (new Fig. 6d). This figure complemented our results. It clearly demonstrated the rise of bbp in the summer period in the upper layer, related to the very intense coccolithophores bloom in 2017. We have added this information to the text: "This fact reflected in the strong rise of the bbp in 2017 (see new Fig. 6d), which in summer period of 2017 reached its maximum over 2014-2019 period (Kubryakov, Mikaelyan, et al., 2019). The rise was observed in the upper layers (0-30 m), which are usually occupied by coccolithophores bloom (Mikaelyan et al., 2005; Kubryakov, Mikaelyan, et al., 2019). In May-August, bbp in the upper 0-20 m layer was higher on 0.015 m-1 (new Fig. 6d) or threefold higher compared to 2016. At the same time, new Fig. 6d shows the decrease of bbp in the deeper layers (30-60 m) in the summer of 2017. Coccolithophore blooms usually are not observed in these deep layers, and this decrease can be attributed to the decrease of phytoplankton biomass at these depths in 2017, which is in agreement with Chl variability (new Fig. 6a)".

Minor comments (MC)

MC1: "Line 11 – "caused an increase of Chl in winter up to 0.6-0.7 mg/m3 compared to a warm winter of 2016": It is unclear. There is an increase of Chl in winter in both years".

Answer MC1. We have rewritten this part of the abstract: "In cold 2017, nutrient-rich waters from deeper isopycnal layers were entrained to the surface. As a result, Chl during early-spring bloom in 2017 was in 1.5-2 times higher (0.6-0.7 mg/m3) than in warm 2016 (0.4-0.5 mg/m3)".

MC2: "Line 19 – "more productive." That is a suggestion. Chlorophyll-a concentration measurements are not primary production estimates".

Answer MC2. We agree and have corrected it as "in the year with intense winter mixing, Chl in upper layers is higher."

MC3: "Line 24 – "With the rise of stratification and irradiance vertically. . ." A comma is needed after the word "irradiance."

Answer MC3. Corrected.

MC4: "Line 26 – "After the bloom, part of the nutrients. . .fuel the phytoplankton bloom". How many blooms are there in a year?".

Answer MC4. Corrected on "which fuels the phytoplankton growth in the warm period of the year."

MC5: "Line 27 – "nitrocline." It is a wrong spelling, used several times in the manuscript. Need to be replaced everywhere by "nitracline" or "nutricline." However, here it could be replaced by "euphotic zone."

Answer MC5. Thank you. In the revised manuscript, "Nitrocline" was replaced everywhere by "nutricline." At line 27, it was replaced by a "euphotic zone."

MC6: "Line 31 – ". . .convection in the Black Sea, impact on the. . .". Need to be replaced by ". . . convection in the Black Sea impacts on the. . .".

Answer MC6. Thank you. It was replaced.

MC7: "Line 35 – replace "biomodelling" by "modelling".

Answer MC7. It was replaced.

MC8: "Line 45 – The diapycnal diffusivity could be an important physical process for nutrient supply. Maybe it is the most important in summer".

Answer MC8. We have corrected the phrase as "The nutrients entrainment in the euphotic layer in the warm period is strongly related to the diapycnal mixing (or diffusivity) enhanced by short-period mixing events (Williams & Follows, 2003), such as storms

(Iverson et al., 1974; Zhang et al., 2014; Kubryakov, Zatsepin, et al., 2019), wind-driven or dynamic upwelling (McGillicuddy et al., 1998; Mikaelyan et al., 2020)".

MC9: "Line 52 – The relationship between expressions: "high values of irradiance may cause photoinhibition", "photoadaptation" and "increase of Chl content per cell" is unclear".

Answer MC9. Thank You. In the revised manuscript, this phrase was corrected as "At the same time, high values of irradiance cause the decrease of Chl and fluorescence near the surface (Platt et al., 1982) due to several effects including non-photochemical quenching, photoinhibition, and photoacclimation (Falkowski & Raven, 2013). The later lead to the decrease of Chl content per cell (MacIntyre et al., 2002), which is observed in the upper layers of the Black Sea in the summer period (Finenko et al., 2002, 2005; Silkin et al., 2013; Churilova et al., 2019)".

We also have extended the Discussion of the photoacclimation in the Discussion part of the revised manuscript (please see answer GC4).

MC10: "Line 66 – Replace "Bio-Argo buoys" by "biogeochemical-Argo floats". Throughout the manuscript, the word "buoys" should be replaced by "floats".

