Answer to reviewer 1

Review of "Physical mechanisms for biological carbon uptake during the onset of the spring phytoplankton bloom in the northwestern Mediterranean Sea (BOUSSOLE site)" by Merlivat et al.

This manuscript addresses the question of what mechanisms trigger the start of the spring phytoplankton bloom and associated DIC drawdown in the Northwest Mediterranean Sea. To do this they used a suite of autonomous at sea and satellite data (2016-2019). They argue that reduced wind stress and positive air-sea heat flux leads to stratification and elevated mixing layer irradiance levels, which leads to growth of previously light-limited phytoplankton (nutrients assumed to be replete due to prior deep winter mixing). Whilst I do not believe this is an especially novel finding, a nice ¢dataset is nevertheless brought together. My main recommendation is addition of calculated light data where possible (i.e., calculating and presenting average mixing layer irradiance) – further details provided within the comments below

Calculations, an update of the figure 2 (attached) and a new figure (included) have been made.

Lines 46–55 of the introduction would benefit from supporting references.

We have revised the introduction and add references.

Lines 57–59: I think it would be beneficial here to outline the mechanism by which atmospheric forcing is important for bloom initiation (i.e., by regulation of the mixed/mixing layer depth and thereby light availability).

It is now written: " the timing of the initiation of the surface spring phytoplankton bloom depends in particular on atmospheric forcing. The physical processes of wind stress, heat flux and vertical mixing control the depth of the mixed/mixing layer and thus the availability of light [Siegel et al, 2002, Chiswell, 2011; Taylor and Ferrari, 2011; Brody and Lozier, 2015; Enriquez and Taylor, 2015, Rumyantseva et al, 2019]. "

Lines 60–61: I think the justification for hourly-daily timescale observations should be expanded on a little; for example, bloom initiation might be rapid and the bloom duration transient, therefore stressing why driving factors need to be observed at high frequency

The formation of organic matter from phytoplankton at the surface occurs a few days before the accumulation of phytoplankton biomass integrated at depth, as indicated by the chlorophyll distribution observed in 2016 (Fig. 2e). This is a rapid phenomenon, at a daily scale, caused by the decrease in wind stress and change in sign of the heat flux associated with intermittent mixing and restratification events . For this reason, atmospheric driving factors must be observed at high frequency.

Lines 77–80: I think this sentence needs adjusting – the 'variability' in atmospheric forcing is not the factor leading to deep convection, rather the combination of atmospheric cooling and strong winds?

The sentence has been changed. It is written: « Intense convection resulting from repeated high wind events in winter or early spring when atmospheric temperatures are

low bring nutrients to the surface layer [Andersen and Prieur, 2000; Antoine et al., 2008b; Marty et al., 2002; Pasqueron de Fommervault et al., 2015].”

Lines 143–144: Provide here the mixed layer depth criterion that was used in Holte and Talley (2009)?

The mixed layer depth was estimated using the potential density algorithm.

Line 164: Suggest ‘sunlight-induced fluorescence quenching’ rather than ‘quenching’ alone

This has been modified.

Line 199-200: How did the authors objectively define the ‘onset period of the bloom’?

We define the first day of the onset period when DIC decreases and temperature increases during identified periods of stratification when vertical mixing events are negligible. For these identified periods, biological production and air-sea exchange are the dominant processes responsible for daily changes in DIC (cf the figure below). Similarly, an increase in surface chlorophyll is observed simultaneously with the decrease in DIC and an increase of average mixing layer irradiance.`

