Response to reviewer #1 for the manuscript "On the vertical distribution of the chlorophyll a concentration in the Mediterranean Sea: a basin scale and seasonal approach" by H. Lavigne et al.

We have modified the manuscript according to your suggestions and to those of the three other reviewers. We think that the new manuscript has been accordingly improved.

Although we answer to each referees separately, in the following points we resume the main modifications of the manuscripts (considering all the reviewers comments):

- A better qualification of the limits of the non photochemical quenching correction method in case of stratified water column.
- The consideration of climatological density profiles in the description of [Chl-a] vertical profiles (cf. Fig. 3).
- The quantitative analysis of some characteristics of the standard shape of profiles. A new paragraph (Sect. 3.2.1) and a new table (Table 3) have been introduced. These results are also discussed in the section 4.1.2
- A new table (Table 4), which aims to highlight differences between Mediterranean regions, has been added. The new table allows to better discuss the observed differences between seasonal cycles of [Chl-a] vertical profile in the Mediterranean Sea (Sect. 4.2.1) and the regional differences in DCM depth (Sect. 4.2.2).
- A new figure presenting [Chl-a] vertical profiles as a function of light has also been added. It allows supporting our hypothesis on the impact of light on seasonal variability of the DCM depth.

In the following, we answer to the specific comments of the referee #1:

General Comments

A) First, the authors need to discuss the Chl profiles in relation to the hydrography. The conventional explanation for a DCM is that there is nutrient depletion in the mixed layer, and that summer time production is supported by a flux of nutrients across the pycnocline. At the end of the summer, vertical mixing destroys the DCM, and the water column enters a well-mixed regime. Under such an explanation, Chl should show a DCM coincident with the pycnocline until autumn, when it is eroded by vertical mixing – and maybe lack of light. The authors' figure 3 shows Chl(z) climatology for 4 different regions. All four regions show a summer time DCM and more mixed profiles in winter, but there are substantial differences in the seasonal evolution at the four locations, that are probably explained by the water column density cycles. For example, the northwest region shows a near-classic spring- and autumn-bloom scenario. Starting in winter with deep mixed layers, there is then a near-surface spring bloom, followed by summer DCM, which in turn is followed by an autumn bloom and then the profiles revert back to winter conditions. The DCM emerges in May with the deepest DCM in August of about 50 m, and then a shoaling DCM that is disappears by November. In contrast, the region to the south shows a DCM all year around, even in winter, with deepest DCM >100 m in September.

Presumably these differences are forced by different physics at each location, and they need to address questions such as why do these locations have such different climatology – do the

differences in the annual Chl cycles at each location reflect differences in vertical mixing at each location, leading to differences in mixed layer depth (MLD), etc.
They need to ask how does the Chl structure reflect the background density. For example – is the DCM always found at the pycnocline? re the HSC profiles found during deep mixed layers – or do they reflect stratification in the water colomn. The discussion of Fig. 6 also needs to discuss the water column hydrography – I presume the longitude variation in DCM depth reflects longitude variation in pycnocline depth? Similarly, the discussion of Fig. 7 needs to be done in context of the different hydrography at each location.

Authors response:
We agree with referee that a discussion on the regional differences on the DCM and CHL profiles and on the role played by the hydrological patterns in their shaping was missing in the old version of the manuscript.
Climatological vertical profiles of density have been then added to the figure 3. A new table 4 was also introduced in the new version. The new table includes both hydrological and biogeochemical parameters at regional level.
The text has been accordingly modified to discuss the changed figure and the new table:
In the results section: p12, lines 6 to 28
In the discussion section: page 19, lines 7 to 15, pages 19-20, lines 33 to 12 and pages 21-22, line 20 to 11.

B) The second thing the authors need to do is a comparison of the vertically-integrated Chl (hereafter Ctot) with Surface Chl (hereafter C0). Interestingly, the authors set the reader up for such a comparison (p 4143, line 20) but fail to do so . This is of extreme interest, because C is measured with ocean color satellites (Seawifs Modis) but it is the water column integrated biomass that determines the oceans productivity. Many authors estimate Ctot from C0 using Ctot = MLD times C0 and this relationship goes into estimates of total biomass, net primary production algorithms, etc. This article shows that Chl is rarely homogenous in the mixed layer, and (From Fig. 2), it becomes fairly obvious that the relationship Ctot and C0 is different for each type of profile (DCM, HSC, etc). Thus there will not be a universal easy relationship between Ctot and C0. The plots shown in Fig. 7 (DCMdepth vs C0, DCMdepth vs C(DCM), C(DCM) vs DCM width) describe the structure of the DCM, but are of relatively little interest to the real issues relating to water column production. The authors should perform similar regressions, but comparing Ctot vs C0. The authors should explore when Ctot is correlated with C0, and when it is not - for example they could regress Ctot vs C0 by region and month.

Authors response:
We fully agree with referee #1 that the relationship between Ctot and C0 is of extreme interest. However, we think that our calibration method does not allow us to properly investigate this point, especially at the seasonal scale, as the vertically-integrated chlorophyll-a over 1.5Ze is derived from the satellite surface [Chl-a] observation. Indeed the log-log relationships between the surface [Chl-a] value and the vertically integrated [Chl-a] proposed by Uitz et al., (2006) have been used for calibration (see Lavigne et al., 2012 for

further details). In these conditions, the analysis of Ctot versus C0, as suggested by referee #1 should have little interest.
Nevertheless, we get round this limitation and we analysed, from non-calibrated profiles, the ratio between the vertically-integrated [Chl-a] over the 20 upper meters to the total water column. This ratio with other parameters (MLD, surface [Chl-a], Ze) was calculated for each type of standard shape and is presented on Table 3 and section 3.2.1 (pages 14-15, lines 30 to 5).