Answer MC10. Line 66 is corrected. Throughout the manuscript, the word "buoys" was replaced by "floats."

MC11: "Line 89 – "Long-term rise of temperature observed globally (Behrenfeld et al., 2016)" This study did not focus on the long-term rise of temperature."

Answer MC11. Thank You. We agree and have changed the reference on the proper one: Boyce, D. G., Lewis, M. R., & Worm, B. (2010). Global phytoplankton decline over the past century. Nature, 466(7306), 591-596.

MC12: "Line 121 – "The letter z is missing in the parentheses".

Answer MC12. We have corrected this formula and excluded λ from it, as we use here

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only Kd of PAR: K_d (z)=lnâĄą((E_d (z+dz))/(E_d (z)))/dz

MC13: "Line 124 – All measurements from Argo floats have quality control flag values. Did authors check them?"

Answer MC13. Yes, we checked QC flags. However, our analysis showed that many data marked as bad (QC=4) was, indeed, reasonable. That is why we carefully checked all the bio-optical data using visual analysis, as it is shown in Fig. R2 below. In fact, there were almost no spikes in the data, with the exception of deep layers with depths more than 100-200 m, which are out of the zone of interest for our study.

MC14: "Line 125 – Information about the process to obtain potential density values from in situ temperature and salinity measurements are missing".

Answer MC14. Potential density was computed from data of temperature and salinity on the base of UNESCO formulae using seawater Matlab codes (Morgan, 1994). We added this information to the text.

MC15: "Figure 2 – Is it in situ or potential temperature? Potential density? The colorscale or isolines are inconsistent. For example, in panel C, the isopycnal 1014.2 has a yellow background and in the panel D has an orange background.

Answer MC15. This is in-situ temperature and potential density. This information is added to the revised Fig. 2 caption (see it in answer GC2). We also redraw Fig. 2c, d to show the proper position of the contour lines. Thank You for this mark.

MC16. Here and throughout the manuscript, could the authors use another colormap, not a rainbow one: "In the 2007 IEEE article, Rainbow Color Map (Still) Considered Harmful, authors David Borland and Russell M. Taylor II from the University of North Carolina at Chapel Hill stated, "The rainbow color map confuses viewers through its lack of perceptual ordering, obscures data through its uncontrolled luminance variation, and actively misleads interpretation through the introduction of non-data-dependent gradients."

Answer MC16. Thank you for the information. Until now, we have not paid attention to this. We have read the article which You cite. In conclusion, the authors wrote: "The selection of the best color map depends so critically on the data set and addressed questions that there is not a single best choice, but rather a collection of sets with different characteristics. The best solution would present the user with a choice whenever a color map is created, listing best types for each circumstance".

Interested in this question, we have read the results of one more recent study (Khairi Reda, Pratik Nalawade, and Kate Ansah-Koi. 2018. Graphical Perception of Continuous Quantitative Maps: the Effects of Spatial Frequency and Colormap Design. Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems. Association for Computing Machinery, New York, NY, USA, Paper 272, 1–12. DOI:https://doi.org/10.1145/3173574.3173846). The authors concluded that "...data reveals that, counterintuitively, rainbow is robust for estimating a smoothly varying quantitative attribute, regardless of spatial complexity. Moreover, rainbow provides good support for gradient estimation at high spatial frequency. These two tasks correspond to elementary visual analytic primitives, including characterizing distributions, determining ranges, and filtering [1]. Moreover, studies show that when experts attempt to form a mental model about a visualization, they first go through a time-consuming process of extracting quantitative data "at a rather detailed level" [38].

For instance, a weather forecaster will lookup pressure and wind changes, estimating current readings at landmark locations in the map before making a forecast. Our data suggests that rainbow provides good support for these tasks, making it a potentially reasonable choice for weather forecasters...".

In our manuscript, we use rainbow to estimate a smoothly varying quantitative attribute (e.g. temperature, density etc.), so we would like to keep this colormap. In the future, we will take the information you provided into account to choose the colormap.

MC17: "Line 154 – "conventional mixing", is it the right term?".

Answer MC17. Thank You. It was changed to "convective mixing."

MC18: "Section 3.1, Figure 2 and Figure 3 – Regarding physical parameters, there are no information or comments about potential differences between the two floats for a same year due to differences in their geographical locations. Are there any differences in the vertical distribution of temperature, isopycnals and MLD between the two floats for a same year? In addition, time series of temperature and density for each float should be added in supplementary materials. The sentence, line 101: "As we will show below, despite these differences in the geographical position both buoys show similar results concerning the paper topic" needs to be supported by figures and values for all physical and bio-optical parameters used here".