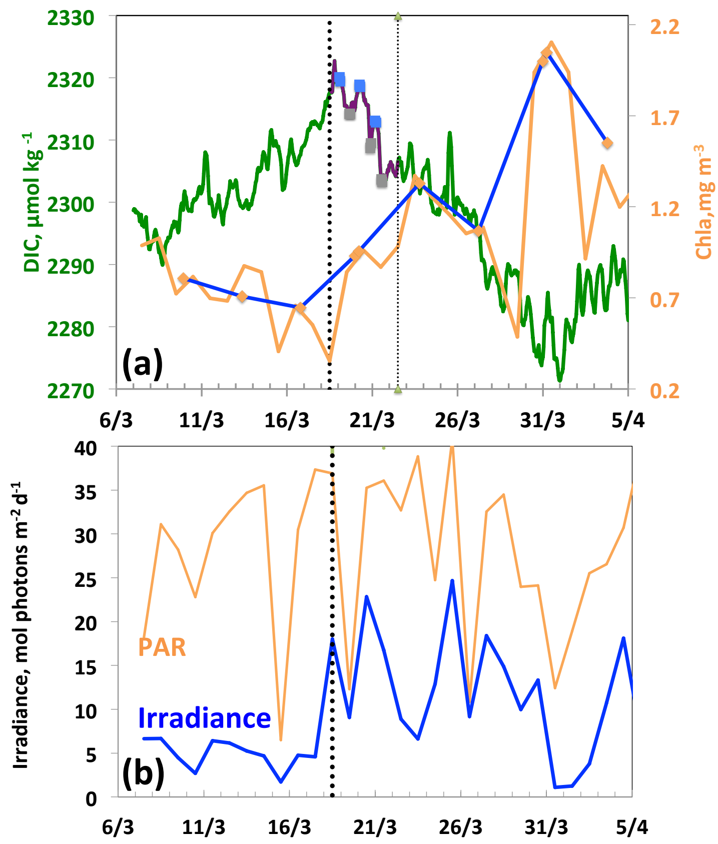


Figure 5. From March 7 to April 5, (a) DIC and Chla. The purple line and the squares (blue,morning; grey, evening) indicate the 3 days biological diurnal DIC changes during the period considered to compute NCP The blue and orange lines indicate the surface Chla when the glider was at a distance of less than 5 km (blue) and less than 20 km (orange) respectively

from the Boussole buoy. (b) PAR and I average mixing layer irradiance. The vertical dotted black line indicates the onset of the bloom on March 18.

Figure 3. Can satellite chlorophyll-a concentration be added to these plots (e.g., 8-day averages

Over the period 2017 to 2019, GlobColour merged Chla products based on satellite observations with a resolution of 25 km, and a binning period of 8 days (http://www.oceancolour.org) were used . As a limited number (~ 7) of measurements are available during the studied period, in panels g, h, i of figure 3, only the depth of the euphotic layer is indicated (the orange line). It is calculated as a function of Chla based on the equation of Morel and Berthon (1989):

Zeu = 34 (Chla) -0.39 (equation 2)

The objective is to compare the euphotic layer depth to the mixing layer depth over the studied period.

The labels are also cut off from panels ‘a’ and ‘g’. Also a ‘red dotted line’ is mentioned in the figure caption, but I cannot see it in the figure? `

The figure has been corrected. The red dotted line indicates the change of sign of the net heat flux from negative to positive values on panels d,e,f. This is now indicated in the figure caption.

Figure 4: I don’t understand panel b: How is the euphotic depth being added on, with an x-axis of wind stress? How does wind stress increase with water depth? Or is the y-axis “Mixed layer depth” or ‘Euphotic depth”? If so, better to add both these labels on, otherwise it is confusing!

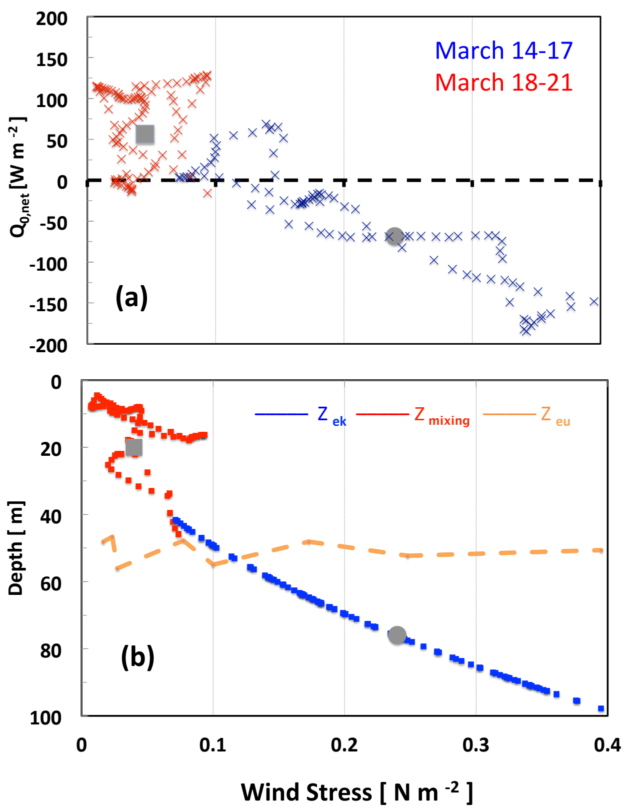


Figure 4. Changes of physical parameters (hourly values) at the onset of the 2016 bloom during 2 consecutive periods of 4 days, March 14-17 (blue) and March 18-21 (red) as a function of wind stress (a) net surface heat flux (b) depths of the Ekman, mixing and euphotic layer. Grey circles and grey squares indicate mean values respectively on March 17 and March 18. For comparison, the orange line shows the euphotic layer depth (March 14-21).