Specific comments
Overall, the figures are good, and for the most part the English is good, although it could use a little editing from a native English speaker.

For example, the 6-line sentence on page 4143, lines 4-9 is a struggle to read.
Authors response:
Sentence line 6 has been modified accordingly:
"Indeed, focusing on ocean color observations, D'Ortenzio and Ribera d'Alcalà (2009) confirmed the presence, in the Mediterranean Sea, of surface [Chl-a] annual cycles, displaying similarities with subtropical or with temperate regions. The authors demonstrated that a subtropical-like [Chl-a] seasonality (highest [Chl-a] during winter and lowest during summer) encompasses most of the basin whereas a temperate like seasonality, marked by a high peak of surface [Chl-a] in spring (in March/April), is recurrently observed in the North-Western basin and occasionally in other Mediterranean regions."

Pg 4143 Line 15 - the authors miss some of the most important controls of primary production – mixing due to winds and/or vertical overturn.
Authors response:
The section 1.2 has been restructured and the sentence corresponding to page 4143 line 2 has been modified accordingly:

"As discussed in a recent review by Cullen (2015), there is no unique DCM and its dynamics result from the interactions among external forcing, e.g., the penetration of light in water, the intensity of vertical mixing and subsurface nutrient distribution and biotic processes, e.g., photoacclimation, grazing, phytoplankton composition."

Fig. 3 and elsewhere – the authors need to compute the number of independent profiles – two profiles taken on the same day, for example, are not independent, and only show climatological profiles computed from a significant number of profiles. For example, in Fig. 3 the April climatology derived from one profile for location B is meaningless – and it is misleading to plot it (even though the authors do label it as a mean of one profile).

Authors response:
We agree with the referee that when the number of profiles is low or when profiles are close (in time and/or space) they are not independent, and then that the average profile (as shown for example in figure 3) is not strictly "climatological". We are convinced, however, that, given the low number of profiles during some seasons and for some regions, showing the mean profile could be interesting for Mediterranean scientists. However, to highlight the

problem for the reader, and to prevent any misinterpretation of the figures, we added some text.

Page 11, line 23-26: *"Although, in the following, we refer to these time-series as "climatological", certain average profiles result from a low number of fluorescence profiles (sometimes less than 10, see numbers on Fig. 3) and therefore do not strictly represent a climatological pattern."*

Response to reviewer #2 (G. Dall'Olmo) for the manuscript "On the vertical distribution of the chlorophyll a concentration in the Mediterranean Sea: a basin scale and seasonal approach" by H. Lavigne et al.

We have modified the manuscript according to your suggestions and to those of the three other reviewers. We think that the new manuscript has been accordingly improved.

Although we answer to each referees separately, in the following points we resume the main modifications of the manuscripts (considering all the reviewers comments):

- A better qualification of the limits of the non photochemical quenching correction method in case of stratified water column.
- The consideration of climatological density profiles in the description of [Chl-a] vertical profiles (cf. Fig. 3).
- The quantitative analysis of some characteristics of the standard shape of profiles. A new paragraph (Sect. 3.2.1) and a new table (Table 3) have been introduced. These results are also discussed in the section 4.1.2
- A new table (Table 4), which aims to highlight differences between Mediterranean regions, has been added. The new table allows to better discuss the observed differences between seasonal cycles of [Chl-a] vertical profile in the Mediterranean Sea (Sect. 4.2.1) and the regional differences in DCM depth (Sect. 4.2.2).
- A new figure presenting [Chl-a] vertical profiles as a function of light has also been added. It allows supporting our hypothesis on the impact of light on seasonal variability of the DCM depth.

In the following, we answer to the specific comments of the referee #2:

General Comments

I would have a native English speaker proofread the manuscript, as I found several typos (for some of them I added corrections).

Authors response:
We agree, the manuscript was proofread by an English native speaker.

The manuscript would be stronger if you could provide (in section 1.2) a better justification as to why it is important to understand the dynamics of the vertical distribution of chla.

Authors response:
We agree and restructure the whole section 1.2. In particular, the last paragraph of this section should provide a better justification of why it is important to understand the dynamics of the vertical distribution of Chla.

"As discussed in a recent review by Cullen (2015), there is no unique DCM and its dynamics result from the interactions among external forcing, e.g., the penetration of light in water, the intensity of vertical mixing and subsurface nutrient distribution and biotic processes,

e.g., photoacclimation, grazing, phytoplankton composition. To assess which and how many DCMs exist in the Mediterranean sea because of its known geographical and dynamical gradients, a starting step is to produce a quantitative characterization of their shapes and their seasonal evolution, which is one of the main scope of this contribution. In addition, a good appreciation of seasonal changes in vertical [Chl-a] distribution, the other objective of this study, is a first step towards a better understanding of mechanisms controlling seasonal phytoplankton development. It is also essential to better interpret changes in surface [Chl-a] as detected by satellite sensors. This study will allow for the integration of the biogeographical characterization of the basin built on surface [Chl-a] patterns, thus paving the way to focused area studies based on in situ sampling or autonomous vehicles." page 5, lines 6-18

The analysis is based on fluorescence data corrected for non-photochemical quenching (NPQ) using a previously published method, which is based on extrapolating the maximum fluorescence value in the mixed layer to the surface. I would expect this method to be insufficient to correct for NPQ in most of the Mediterranean Sea, where relatively shallow mixed layers and clear waters would allow NPQ to affect fluorescence profiles much deeper than the mixed layer. I think it would be important to address and discuss this issue.

Authors response:
As also suggested by referee 3 and 4, we further discussed the impact of the limits of the NPQ correction method in case of stratified water column.