Answer MC18. Yes, there were differences in the physical parameters measured by these two floats. This was related to their different geographical position. Float #7900591 was moving mostly in the center of the sea, corresponding to the center of cyclonic gyres. Therefore, isopycnal positions were located closer to the surface according to its measurements compared to floats #6901866, located in the downwelling area (Fig. R3). The same is observed for the temperature variability (Fig. R4). The cold intermediate layer (white color in Fig. R4) is situated deeper over the continental slope (float #6901866) than in the basin's central part (float #7900591).

Despite these differences in physical parameters, Fig. 4 evidences that the main feature of the interannual variability in Chl distribution is similar for both floats: in the cold 2017, Chl was higher in the upper layers, while in warm 2016, it was higher in deeper layers.

For clarity, in the revised manuscript, we have rephrased this sentence: "As we will show below, despite these differences in geographical locations, both floats show similar results concerning year-to-year variability of Chl vertical distribution."

This is also clearly demonstrated below in Fig. S2, which shows average annual Chl profiles measured by two floats.

We decided not to include the Fig. R3 and R4 in the manuscript as they are not crucial for the goal of the paper but may increase and overload the manuscript.

MC19: "Line 201 – "productivity" chlorophyll-a concentration is a proxy for phytoplankton biomass not phytoplankton production".

Answer MC19. It was changed on "to an increase of Chl."

MC20: "Line 256 to 259 – This is a suggestion, it should be discussed in the discussion section".

Answer MC20. We agree and have moved this paragraph to the Discussion.

MC21: "Figure 7 – Why yearly-averaged profiles and not only summer (and winter) profiles".

Answer MC21. Thank You for this advice. We have inserted summer (and winter) profiles to the text (see revised Fig. 7, now it is Fig.8). This helps to visualize our results more clearly.

MC22: "Line 267 and figure 3b – It would be better to describe time series of depth integrated chlorophyll-a concentration and not column-averaged".

Answer MC22. We have added the graph of the time variability of depth-integrated Chl to Fig. 3 and added their values in the text.

MC23: "Line 274 to 276 – This is a suggestion, it should be discussed in the discussion section".

Answer MC23. We agree and excluded this phrase from the results.

MC24: "Line 308 – "the euphotic layer deepens, and the surface layer becomes overilluminated" It would be better to use the euphotic depth definition. What is the meaning of "over-illuminated"?".

Answer MC24. We have rewritten this phrase as: "In the warm period of a year

PAR strongly increases, light penetrate to deeper layers. At the same time, PAR in the surface layers becomes too strong, which leads to the photoacclimation of phytoplankton and a decrease of Chl in upper layers (Falkowski & Raven, 2013)".

Please also note the supplement to this comment:
https://bg.copernicus.org/preprints/bg-2020-366/bg-2020-366-AC1-supplement.pdf

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Interactive comment on Biogeosciences Discuss., https://doi.org/10.5194/bg-2020-366, 2020.