In the caption of figure 4, it is indicated that the blue dots correspond to the period March 14-17 and the red dots to the period March 18-21 respectively. On panel b, blue and red dots represent the mixing layer depth (Ekman depth for $Q_{0net}<0$) over these 2 periods. It is exact that the euphotic depth (purple line) does not depend of the wind stress. The depth of the euphotic layer is shown to illustrate that it varies little throughout the period March 14-21, but is shallower than the mixing layer in the period before the onset of bloom (blue dots) and the opposite thereafter (red dots).

Lines 275–289: Please can the authors calculate the average mixing layer irradiance and show this on Figures 2 and 3? This will be a function of the incident irradiance, the mixing depth, and the diffuse attenuation coefficient (see e.g., Behrenfeld et al. 2005 Section 2.1; Venables and Moore, 2010 Eq. 2). The diffuse attenuation coefficient can be estimated from surface chlorophyll-a concentrations. It is difficult to imagine how average mixed layer irradiance is changing (i.e., if this is increasing as the authors imply) without doing and presenting the results of this calculation. This is also needed to support the final statement in lines 288–289. It is also relevant for how the problem is framed in the abstract.

We have calculated the average mixing layer irradiance, I, which is a function of the incident irradiance, PAR, the mixing layer depth, h, and the diffuse attenuation coefficient, Kd, estimated from surface chlorophyll-a concentrations (Venables and Moore, 2010).

$$K_d = 0.05 + 0.057\ Chla^{0.58}$$

$$I = \frac{PAR}{K_d h}\left(1 - e^{-K_d h}\right)$$

The results are shown in figure 2d of the manuscript (attached). In 2016, the start of the increase in irradiance from March 15 precedes the increase in PAR by 3 days as a result of the decrease of the mixing layer depth observed only after 18 March (see the above figure 5) which will be inserted in the manuscript). For the period between 2017 and 2019, only satellite chlorophyll-a concentrations with a binning period of 8 days were available, which is too large to calculate the average mixing irradiance as it is highly variable on a daily scale.

Concluding remarks section: It would be nice if the authors could use their findings to make a comment on the relative support of the different mechanisms proposed for initiation of the spring boom discussed in the introduction (i.e., from the perspective of surface DIC drawdown, whereas other studies have mostly focussed on chlorophyll).

We want to outline that in our paper we focus on the role of physical drivers to control the start of DIC biological uptake and the concomitant surface phytoplankton growth which develop in shallow weak stratification of the mixed layer that appears once deep-mixing ceases. The increase in surface Chla, precedes by a few days the surface and depth integrated chlorophyll maximum detectable from space by satellites with a binning period of 8 days. This time span does not allow to identify precisely the contribution of atmospheric drivers to trigger the onset of the formation of phytoplankton biomass as it occurs on a daily basis.

References

Behrenfeld, M.J., Boss, E., Siegel, D.A. and Shea, D.M., 2005. Carbon based ocean productivity and phytoplankton physiology from space. Global biogeochemical cycles, 19(1).

Venables, H. and Moore, C.M., 2010. Phytoplankton and light limitation in the Southern Ocean: Learning from high nutrient, high chlorophyll areas. Journal of Geophysical Research: Oceans, 115(C2).

Answer to reviewer E.Boss 1

Reviewer: Emmanuel Boss, UMaine.

This paper focuses on the dynamics of DIC, light and chlorophyll in March and April at two sites in the Ligurian Sea, linking those dynamics to atmospheric forcing and stratification. The measurements from two buoys are also enhanced with measurements with a glider. The claim in the paper is that 'These analysis support the hypothesis that decreases in the depth of active mixing, a result of the transition from buoyancy-driven to wind-driven mixing, control the timing of the spring bloom.'

Since what is considered a bloom is not defined in this paper, it is impossible to judge whether the result support this hypothesis .

The paper is short, clear and of interest to the readers of Biogeosciences. I have, however, several comments, that if addressed will make this paper of much more interest. Since these comments are significant I suggest a major revision is necessary.

1.The concept of a 'bloom' is never defined as is that of the 'onset of the bloom'. The two competing theories you relate two (Sverdrup's and Behrenfeld's) are focused on when the depth integrated phytoplankton biomass starts accumulating. This, I believe, occurs much earlier than at March in the region in question.