To assess this impact, two analyses were carried out.

1- From calibrated [Chl-a] profiles (1998-2014 database) we compared the surface satellite [Chl-a] estimations with the surface [Chl-a] concentrations derived from calibrated fluorescence profiles. Our results showed that surface [Chl-a] can be underestimated for profiles with MLD lower than 50m. In the worst cases (MLD around 10m), the underestimation is of a factor 2.5.

2- From the climatological [Chl-a] profiles displayed on Fig. 3, we calculated profiles of instantaneous PAR, using the monthly MODIS climatology for the instantaneous PAR at profiles geographical position. The equation of Sackmann et al., (2008) has been then applied to estimate the relative error, which could be introduced by NPQ. Results showed that for depths deeper than 60m, the error on [Chla] is always lower than 10%. In the worst cases (surface in summer), this error is up to 60% (equivalent to an underestimation of a factor 2.5).

We are convinced that the above results provide an estimation of the limits of NPQ correction method that we proposed in the manuscript. This estimation proves also that the NPQ correction has only a minor impact on our results and their interpretation. For most of the "DCM" profiles, the surface [Chl-a] are enough low that doubling or tripling their values does not induce any substantial variation of the vertical shape.

Our main concern is for the estimation of F_{surf}/F_T ratio (surface Chl-a content to total Chl-a content, see Table 3 in the new version of the manuscript) for the profiles of the "DCM" category. We estimated a value of 6% and we are now convinced that this value is underestimated (a more realistic value is probably 12-15%), although the interpretation that we gave is not substantially changed.
We thank the referee for this highlight and we added, in the new version of the paper, the following paragraph to explain the new analysis and to advise the reader:

"By applying the equation proposed by Sackmann et al. (2008) on monthly averaged light fields, the impact of NPQ was observed to be significant only above 60m, thus leading a two-fold underestimation of surface [Chl-a]. Considering this result, the weak efficiency of the NPQ correction method in stratified conditions should not have major consequences on the present study. Only the analysis of the surface to integrated content chlorophyll ratio (see Table 3) should be considered with caution." Page 9 lines 5-11.

I would restructure the Conclusion section so that it summarizes the most important findings. As it stands now, it seems like a continuation of the Discussion

Authors response:
We thank the reviewer for this suggestion and modified the conclusion in order to better sum-up main [Chl-a] patterns in the Mediterranean Sea.
In particular, the following paragraph was introduced:

"The present analysis, in agreement with previous satellite results (D'Ortenzio and *Ribera d'Alcalà, 2009), demonstrates the coexistence of two main types of dynamics (i.e. subtropical and mid-latitude dynamics) in the Mediterranean Sea. Mid-latitude dynamics are observed in the North-Western basin. Their main specificity is the high occurrence of "HSC" profiles in March and April, whereas this type of shape, associated to bloom conditions, is nearly absent elsewhere during this season. The subtropical dynamics encompass most of the remaining basin. It is characterized by an omnipresent DCM from spring to autumn and by a large variety of [Chl-a] vertical shapes during winter. The present analysis also demonstrated that the [Chl-a] pattern in the Mediterranean Sea is not uniform. Even among regions with subtropical dynamics, a strong variability was observed in [Chl-a] values or DCM characteristics. At the basin scale, this variability follows an eastward oligotrophic pattern."* Page23, lines 3-14.

I have also added some minor comments to the original text: see attached pdf file.
We thanks the referee #2 for all of his comments and corrections. Most of the time we change text accordingly.

Response to reviewer #3 for the manuscript "On the vertical distribution of the chlorophyll a concentration in the Mediterranean Sea: a basin scale and seasonal approach" by H. Lavigne et al.

We have modified the manuscript according to your suggestions and to those of the three other reviewers. We think that the new manuscript has been accordingly improved.

Although we answer to each referees separately, in the following points we resume the main modifications of the manuscript (considering all the reviewers comments):

- A better qualification of the limits of the non photochemical quenching correction method in case of stratified water column.
- The consideration of climatological density profiles in the description of [Chl-a] vertical profiles (cf. Fig. 3).
- The quantitative analysis of some characteristics of the standard shape of profiles. A new paragraph (Sect. 3.2.1) and a new table (Table 3) have been introduced. These results are also discussed in the section 4.1.2
- A new table (Table 4), which aims to highlight differences between Mediterranean regions, has been added. The new table allows to better discuss the observed differences between seasonal cycles of [Chl-a] vertical profile in the Mediterranean Sea (Sect. 4.2.1) and the regional differences in DCM depth (Sect. 4.2.2).
- A new figure presenting [Chl-a] vertical profiles as a function of light has also been added. It allows supporting our hypothesis on the impact of light on seasonal variability of the DCM depth.

In the following, we answer to the specific comments of the referee #3:

General Comments

Editing of English would be useful for clearer understanding. I strongly suggest this.

Authors response:
We agree, the new version of the manuscript was proofread by a native English speaker.

It might be useful to be more explicit about what this study seeks to achieve and what it contributes to future work. You have painstakingly calibrated a database, built vertical climatologies and shown really interesting variations of vertical [Chl-a]. As I understand it, one key outcome is that regional and seasonal variations in DCM depth are potentially light-driven. This is discussed within the context of previous work, but not strictly assessed beyond what is shown in Figure 9(a). It may help to clarify in the introduction that turbulence, nutrients and grazing may contribute to vertical dynamics, but will not be assessed in this paper. Further, to state that the work done here is important for future studies addressing the more specific physical, chemical and biological questions.

Authors response:

We agree with the referee comment statement. Section 1.2 was restructured in the new version. In particular, the following text was added page 7 lines 5 to 9.