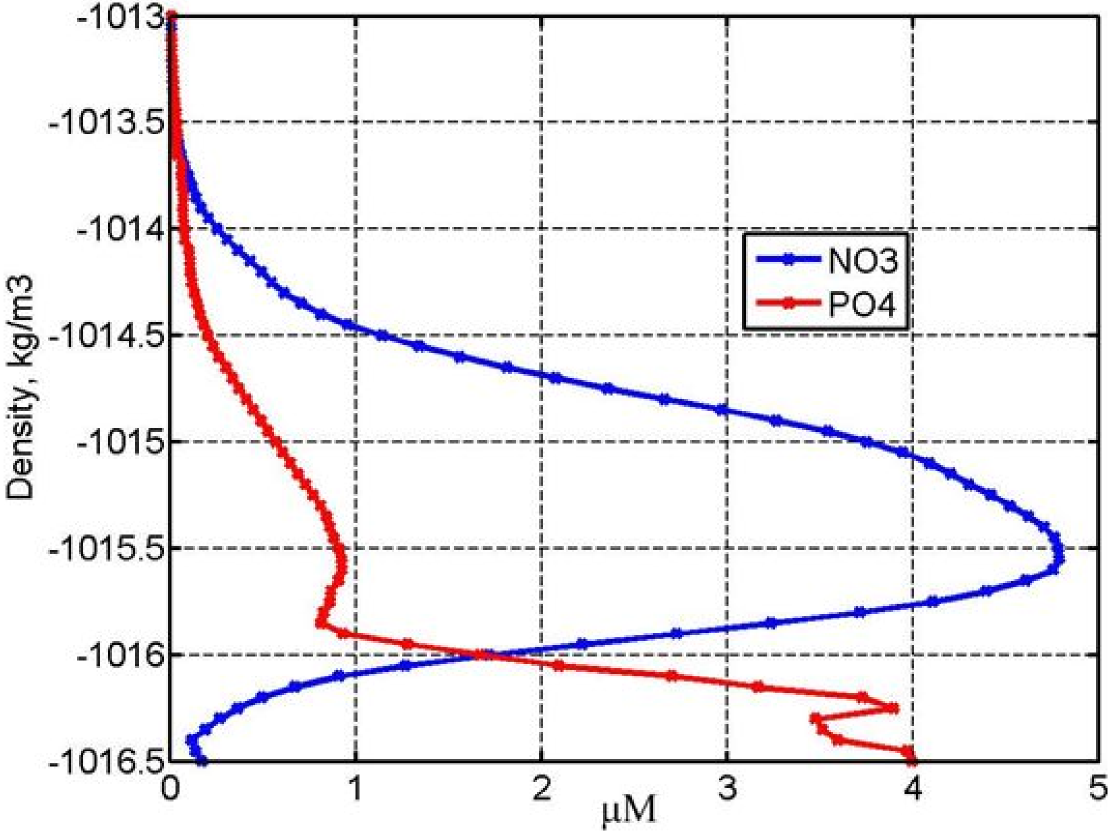

Fig. 1. Fig. R1. Multiannual-averaged profile of nitrates (blue) and phosphates (red) in the central part of the Black Sea in σ-coordinates

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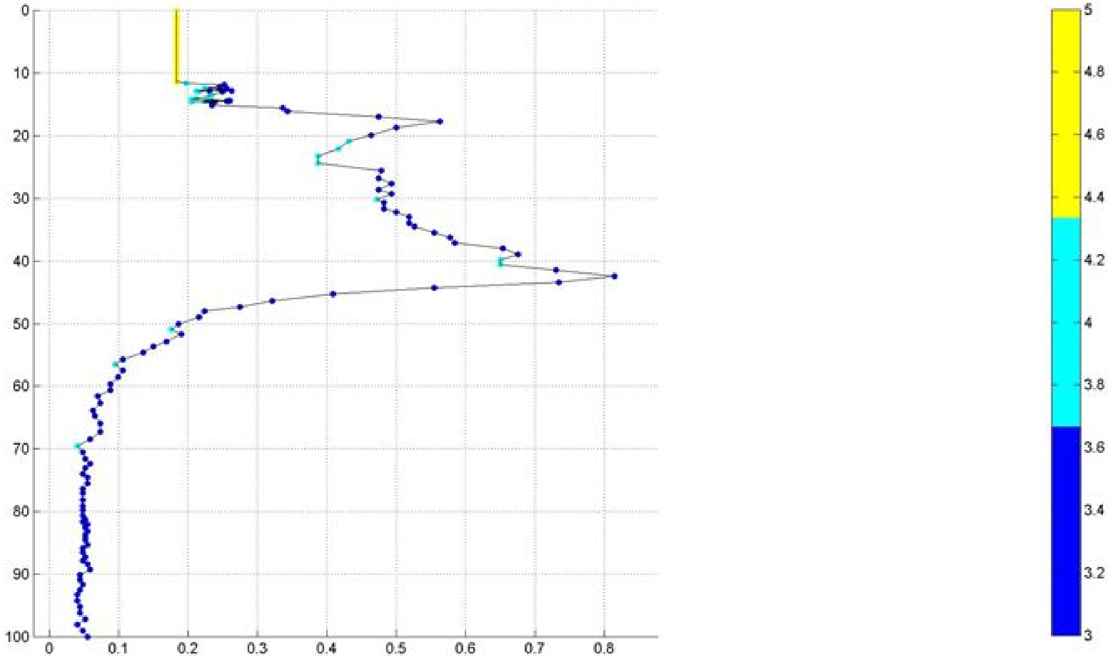

Fig. 2. Fig. R2. Example of Chl profile for 31 August 2020 with QC flags shown by colors.

