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Biogeosciences
Discussions

Interactive comment on "Modelled interannual variability of vertical organic matter export related to phytoplankton bloom dynamics – a case-study for the NW Mediterranean Sea" *by* R. Bernardello et al.

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We would like to thank the Referees for their valuable comments and suggestions all of which are addressed in this document.

REPLY to Referee #1

Referee:

This is just a suggestion. I think the authors should change the title of the manuscript to something more specific that highlights the paper's findings like "Factors controlling

interannual variability of vertical organic matter export and phytoplankton bloom dynamics - a numerical study for the NW Mediterranean Sea". The current title does not reflect the interesting results shown in the manuscript.

Answer:

We agree on the need of a more highlighting title and would like to thank Referee #1 for his suggestion. The title of the revised manuscript will be: " Factors controlling interannual variability of vertical organic matter export and phytoplankton bloom dynamics. A numerical case-study for the NW Mediterranean Sea". We conserve "case-study" from the previous title to stress the fact that our results might apply also for other regions of the world's oceans.

Referee:

The Introduction could be improved by shortening it and making it more focused on the core ideas of the paper, namely: (1) blooms play an important role in the vertical flux of organic matter, (2) blooms show considerable variability in time, space and intensity and (3) that variability is related to physical processes that affect vertical mixing. In its present form, the authors relate various results from studies in the North Atlantic and Mediterranean and explain basic ideas (Sverdrup hypothesis) in biological oceanography, which sometimes leaves the reader wondering where they are going with this.

Answer:

We recognize that the text is too long and, as suggested, could be improved by focusing more on the core ideas of the paper. However, the mechanisms regulating the onset of the bloom and thus its interannual variability are also discussed because they are related to the core ideas of the paper. Early blooms are also more likely to be repeatedly interrupted and thus more likely to produce high export fluxes. We will modify the Introduction in the following way:

Page 9094, line 2, after: "....a seasonal bloom at all mid-latitude oceans." we will introduce the following:

“Blooms play an important role in the oceanic CO2 uptake (Takahashi et al., 2009) which is achieved through the export of organic matter to the deep ocean. Blooms show considerable variability in time, space and intensity, and this variability is related to physical processes that affect vertical mixing.”

Page 9094, the two paragraphs from line 2 to line 10 and from line 11 to line 20 will be merged together and shortened as follows:

“Timing and intensity of the bloom show latitudinal and interannual variability mainly determined by the variability in atmospheric forcing (Henson et al., 2009; Ueyama and Monger, 2005; Waniek, 2003). Henson et al. (2009) showed that the onset of the bloom in the North Atlantic, between 40 N and 45 N, can vary from year to year by as much as 20 weeks. This area represents the transition between subpolar light-limited and subtropical nutrient-limited environments (Dutkiewicz et al., 2001). The NW Mediterranean Sea is enclosed between these latitudes and its seasonal bloom shows high variability concurrent with its latitudinal counterpart in the North Atlantic Ocean. The NW Mediterranean bloom has been studied using remote sensing chlorophyll. Results show an earlier bloom in SeaWiFS (1998– 2003) data compared to historical CZCS (1978–1986) data, interannual variability in the size of the bloom area and correlation between the spatial-temporal extent of the bloom and the amount of nutrients transported to the upper layer during the winter deep water formation process (Bosc et al., 2004; Barale et al., 2008; Volpe et al., 2012).”

The paragraph from page 9094, line 21 to page 9095, line 5 will be shortened as follows:

“ The depth of the mixed layer is commonly related to the onset of blooms according to the “critical depth hypothesis” (Sverdrup, 1953). Since the hypothesis assumes phytoplankton to be homogeneously distributed over the mixed layer, the mixed layer depth regulates phytoplankton mean exposure to light. The bloom develops as soon

as the mixed layer, at the end of winter, shoals and becomes shallower than a critical depth, such that vertically integrated phytoplankton growth wins over phytoplankton losses. According to this theory, the interannual variability in the timing of the bloom would be the result of the interannual variability in the timing of re-stratification. For the Irminger basin (NE Atlantic), Henson et al. (2006) described a preconditioning effect of the winter atmospheric forcing on the bloom timing: a deeper mixed layer would take longer to shoal up to the critical depth, resulting in a later start date for the bloom. ”

The paragraph at page 9095, line 6-17 will be shortened:

“The critical-depth hypothesis has been questioned as a predictor of the onset of the bloom, after growing evidence of blooms taking place in deep mixed layers (Townsend et al., 1992; Eilertsen, 1993; Dale et al., 1999; Koertzinger et al., 2008). Huisman et al. (1999) used a turbulent diffusion model to show that a bloom can develop if turbulent mixing is less than some critical value, regardless of the depth of the mixed layer. Recently, Taylor and Ferrari (2011) related this critical turbulent diffusivity to the atmospheric forcing, showing that when cooling subsides (heat flux is close to zero) turbulent mixing becomes weak, increasing phytoplankton residence time in the euphotic layer and allowing blooms to develop even in the absence of stratification. The authors focused their analysis on thermally driven convection pointing out, however, that their results can be extended to scenarios with turbulence generated by wind forcing and evaporation.”