It is important to distinguish blooms in surface phytoplankton from blooms in depth-integrated phytoplankton. Much of the support for the existing hypotheses is based on satellite measurements of surface biomass (e.g. Siegel et al., 2002), and often there has been little or no distinction made between blooms in the surface biomass from those in the depth-integrated biomass. Chiswell (Chiswell, 2011) and Behrenfeld (Behrenfeld, 2010), among others, showed that the annual cycles of surface and depth-integrated biomass can be driven by quite different processes and that it is important to distinguish between them.

We agree that we should have been clearer on what a bloom means in the context of this study. We actually do not define the bloom here with respect to phytoplankton biomass, either as a surface concentration or an integrated quantity. We simply consider that the decrease of DIC in the mixed layer, when corrected for possible contributions from air-sea exchange and mixing, is the indication that significant net phytoplankton growth occurs, whatever may happen with the phytoplankton biomass. For instance, a passive accumulation of phytoplankton in the mixed layer caused by physical mechanisms but without significant phytoplankton growth would not have a signature on DIC and would not be considered a bloom here. On the contrary, a strong phytoplankton growth paralleled by a significantly redistribution of biomass in a deepening mixed layer could still be identified by a drawdown in DIC while there would likely be no observable increase in phytoplankton concentration.

In this study, we do not define the bloom in terms of phytoplankton biomass accumulation. We focus on the onset of the decrease of DIC in the mixed layer when biological processes are prevalent. We observe that the DIC decrease is paralleled by an increase of surface and depth- integrated chlorophyll concentration (cf the attached figure and the figure 2 in the manuscript).

2.For surface concentration to accumulate, mixing with phytoplankton deplete waters needs to cease, which requires a change in heat flux. This indeed happens around March-April as described here, though it is not, typically, a smooth process but rather involves passages of storms.

For the 4 years, we observe that the initial decrease of DIC takes place after a storm (figures 2 and 3).

It is also a period of very rapid phytoplankton accumulation as stratification drives higher phytoplankton growth rates. For this to be the bloom initiation, one needs to define the bloom based on accumulation rate of surface concentrations being above a certain threshold.

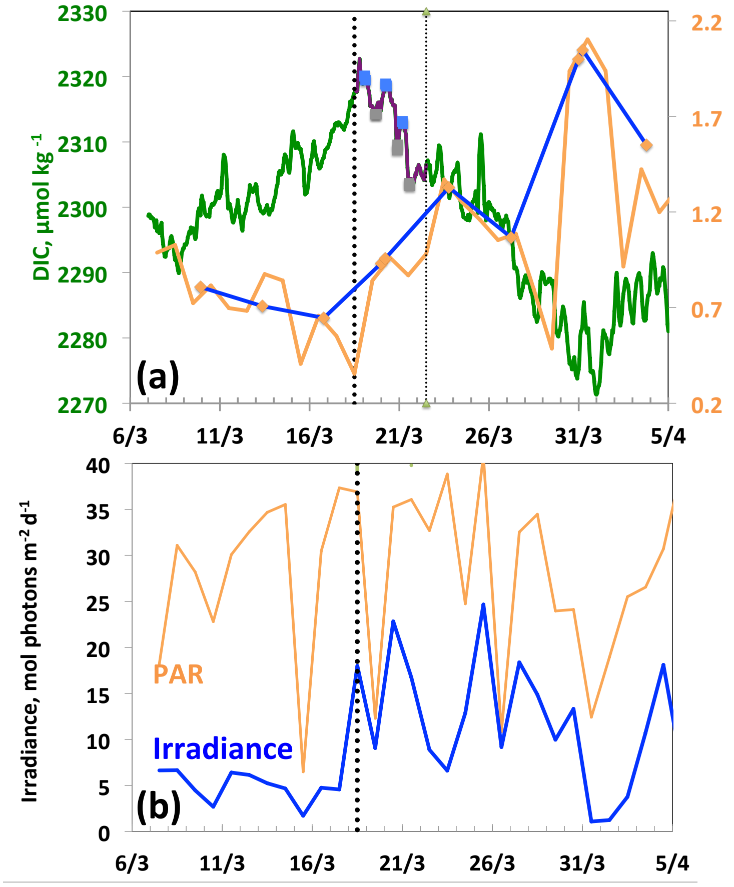
We examine the contribution of atmospheric processes that control the decrease in DIC in the mixed layer as a response to high phytoplankton growth rates. The decrease of surface DIC is simultaneous of surface Chla increase as shown on the figure below. The maximum increase of surface Chla and depth-integrated accumulation occurs 13 days later (cf fig 2e of the manuscript). A similar observation was reported in Pelicherro et al, 2020, fig 3d and S7.