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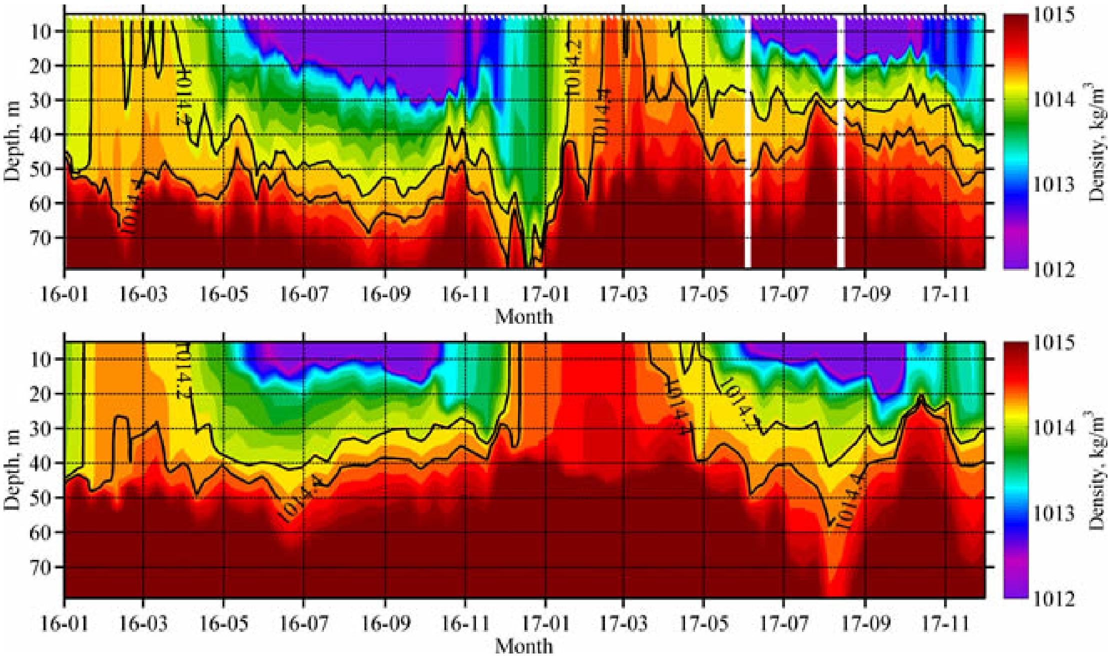

Fig. 3. Fig. R3. Time variability of density according to measurements of the float #7900591(top) and float #6901866 (bottom)

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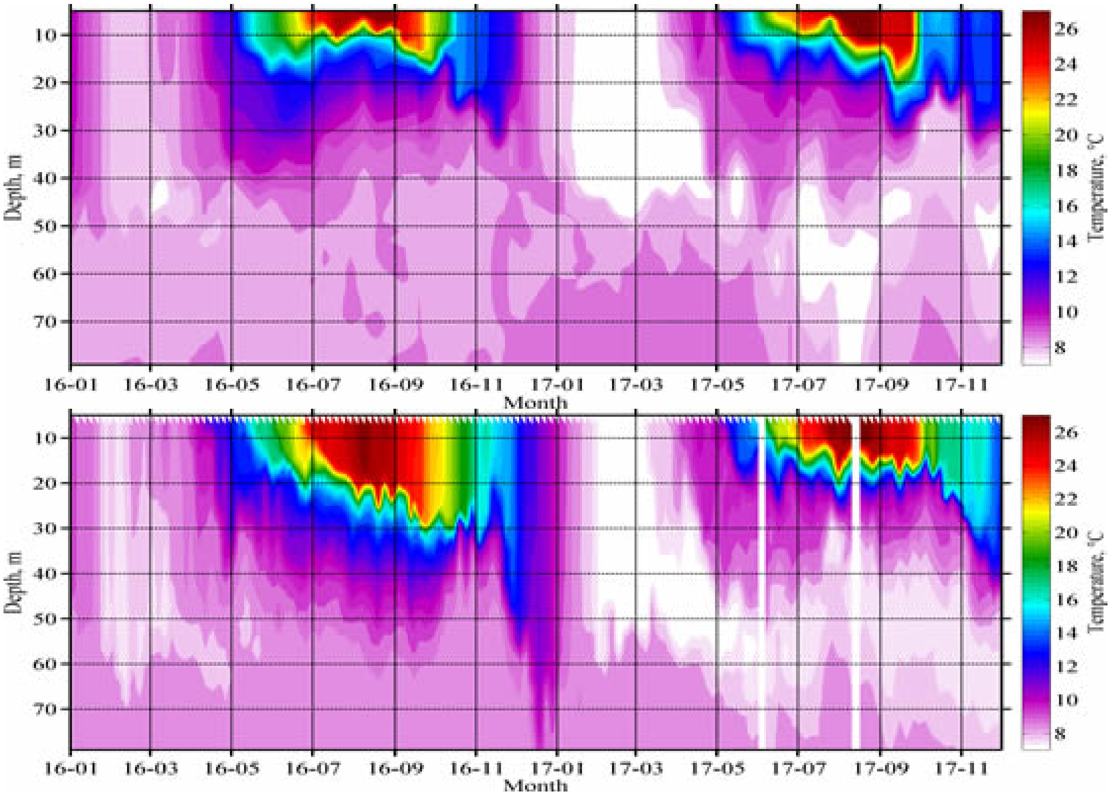