Referee:

In the last paragraph on page 9100 and the beginning of page 9101, the text refers to wind speed as WS but Table 1 uses WSP. The text and Table should use the same notation.

Answer:

We will change the notation in Table 1 to WS.

Referee:

In the beginning of page 9105, I believe the units for the model estimate of export flux is "mg" and not "g" as stated (40 gC/m2/d). If not the model estimate is over 1000 times higher than observations.

Answer:

We mistyped the units. The actual estimate of the model is 39.897 mg C m-2 d-1 . This will be corrected in the revised manuscript.

REPLY to Referee #2

Referee:

Page 9098, Line 2-3: Briefly describe which specific processes are modified.

Answer:

The sentence at lines 2-5, Page 9098: “Some specific processes are modified with respect to the reference works and some degree of complexity is added by allowing variable C : N ratios in both detritus and dissolved organic matter.” will be substituted by:

“Some degree of complexity is added by allowing variable C:N ratios in both detritus and dissolved organic matter. Bacterial processes are modified from Fasham et al. (1990) by introducing a bacterial stoichiometric sub-model (Anderson,1992) that depends on the variable C:N ratio of labile dissolved organic matter. Also, a temperature dependent limitation is introduced for zooplankton growth following Simonot et al. (1998).”

Referee:

Page 9098, Line 15: ‘bottom depth is higher than’ – do you mean deeper or shallower than 200m?

Answer:

It’s deeper than 200m. This will be corrected.

Referee:

Page 9102: comparison of modelled and Argo MLD. Please provide some statistics to confirm the model reproduces the data, e.g. correlation coefficient.

Answer:

The correlations were significant but weak:

0.33 ($p<0.05$) -2005- 0.23 ($p<0.05$)-2008-

We will change text at page 9102, line 13-15 to:

“The model tends to overestimate the MLD throughout the winter in both years. Argo data and model estimates are significantly, though weakly, correlated in both cases (2005, $r=0.33$, $p<0.05$; 2008, $r=0.23$, $p<0.05$).”

Referee:

Page 9103: similarly, please include some statistics for model vs data chlorophyll

Answer:

The correlation was $r=0.76$ ($p<0.01$). We will include this in the text at page 9103, line 16-17:

“The timing and intensity of the spring bloom is well captured by the model ($r=0.76$, $p<0.01$) although the yearly maximum concentration is systematically underestimated.”

Referee:

Page 9104, Lines 1-5: Would including a criteria for persistence help here? E.g. chl must be higher than the threshold for at least 2 time steps

Answer:

We explored several criteria for the onset of the bloom including a constraint for 2 time steps persistence as suggested by Referee #2. The criteria chosen is the one that gives the most realistic onset timing for both model and MODIS series. With respect to the method of Siegel et al. (2002) we raised the threshold from 5% to 10% above the median in order to avoid false detection of bloom onset with transient increases of surface chlorophyll. For the same reason, we considered as a reference the median value for the period January-May instead of the whole year because, in the second case, this value would be too low given the summer oligotrophic character of the area. The use of a 2 time-step constraint offers a solution in the case of year 2009 but it gives unrealistic results for other years such as 2007 and 2008. In the latter case the onset of the bloom would be set to week 12 which corresponds to just the maximum chlorophyll concentration for the period considered. During years with intermittent discontinuous blooms the median value for the period January-May tends to be higher than in other years. The use of a 2 time step constraint results to be too restrictive in cases where several pulses of chlorophyll are interrupted for just one time step, leading to an oscillation of the mean chlorophyll around the threshold considered.

Referee:

Page 9104, lines 6-17: Would this be better represented graphically? E.g. present a scatter plot of MLD vs EF, HF vs EF, HF vs PP etc.

Answer:

Effectively, a group of four scatter plots would assist the exposition of these results. We plan thus to introduce such a figure in the revised manuscript as Fig. 5 (see Fig. 1 below).

Note that for the second plot (upper right) we calculated the first day that met the chosen criteria for the bloom onset within the week identified as the first week of the

bloom. This is possible for the simulated fields as we saved daily averages but not for the MODIS data because the percentage of valid data decreases drastically when average periods shorter than 8 days are considered. The caption of the new figure reads:

Fig 5. Scatter plots of modeled heat fluxes vs mixed layer depth (upper left), bloom onset date (upper right), primary production (lower left) and export flux (lower right). Each point represents the December through May average for an individual year (2002-2010). The bloom onset date is calculated as the first day that meets the chosen criteria for the bloom onset within the week identified as the first week of the bloom (see Section 3, Data treatment).