3.In todays ocean DIC dynamics are driven primarily by the solubility pump (which keeps increasing as anthropogenic CO2 is put in the atmosphere) and to a significantly lesser degree by ocean biology. Be good to provide the relative strength of each and hence the sensitivity of the DIC measurements to NPP.

Air-sea exchange of CO_2 at the atmosphere - ocean interface controls the uptake of anthropogenic atmospheric CO_2 by the ocean. The air-sea flux depends on wind speed, gas solubility and the pCO_2 gradient between the atmosphere (pCO_2 air) and seawater (pCO_2 sw) at the ocean surface. The seasonal cycle of pCO_2 sw depends on the SST (4.2% per degree) and on the biological consumption of carbon by photosynthesis (seasonal variability of the DIC). pCO_2 sw normalized at constant temperature is a proxy of DIC. It is therefore important to be able to disentangle the physical and biological factors that control the seasonal cycle of pCO_2 sw in order to constrain the implementation of these factors in models and forecasts of the evolution of anthropogenic carbon uptake by the ocean. Ocean biology plays a significant role in air-sea CO_2 fluxes, because the biological carbon pump or export flux, removes carbon from the surface ocean.

4.The neglect of advective effect is justified on longer time scales rather than short scales (as claimed here) as spatio-temporal scales tend to correlate in the ocean. While ML deepening is often well described as a 1-D process, restratification is most often a 2-3D process driven by horizontal gradients (e.g. papers from the MLML experiment in the N. Atlantic, and many papers trying to use PWP model to study upper ocean dynamics). To convince one that indeed here 1D dynamics control restratification locally, such an exercise needs to be shown (e.g. PWP modeling showing that the density structure is consistent with local forcing only).

We isolated times when local physical processes were largely one dimensional to study changes in biological and chemical parameters that occurred during rapid transitions from deep mixing to intermittent stratification. In 2016, over a four-day period, March 18-21, the diurnal cycle of DIC values characterized by a maximum in the morning followed by a minimum at the end of the day indicates the onset of organic matter formation. On March 18, the decrease in DIC is accompanied by an increase of the concentration of the glider surface Chla and an increase in the average mixing layer irradiance .It is worth to underline that the surface Chla maximum does not occur until March 31, 13 days after the initial decrease in DIC. This maximum is likely to be the one detected by the satellite measurements with a binning period of 8 days.



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5.The abstract ends with ‘We estimate net daily community production in the mixing layer over periods of 3 days between 2016 and 2019 as between 38 mmol C m−2 and 191 mmol C m−2. These results have important implications on the oceanic carbon cycle and biological productivity estimates in the Mediterranean Sea in a scenario of climate-driven changes of the wind regimes.’ – there no discussion of climate-driven changes of the wind regimes or the importance of the specific values reported anywhere else in the paper.

The 2nd sentence has been deleted in the abstract. It is now written: “These results have important implications as biological processes play a major role in the seasonal evolution of surface pCO_2 and thereby the rate of reduction of atmospheric CO_2 by exchange at the air-sea interface.”

Given given the above major issues, I am not providing minor comments (e.g. significant digits in DIC values, etc'). Those could be dealt with in future iterations.

Answer to reviewer E.Boss 2

Reviewer: Emmanuel Boss, UMaine. RC 3

I would like to add that it would be very helpful, as a diagnosis, to see a time series of dDIC/dt and NCP, and, in general, time series spanning a year where possible (or at least from Nov. to May).

In our paper (Merlivat et al, 2018), we report the carbon data measured at the Boussole buoy over the period 2013-2015. We show in figure 2f the annual variation of pCO2@ 13°C which is a proxy for DIC. We observe for the years 2013-2015, that the initial spring decrease in DIC occurs in March-April, which is in agreement with the results for the years 2016-2019.

There have been several paper comparing NCP from chemistry and from optics (e.g. from the NABE and EXPORTS experiments) and it may be useful to compare with those.

We have confined ourselves to comment the NCP values estimated at the nearby Dyfamed station based on oxygen or carbon-14 measurements at time scales of the order of months. In our paper, we want to focus on the role of physical drivers to control the start of DIC biological uptake and the concomitant surface phytoplankton growth which develop in shallow weak stratification of the mixed layer that appears once deep-mixing ceases.

Also, the labels on the left-hand side of Fig. 3 are cut

This has been corrected.