Fig. 4. Fig. R4. Time variability of temperature according to measurements of the float #7900591(top) and float #6901866 (bottom)

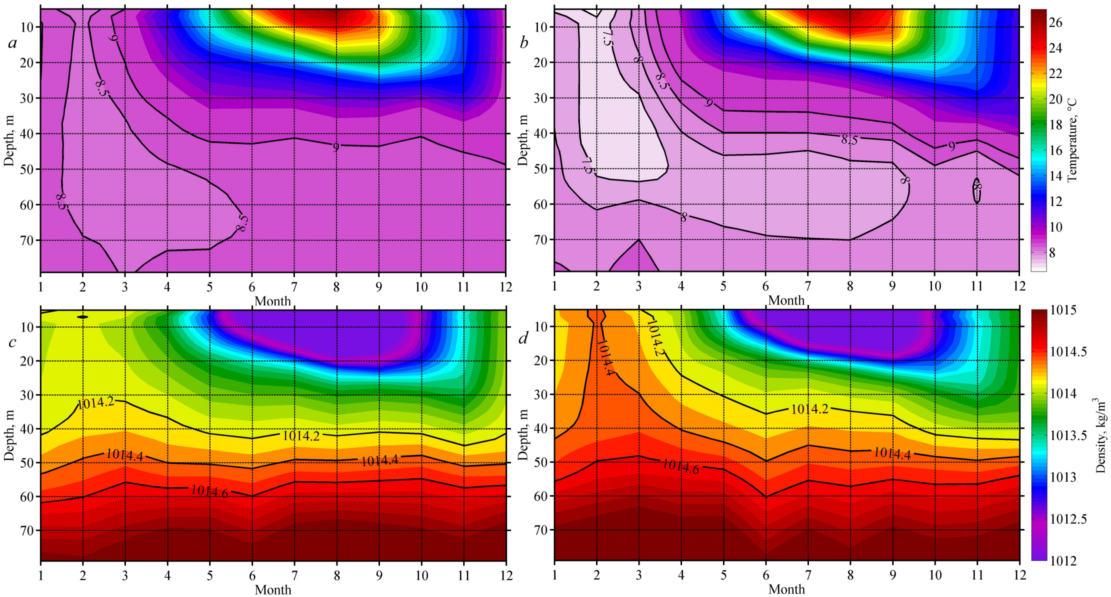

Fig. 5. (Revised) Figure 2: Monthly vertical diagram of temperature in 2016 (a) and 2017 (b), potential density in 2016 (c) and 2017 (d).