Accordingly, Figures from 5 to 9 in the original manuscript will be renumbered from 6 to 10.

We will change the paragraph on Page 9104 (6-15) with the following:

"MLD and HF show evident interannual variability with years characterized by a less severe heat loss having shallower MLD and vice versa (Table 1, Fig 5). Cold years are characterized by a late bloom onset and low mean phytoplankton biomass (PHY) and primary production (PP) with respect to warm years. These magnitudes are significantly correlated with the mean heat flux while the export flux (EF) does not show the same behavior as can be observed in Fig. 5. Higher than average values of EF occur during both warm (i.e. 2008) and cold (i.e. 2006) years as well as for lower than average EF values (i.e. 2007 and 2005)."

Referee:

Page 9104, line 17: what are the percentages quoted here?

Answer:

These percentages represent the relative difference in MLD and HF between the two years mentioned. We will change this sentence to a more clear form:

“The relative differences between the two years in the mean MLD and HF are 57% and 56%, respectively. These two years also show very different bloom dynamics (Fig. 3).”

Referee:

Page 9106, lines 21-24: Can the authors show model results that demonstrate that a marked drop in turbulent diffusion accompanies the start of the bloom? It would make an interesting comparison to a recent paper Taylor and Ferrari (2011), Limnology & Oceanography which looked at bloom timing in comparison to decrease in turbulent diffusion.

Answer:

We did not save the vertical diffusivity in the first place because of storage limitations. We ran again the simulation saving the daily average of the vertical diffusivity and we will include it as Fig. 9 (previously Fig. 8 , see Fig. 2 below).

The caption of the figure reads:

Fig. 9. Detail of heat flux (HF, red), mixed layer depth (MLD, black) and vertical diffusivity (mean 0-75m depth, Kh, blue) from 10 days before up to 10 days after the onset of the bloom (vertical black thin line). The zero heat flux line is also shown for reference (horizontal black thin line).

Consequently we will change the text at page 9106, lines 8-14 to:

“Our results show that a condition of close-to-zero heat flux is indeed a better estimator than the mixed layer depth for the bloom timing (Fig. 9). Also the onset of the bloom is clearly associated to a drop in the vertical diffusivity which depends on the turbulent kinetic energy, as posited by Taylor and Ferrari (2011). Although we do not explicitly calculate the Sverdrup’s critical depth, Fig. 9 shows how the bloom can start when the mixed layer is several hundred meters deep, as long as the heat flux approaches zero and the vertical diffusivity is low. Since the timing of the bloom is independent of the depth of the mixed layer we conclude that there is no preconditioning effect on the

timing of the bloom.”

New references introduced:

Anderson, T. R.: Modelling the influence of food C:N ratio, and respiration on growth and nitrogen excretion in marine zooplankton and bacteria, J. Plankton Res., 14, 1645–1671, doi:10.1093/plankt/14.12.1645, http://plankt.oxfordjournals.org/cgi/content/abstract/14/12/1645, 1992.

Simonot, J., Dollinger, E., and Le Treut, H.: Thermodynamic-Biological-Optical Coupling in the Oceanic Mixed Layer, Journal of Geophysical Research, 93, 8193 – 8202, 1988.

Takahashi, T., Sutherland, S. C., Wanninkhof, R., Sweeney, C., Feely, R. A., Chipman, D. W., Hales, B., Friederich, G., Chavez, F., Sabine, C., Watson, A., Bakker, D. C. E., Schuster, U., Metzl, N., Yoshikawa-Inoue, H., Ishii, M., Midorikawa, T., Nojiri, Y., Koertzinger, A., Steinhoff, T., Hoppema, M., Olafsson, J., Arnarson, T. S., Tilbrook, B., Johannessen, T., Olsen, A., Bellerby, R., Wong, C. S., Delille, B., Bates, N. R., and de Baar, H. J. W.: Climatological mean and decadal change in surface ocean pCO(2), and net sea-air CO2 flux over the global oceans, DEEP-SEA RESEARCH PART II-TOPICAL STUDIES IN OCEANOGRAPHY, 56, 554–577, doi:{10.1016/j.dsr2.2008.12.009}, 2009.