"The scope of this paper is essentially restrained to the description of the variability of [Chl-a] vertical profiles, as they result from the interactions between many factors that can be complex as well as poorly documented. This variability will be only discussed with regard to Mediterranean hydrology and light fields."

As suggested, the following sentence was also added to conclusion:
"Although it is a first and necessary step for a better understanding of processes which impact seasonal variability of [Chl-a] vertical profiles, it would be interesting to further study certain particular cases showing, with a high frequency, annual series of vertical [Chl-a] profiles." (page 23, line 20-23)

Specific comments

Introduction: Figure (1) might benefit from the addition of seasonal subplots showing (a) winter and (b) summer surface Chl-a. Otherwise, maybe summarise section 1.1 into one explanatory paragraph (to give section 4.2.1 context) and focus more on the vertical story.

Authors response:
We agree with this comment and add two subplot in the Fig. 1 to display average surface [Chl-a] in summer and winter.

PG 4142, line 14: As you are including all seasons and all regions, perhaps 'oligotrophic' is a more robust description of the entire basin.

Authors response:
We agree "ultra-oligotrophic" has been changed to "oligotrophic".

PG 4144, line 3: I'm a little uncertain about this. Firstly, Mignot et al. (2014) attribute DCM patterns in the Mediterranean to a combination of photoadaption and biomass, and Macias et al. (2014) base their DCM on model data (which you later show does not agree with in situ data in the eastern basin). While some (or even most) of these DCM may be due to biomass maxima at depth, their contributions to vertically integrated primary production may also not necessarily be limited to this distinction. DCM generated by photoacclimation (Chl-a packaging) are not to be discounted. For this reason, I'd be cautious about how explicitly you link high primary production to biomass-DCM. However, biomass-DCM are important for structuring food webs, so this is interesting from that perspective and leads me to my next comment.

Authors response:
As mentioned above, the section 1.2 was fully modified. In the new version, DCM dynamic is discussed within the following text:
"As discussed in a recent review by Cullen (2015), there is no unique DCM and its dynamics result from the interactions among external forcing, e.g., the penetration of light in water, the intensity of vertical mixing and subsurface nutrient distribution and biotic processes, e.g., photoacclimation, grazing, phytoplankton composition. To assess which and how many

DCMs exist in the Mediterranean sea because of its known geographical and dynamical gradients, a starting step is to produce a quantitative characterization of their shapes and their seasonal evolution, which is one of the main scope of this contribution." Page 5, lines 6-12.

PG 4145, 23: The variability of fluorescence to [Chl-a] is indeed compounded by environmental conditions, as well as taxonomy. It is good that you have mentioned this; however, you should say more especially IF you want to maintain the previous assumption about these DCM being deep biomass features. Although the fluorescence to [Chl-a] ratio can be affected by packaging (as you say), the Chl:C (cell) relationship is profoundly altered. This may simply have been lost in translation, but the links between fluorescence, [Chl] and biomass need to be carefully described.

Authors response:
We agree with the referee that the complex relationships between fluorescence, [Chl] and biomass are critical and still not fully understood. Any passage from fluorescence to chlorophyll and from chlorophyll to biomass is submitted to hypothesis that could be different following regions, time and environmental conditions (including species composition).
In the present manuscript we deliberately decided to address the [Chl-a] variability in a specific oceanic region, the Mediterranean Sea. Consequently, we discussed more the assumptions relating fluorescence to chlorophyll (because fluorescence is our primary source of data) than those relating chlorophyll to biomass. Moreover, at basin scale and in a climatological approach, we lack most of the data allowing to estimate the autotrophic organic carbon content. We then decided to restrain the scope of our analysis to the [Chl-a] and not to deal with the phytoplankton carbon variability.

Data processing and Calibration:

PG 4148, line 27: With regards to your quenching correction procedure, I have a few suggestions:

(a) You will need to look at surface values (5-10m) of fluorescence measured during the day (potentially quenched), compared with surface fluorescence measured at night (not quenched). I would suggest doing this for each region and each season separately. If there's no measurable difference between day and night surface fluorescence, you may very well have support for your DCM being mostly deep biomass features. However, if you do see suppression of fluorescence yield in surface waters during daylight hours, then you cannot do as Mignot et al. (2014) did and effectively ignore quenching. The bad news is that if your MLDs are shallow and the water column is stratified, you may not be able to correct quenching.

Authors response:
We acknowledge you for your suggestion. However, given the large diversity of sources for [Chl-a] vertical profiles, we were sometime poorly confident in the time data (when available) of fluorescence profiles. Thus, the analysis you suggested was impossible to carry out. However, to better assess the impact of NPQ in case of stratified water column. We performed the following analyses:

3- From calibrated [Chl-a] profiles (1998-2014 database) we compared the surface satellite [Chl-a] estimations with the surface [Chl-a] concentrations derived from calibrated fluorescence profiles. Our results showed that surface [Chl-a] can be underestimated for profiles with MLD lower than 50m. In the worst cases (MLD around 10m), the underestimation is of a factor 2.5.

4- From the climatological [Chl-a] profiles displayed on Fig. 3, we calculated profiles of instantaneous PAR, using the monthly MODIS climatology for the instantaneous PAR at profiles geographical position. The equation of Sackmann et al., (2008) has been then applied to estimate the relative error, which could be introduced by NPQ. Results showed that for depths deeper than 60m, the error on [Chla] is always lower than 10%. In the worst cases (surface in summer), this error is up to 60% (equivalent to an underestimation of a factor 2.5).