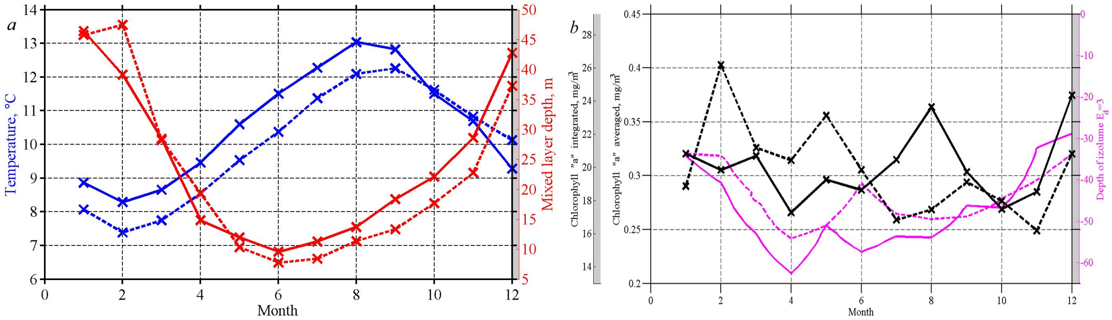

Fig. 6. (Revised) Figure 3. Full caption is in the pdf-version of the response

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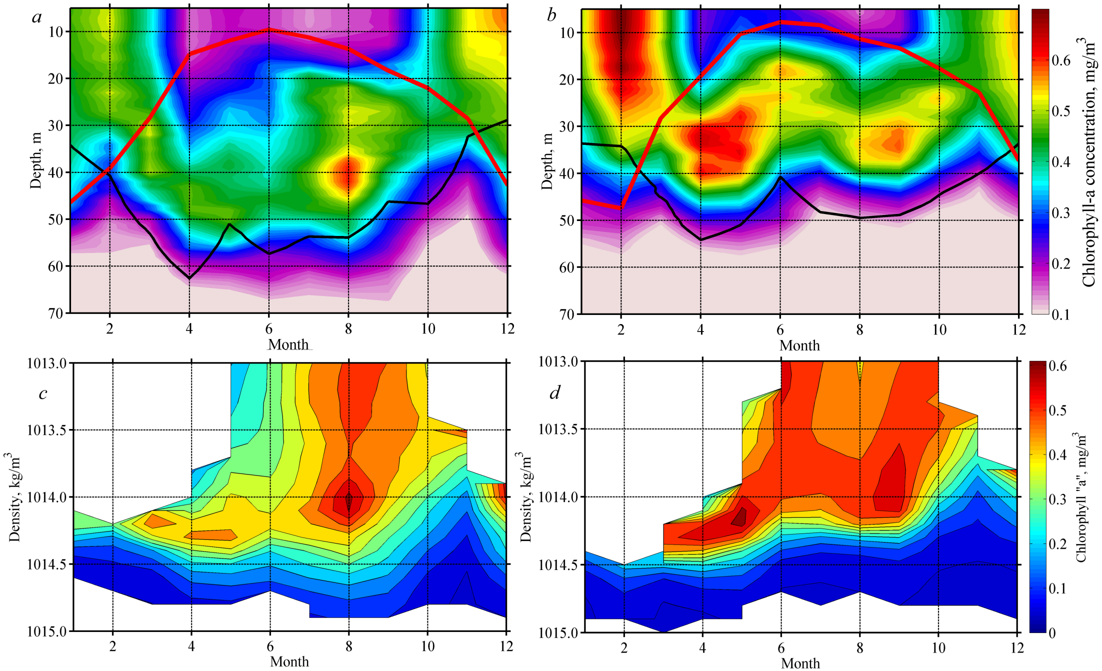

Fig. 7. Fig. 4: Seasonal variability of Chl in 2016 (a,c) and 2017 (b,d) in z-coordinates and density coordinates. The black line-the border of the photic zone (Ed=3 μmol photons m-2 s-1), the red line-MLD

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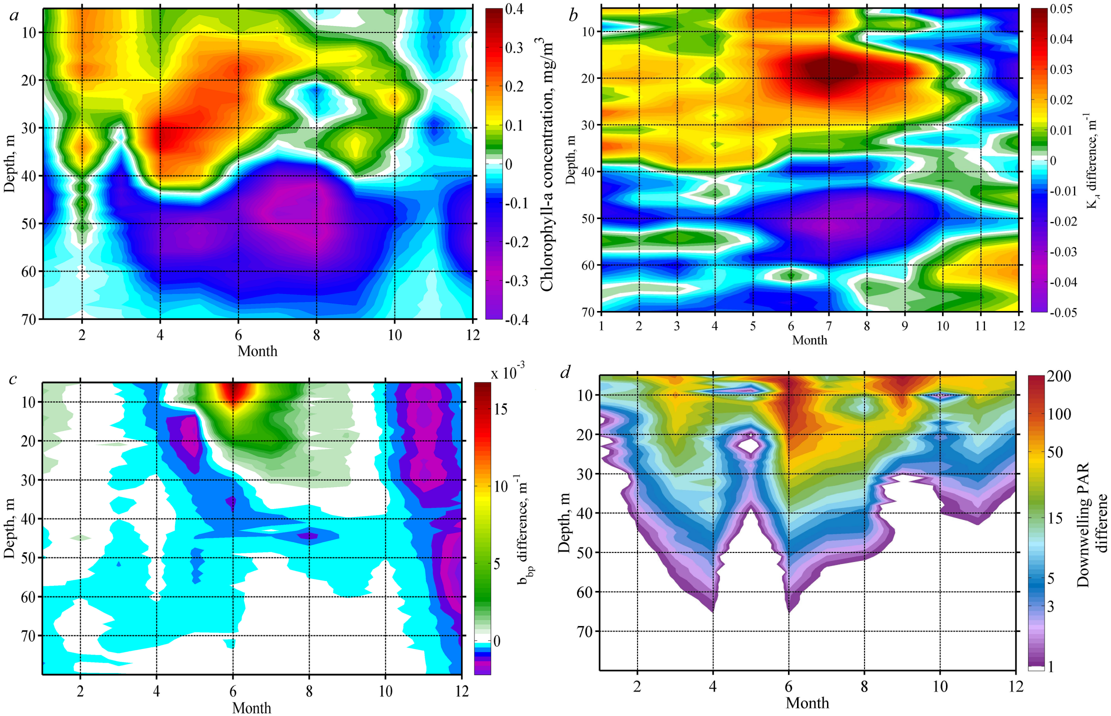