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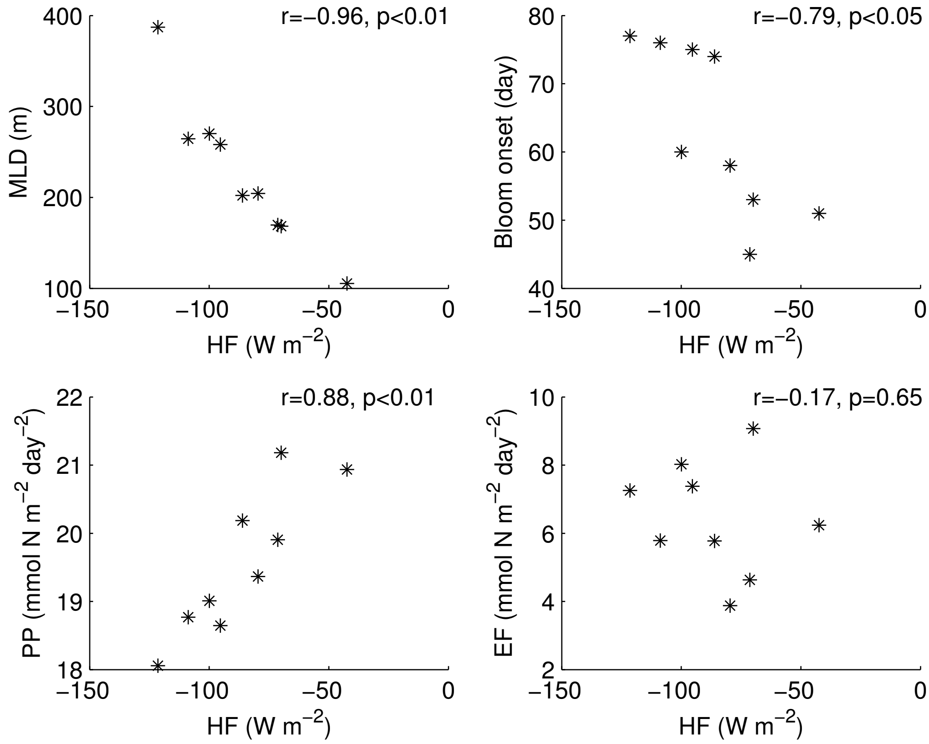
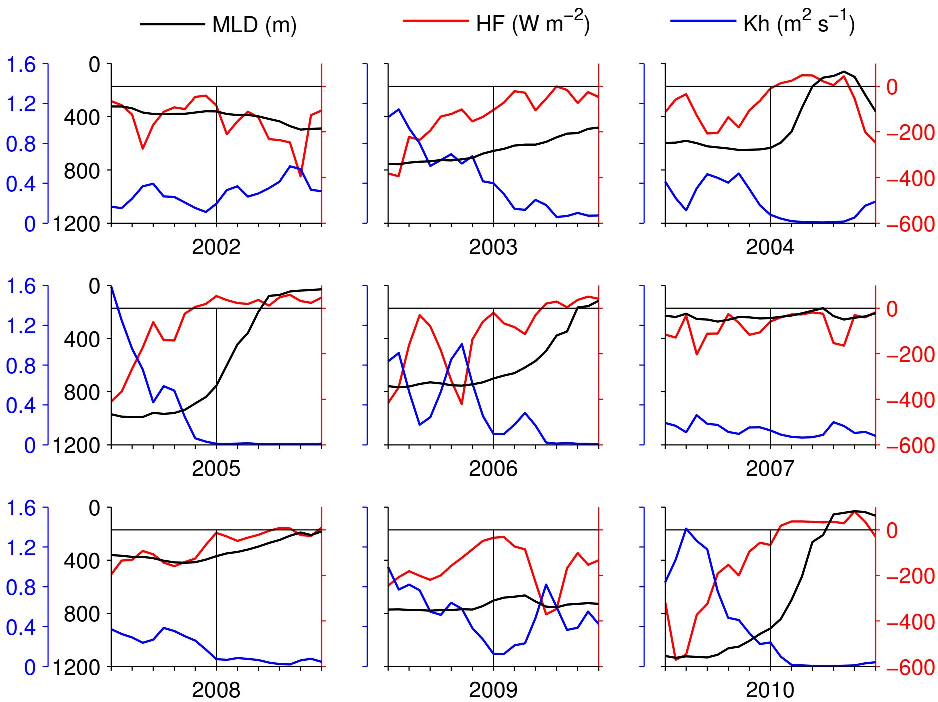


r=−0.96, p<0.01
MLD (m)
HF (W m−2)
r=−0.79, p<0.05
Bloom onset (day)
r=0.88, p<0.01
PP (mmol N m−2 day−2)
r=−0.17, p=0.65
EF (mmol N m−2 day−2)

Fig. 1.



MLD (m)
HF (W m−2)
Kh (m2 s−1)
2002
2003
2004
2005
2006
2007
2008
2009
2010

Fig. 2.