We are convinced that the above results provide an estimation of the limits of NPQ correction method that we proposed in the manuscript. This estimation proves also that the NPQ correction has only a minor impact on our results and their interpretation. For most of the "DCM" profiles, the surface [Chl-a] are enough low that doubling or tripling their values does not induce any substantial variation of the vertical shape.
Our main concern is for the estimation of F_{surf}/F_T ratio (surface Chl-a content to total Chl-a content, see Table 3 in the new version of the manuscript) for the profiles of the "DCM" category. We estimated a value of 6% and we are now convinced that this value is underestimated (a more realistic value is probably 12-15%), although the interpretation that we gave is not substantially changed.
We thank the referee for this highlight and we added, in the new version of the paper, the following paragraph to explain the new analysis and to advise the reader:

"By applying the equation proposed by Sackmann et al. (2008) on monthly averaged light fields, the impact of NPQ was observed to be significant only above 60m, thus leading a two-fold underestimation of surface [Chl-a]. Considering this result, the weak efficiency of the NPQ correction method in stratified conditions should not have major consequences on the present study. Only the analysis of the surface to integrated content chlorophyll ratio (see Table 3) should be considered with caution." Page 9 lines 5-11.

(b) You do acknowledge the limitations of the correction method of Xing et al. (2012) but you do not mention the proportion of your data that is stratified. If it's a small proportion, it might be better to discard your quenched plus stratified profiles.

Authors response:
We agree with the referee, although stratified profiles represent more than 50% of our dataset and then we cannot discard them. However, as explained in the previous point, in the new version of the manuscript, we provide an estimation of the error induced by the NPQ method.

(c) In winter and spring, the deep MLD and potentially high turbulence appears sufficient to generate more homogenous mixing. Having said that, it might not be accurate to assume homogeneity. When the MLD is deep, consider correcting from Zeu rather than the depth of the mixing layer (Biermann et al., 2015). This may help conserve heterogeneous features between the 1% light level and MLD. I strongly suggest this step because of the presence of winter subsurface maxima in the MEDATLAS and sometimes fluorescence-based climatology (Fig.8 and Fig. 3C). These features may not be artefacts as you suggest, and there is a risk of masking them when correcting from MLD.

Authors response:

We thank the referee for this suggestion, which should have generated a bias in our results. In the generation of a climatology, however, we are convinced that a unique data processing method is preferable as the averaging of profiles treated in different ways could introduce artifactual bias. We maintained then the Xing et al. (2012) method for the processing of all Chl profiles.

However, to check the referee point we carried out an additional analysis of our data set. For profiles with an available estimation of Zeu (satellite matchup) and satisfying the condition : Zeu < MLD, we observed that the extrapolation depth (for the NPQ correction) is shallower than Zeu for 82% of profiles. A visual control performed on the remaining 18% of profiles, does not showed subsurface maxima between Zeu and MLD. The use of Zeu and the method of Biermann et al. 2015, although certainly more corrected from theoretical point of view, doesn't improve substantially the analysis of our data.

To advise the reader about the referee concern, we added some text in the new version of the manuscript.

"Although Biermann et al. (2014) proposed an improvement of the method for profiles with euphotic depth above MLD, we preferred to use a unique data processing procedure, to avoid the introduction of an artificial bias due to a heterogenic data treatment." Pages 8-9, lines 30-1

PG 4149, line 10: Please explain why you remove profiles where MLD is "deepest (deeper?) than the deepest fluorescence observation"? I see these make up a tiny part of your dataset, but why is this step required? MLD should have no impact on removing instrumental offset, but it appears this is part of that process?

Authors response:

As explained in the text, the step 2 consists in removing instrumental offset in order that fluorescence value is 0 when there is no chlorophyll (i.e. at depth). To determine this offset, we should focus on regions of the profile where we can expect an absence of chlorophyll. We can expect an absence of chlorophyll for deep depths where there is no light and where mixing does not entrain surface phytoplankton cells. If MLD is deeper than the deepest observation depth (as for example during deep convection events as observed in the North Western Mediterranean area), it is impossible to estimate the offset coefficient (beta). In these cases, profiles are not removed but the coefficient beta is set to 0.

Text was slightly modified:

"Profiles in which MLD was deeper than the deepest fluorescence observation were not processed but not remove of the database (1.1% of data set)." Page 9, lines 16-18

In the text "deepest" has been changed to "deeper", thank you for having identified this mistake.

PG 4149, line 27 Please explain why you impose that integrated fluorescence content (surface to 1.5Zeu) should match surface Chl-a measured by satellite? I may simply have missed something obvious, but this makes no sense to me. For one, you're measuring over all seasons and the depth of the 1% light level will change enormously between summer and winter. Furthermore, shouldn't surface values be imposed on surface values? Would it not be more useful to impose this match-up from one optical depth, thus integrate from 1/kd(490)?

Authors response:

We agree with the referee that this paragraph was not totally clear.

In the sentence "*A multiplicative coefficient (α coefficient in Eq. (1)) is applied to the fluorescence profile, imposing that the integrated fluorescence content matches the value derived from satellite*", the term "value" refers to the integrated chlorophyll content over $1.5Z_e$ estimated from satellite [Chl-a] using empirical relationships (Uitz et al., 2006) which is mentioned just above and not to the surface [Chl-a] value.