Fig. 8. Fig. 6: Seasonal diagram of a difference of vertical distribution of Chl (a), Kd (b), bbp (c) between 2017 and 2016. Difference in PAR (μmol photons m-2 s-1) distribution between 2016 and 2017 (d)

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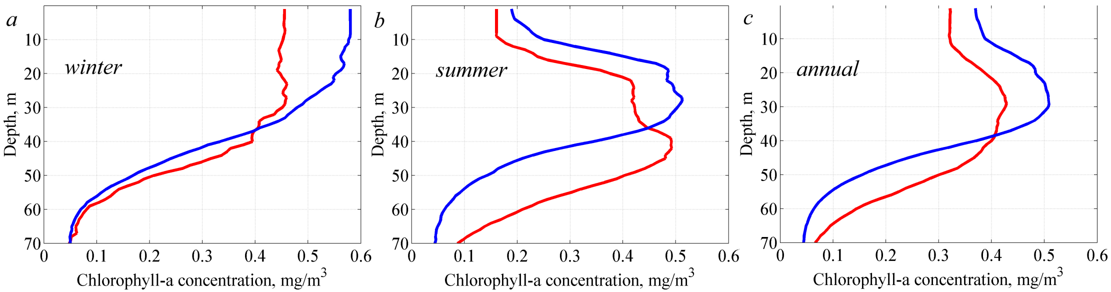

Fig. 9. Figure 8: Average profile of Chl in 2016 (red line) and 2017 (blue line) in winter (January-March) (a), summer (June-August) (b) and annually-averaged (c).

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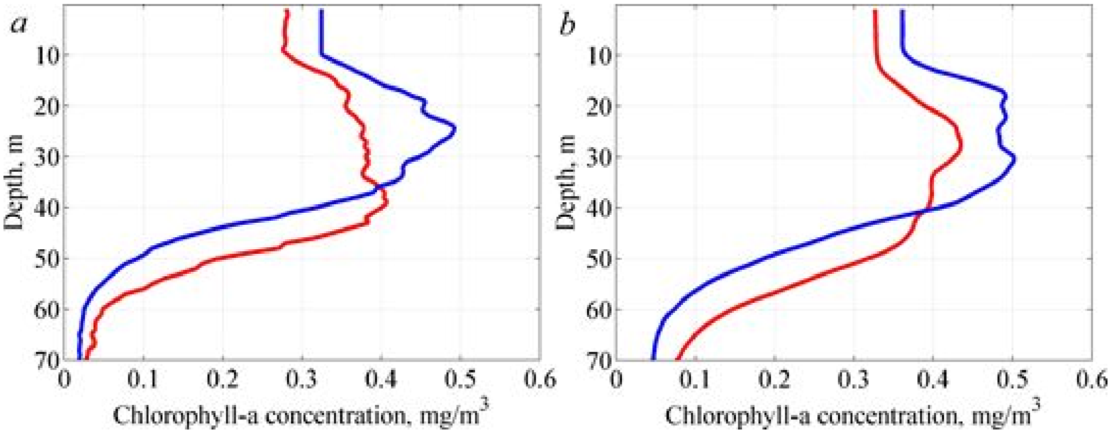

Fig. 10. Supplementary Figure S2: Average profile of Chl in 2016 and 2017 by the measurements of the float #7900591 (a) and float #6901866 (b).