To avoid any confusion, the sentence was modified accordingly:

"*A multiplicative coefficient (α coefficient in Eq. (1)) is applied to the fluorescence profile, imposing that the integrated fluorescence content matches the integrated chlorophyll content derived from satellite*". (pages9-10, lines 32-1)

Discussion:

PG 4160, line 15. I am inclined to agree that the depth of the DCM is driven by light. Longitudinally: Higher surface [Chl-a] in the western basin would cause high light attenuation (self-shading) and shallower DCM. The opposite is true in the eastern sector with very low surface [Chl-a], deeper light penetration and, thus, deeper DCM (discussed for Southern Ocean waters in Holm-Hansen et al, 2005). Anonymous Ref#1 suggests the depth of the pynocline contributes. Either way, I think this is a key point! This part of the discussion should be clarified and Figure 9(a) given more prominence. It's a really interesting part of both the seasonal and basin-scale story. It's also globally relevant in that DCM in the Mediterranean and DCM in other oceans appear to be driven/controlled by similar processes (Fig. 9(a)).

Authors response:

As also suggested by referee #1, we provided in the new version of the manuscript a discussion on the potential environmental causes of [Chl-a] and DCM regional variability. This discussion is supported by the Table 4 (new version of the manuscript). As indicated in the text, for regions were winter mixing hardly reach DCM and nitracline, the eastward deepening of the DCM would be mainly explained by the eastward increase in oligotrophy characterized by lower nutrient concentrations and a deeper nitracline.

These aspects are further discussed in the text page 21 line 20 to page 22 line 11.

Response to reviewer #4 for the manuscript "On the vertical distribution of the chlorophyll a concentration in the Mediterranean Sea: a basin scale and seasonal approach" by H. Lavigne et al.

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Although we answer to each referees separately, in the following points we resume the main modifications of the manuscript (considering all the reviewers comments):

- A better qualification of the limits of the non photochemical quenching correction method in case of stratified water column.
- The consideration of climatological density profiles in the description of [Chl-a] vertical profiles (cf. Fig. 3).
- The quantitative analysis of some characteristics of the standard shape of profiles. A new paragraph (Sect. 3.2.1) and a new table (Table 3) have been introduced. These results are also discussed in the section 4.1.2
- A new table (Table 4), which aims to highlight differences between Mediterranean regions, has been added. The new table allows to better discuss the observed differences between seasonal cycles of [Chl-a] vertical profile in the Mediterranean Sea (Sect. 4.2.1) and the regional differences in DCM depth (Sect. 4.2.2).
- A new figure presenting [Chl-a] vertical profiles as a function of light has also been added. It allows supporting our hypothesis on the impact of light on seasonal variability of the DCM depth.

In the following, we answer to the specific comments of the referee #4:

General Comments

Although the paper is interesting and provides a nice description of the chlorophyll profiles in the Mediterranean sea, someone who has studied general oceanographic textbooks and looked at the MEDATLAS will not be surprised by the results and may not even find much new, except for a finer description of some aspects. I thus feel there is a bit of a lost opportunity in this paper to explain the profile types as a function of such things as temperature gradient (perhaps linking to sea surface temperature and time of year) or other physical characteristics of the water column. Could the authors have used their dataset to provide predictive relationships for the shapes? Why haven't the authors used the accompanying physical datasets?

Authors response:
Mediterranean Sea is a region of great interest for scientists, being the subject of numerous publications. However, the understanding of the spatio-temporal variability of the [Chl-a], one of the most common biogeochemical variable, is very limited and that is why we thought it was important to improve it and to refine some aspects of its variability.
Nevertheless, as also suggested by referees #1 and #3, in the new version of the manuscript, some elements describing the hydrological and biogeochemical context are introduced (i.e. Table 4 and density profiles in Fig. 3). These elements allow to support the discussion on the regional differences although they do not allow us to definitively explain them.

Specific comments

Section 4.1.1. : This section appears a bit weak to me, the authors seems to suggests that the difference between their dataset and the MEDATLAS dataset are only cause by limitations of the MEDATLAS dataset (bad averaging and sparse vertical resolution). While it may be true, that their dataset is the new standard,

it is certainly not shown in this analysis. A particularly interesting difference is found in the Levantine Basin where the MEDATLAS data always shows increasing chlorophyll concentration to the surface while this is not seen in the chlorophyll profiles, it seems like bad averaging would be an unlikely explanation for this systematic difference; there is here a good opportunity to show which dataset represents the trends best. Perhaps the authors need to go back to measured profiles of HPLC (or extracted Chl) to examine which of the two dataset is right.

Authors response:

As referee suggested, we examined MEDATLAS data to understand why there are [Chl-a] increases in surface in the Levantine Sea in the MEDATLAS climatology. First, we observe that for most of seasons there is no [Chl-a] observation close to the studied point (i.e. the Levantine Sea).

http://modb.oce.ulg.ac.be/backup/medar/JPGSTATIONS/medar.winter.med.cphl.20.3.0.stations.jpg

http://modb.oce.ulg.ac.be/backup/medar/JPGSTATIONS/medar.summer.med.cphl.20.3.0.stations.jpg

http://modb.oce.ulg.ac.be/backup/medar/JPGSTATIONS/medar.fall.med.cphl.20.3.0.stations.jpg

The large scale interpolation process (Variational Inverse Model see http://modb.oce.ulg.ac.be/backup/medar/contribution.html for details) produced then a gradient in the Levantine Sea, between the very low value of the Cretan Sea (e.g. ~0.07 mg/m3 for summer) and higher values (e.g. ~0.15 mg/m3, for summer) measured along the Lebanon coast.

http://modb.oce.ulg.ac.be/backup/medar/JPG/medar.summer.med.cphl.23.3.0.jpg

However, the incertitude about this estimation is very high in the Levantine basin (~0.1 mg/m3 for summer http://modb.oce.ulg.ac.be/backup/medar/JPG/medar.summer.med.cphl.23.3.0.error.jpg)

We think that this process may be also responsible of the [Chl-a] surface increase observed in summer in the North-West and South-West region. Indeed, the MEDATLAS database contains coastal observations in the North-Western and South-Western basins but not in the Ionian Sea.

As you suggested we better deal with this matter in the text. In the new version of the manuscript the following paragraph has been introduced:

"*Another particular feature of the MEDATLAS climatology that does not show in the fluorescence-based climatology are the rises in summer and autumn surface [Chl-a] above DCM (Fig. 8, panels A, B and D). We suggest that this feature could result from the* *propagation by interpolation of the high surface [Chl-a] observed on coastal regions (see also Bosc et al., 2004). In addition, considering the geographical positions of the available MEDAR observations, in almost all the studied sub-basin (except Ionian) coastal observations are included in the database. They might therefore be responsible for the observed difference with the fluorescence-based climatology."* Page 17 lines 4-11.

Please, note that Fig. 8 panel D (for Levantine) is slightly changed due to the displacement westward of the studied point (now 34°N, 30°E, see Fig. 1). We wanted to avoid the influence of the Cyprus gyre.

Figure 6 (and accompagnying text): A variation with longitude is not particularly explanatory. You will find this if you go longitudinally across any oceanic gyres. Clearly the factors driving these relationships are more important. I'm surprised that no attempts are made to calculate the light level at the DCM. It could be as simple as using the latest Morel KPAR relationship; I'm sure the authors know where to find it! The
thermocline depth could also be plotted in some way.

Authors response:
As also requested by referee #1, the deepening of DCM with longitude is further discussed in the new version of the manuscript. The discussion is based on Table 4 which gives for each region of the Mediterranean Sea: mean winter MLD, mean DCM depth, average daily PAR at DCM and which provides an estimation of the nitracline depth. The following paragraph has been introduced to discuss Table 4 and the longitudinal gradient in DCM.

"At the first order, the DCM depth variability in the Mediterranean Sea is related to the spatial component and, in particular, longitude. The deepening of the DCM along a longitudinal gradient (in the present study, DCM deepens by 1.6m per 1 degree of longitude east) agrees with the previous review, also based on observations, by Crise et al. (1999). This general deepening of the DCM with longitude covaries with the eastward increase of oligotrophy in the Mediterranean Sea (Béthoux et al., 1998). This pattern is generally attributed to anti-estuarine circulations in the Straits of Gibraltar and Sicily, which generate an eastward inflow of surface nutrient depleted waters and a westward outflow of deep nutrient rich waters. In the Eastern Mediterranean Sea, oligotrophy is also maintained by poor nutrient inputs from the boundaries (atmosphere and coasts) and by the formation of Levantine Intermediate Water, which is not the product of deep convection but of the subduction of surface water into intermediate water layers (Robinson and Golnaraghi). As revealed by Table 4, regional changes in DCM depth, nitracline depth and averaged daily PAR at DCM are correlated in the Mediterranean Sea. The eastward deepening of the DCM depth and of the nitracline depth is accompanied by a decrease in the mean daily averaged PAR at DCM (values ranging from 1 mol quanta m-2 day-1 in the North-West Mediterranean to 0.16 mol quanta m-2 day-1 in the Levantine Sea). This trend concurs with the "general rule" that states that the DCM builds-up where there is an optimal balance between the upward nutrient flux and the downward photon flux and lies on top of the nutricline (Cullen, 2015). The large distance between DCM depth and nitracline depth in the Ionian (36m) and the Levantine (83m) basins may be considered as contradictory with the previous theory. However, according to Table 4, the estimations of nitracline depths are not

likely to be good estimators of the top of the nitracline, if the nitrate gradient is not a enough sharp feature, as is it the case, for example in the Eastern Mediterranean Sea. Indeed, nitracline depths have been computed from discrete vertical profiles, using the 1µM isoline (Lavigne et al., 2013)." Page 21-22, lines 20-11

In addition, a figure 10 was introduced to support the "light driven" hypothesis for the seasonal variation of the DCM depth. The following text was also added:

"Results from Fig. 10 also show that a seasonal component contributes to explain DCM variability in the Mediterranean regions. The observed seasonal pattern of the DCM depth (i.e. deepening from spring to summer and shallowing from summer to autumn) is consistent with previous model results (Macias et al., 2014), and with individual Bio-Argo float observations (Mignot et al., 2014). Letelier et al. (2004) and Mignot et al. (2014) explain this seasonal pattern by considering that the DCM depth might be driven by the light availability and that it would follow the depth of an isolume. This observation is confirmed here by the analysis of the vertical [Chl-a] profile as a function of irradiance for the spring, summer and autumn periods (Fig. 10). For all regions, from spring to summer, PAR at DCM depth remains unchanged although [Chl-a] decreases. Accordingly to Letelier et al. (2004), higher spring [Chl-a] may be explained by the temporal erosion of the upper nitracline from spring to summer, supporting the hypothesis of deep biomass maxima. From summer to autumn, the magnitude of DCMs remains roughly unchanged, similarly to the PAR at DCM." page 22, lines 12-24.

Figure 7: Why so much white space. The Y-axis extends to more than 200 m while there is no data below 125 m.

Authors response:
We thank referee for this comment. The Figure 7 has been changed accordingly.

Figure 8: I'm not sure why a comparison with the Uitz et al. 2006 profiles is not made. I understand that those are used to set the amplitude of the profiles, but surely they would be informative as a comparison of the shapes.

Authors response:
The application of Uitz et al., (2006) method on a case by case basis or even regional one is not recommended (Uitz et al., 2006). In addition, the Uitz et al. (2006) method has been developed to compute primary production from ocean color observations and not to provide patterns of the [Chl-a] vertical distribution. For these reasons, we think it is not relevant to compare our profiles with profiles derived from the Uitz et al., (2006) algorithm.

Figure 9: This figure has multiple problems. First, I do not understand why the paper ends by presenting this figure. It is not, to me, particularly insightful or providing an interesting opening for things to come. Second, the caption is very hard to follow, especially the first section explaining the different panels. Finally, the fits just do not seem to match the data in panels B and C. In B, residuals are clearly positive at low [Chl-a]DCM and negative at high [Chl-a]DCM. Something similar appears to happen in panel C probably driven by a few low

values at low dz. Perhaps looking at a running average may confirm whether or not my eye is right. Of course any discussion (i.e. text) linked to the apparently bad fits may not provide much insights.

Authors response:
We agree that figure 9 is maybe not relevant and too much complex for the end of the discussion. So, we decided to only maintain panel A which displays the most relevant relationship (relationship between surface chlorophyll and DCM depth).

The figure 9 was then modified and the associated text was replaced by:

"*The present study also shows that in the Mediterranean Sea, the specific features of the [Chl-a] profiles with a "DCM" shape have a large variability, comparable to those observed in the Global ocean, although occurring on shorter spatial scales. The most relevant indicator is certainly the DCM depth, which was observed to range between 30m and more than 150m. As expected (e.g. Cullen, 2015), the depth of the Mediterranean DCM is inversely related to the surface [Ch-a] (Fig. 9). In addition, the relationship between the DCM depth and surface [Chl-a] (blue curve on Fig. 9) is similar to the relationship reported for the Global ocean (red curve on Fig. 9, Mignot et al., 2011). This observation suggests that certain DCM properties in the Mediterranean Sea conform to the same generic properties established for the Global Ocean.*" page 21, lines 11 to 19

On the vertical distribution of the chlorophyll-a concentration in the Mediterranean Sea: a basin scale and seasonal approach

H. Lavigne[1], F. D'Ortenzio[2,3], M. Ribera D'Alcalà[4], H. Claustre[2,3], R. Sauzède[2,3] and M. Gacic[1]

[1]{Istituto Nazionale di Oceanografia e di Geofisica Sperimentale – OGS, Dip. di Oceanografia, Borgo Grotta Gigante 42/c, 34010 Sgonico (Trieste), Italy}

[2]{CNRS, UMR 7093, Laboratoire d'Océanographie de Villefranche, 06230 Villefranche sur-Mer, France}

[3]{Université Pierre et Marie Curie-Paris 6, UMR 7093, Laboratoire d'Océanographie de Villefranche, 06230 Villefranche-sur-Mer, France}

[4]{Laboratorio di Oceanografia Biologica, Stazione Zoologica "A. Dohrn", Villa Comunale, Napoli, Italy}

Correspondence to: H. Lavigne (hlavigne@ogs.trieste.it)

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Abstract

The distribution of the chlorophyll-a concentration ([Chl-a]) in the Mediterranean Sea, ~~which is for the most~~mainly obtained from satellite surface observations or from scattered in situ experiments, is updated by analyzing a database of fluorescence profiles ~~calibrated~~converted into [Chl-a]. The database, which includes 6790 fluorescence profiles from various origins, was processed with a ~~dedicated~~specific quality control procedure. To ensure homogeneity between the different data sources, 65% of fluorescence profiles have been inter-calibrated on the basis of their concomitant satellite [Chl-a] estimation. The climatological pattern of [Chl-a] vertical ~~profile~~profiles in four key sites of the Mediterranean Sea has been analyzed. Climatological results confirm previous findings ~~on~~over the range of existing [Chl-a] values and ~~on~~throughout the ~~main~~principal Mediterranean trophic regimes. It also provides new insights on the seasonal variability of the shape of the vertical [Chl-a] profile, inaccessible from remote sensing observations. An analysis based on the recognition of the general shape of the fluorescence profile was also performed. Although the shape of [Chl-a] vertical distribution characterized by a deep chlorophyll maximum (DCM) is ubiquitous during summer, different forms are observed during winter, thus suggesting~~ thus~~ that factors affecting the vertical distribution of the biomass are complex and highly variable. The [Chl-a] spatial distribution in the Mediterranean Sea mimics, at smaller scales, what is observed in the Global Ocean. As already evidenced by analyzing satellite surface observations, mid-latitude and subtropical like phytoplankton dynamics coexist in the Mediterranean Sea. Moreover, the Mediterranean DCM variability appears to be characterized by patterns already observed at ~~global~~the Global scale.

1 Introduction

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1.1 Surface chlorophyll distribution

Chlorophyll-a concentration ([Chl-a] hereafter) is the main proxy of phytoplankton biomass (Strickland, 1965; Cullen, 1982~~) and represents~~), representing a key oceanic biogeochemical variable. However, in the Mediterranean Sea, as in the global ocean, the comprehensive knowledge of the [Chl-a] spatio-temporal variability has been prevented due to a lack ~~of~~in in situ observations (Conkright et al., 2002; Manca et al., 2004~~) has prevented a comprehensive knowledge of the [Chl-a] spatio-temporal variability.~~). The understanding of the [Chl-a] distribution is essentially ~~restrained~~restricted to the surface, as based on remote sensing observations. In the Mediterranean Sea,~~ the~~ ocean color sensors, like CZCS (Feldman et al., 1989) or SeaWiFS (McClain et al., 1998), provide observations with high temporal and spatial resolution over the whole basin (Morel and André, 1991; Antoine et al., 1995; Bosc et al. 2004).

As ~~shown from~~ in situ observations have demonstrated (Dolan et al., 1999; Dolan et al., 2002; Ignatiades et al., 2009), satellite data ~~confirmed~~confirm the ~~ultra-~~oligotrophic nature of the basin (Dugdale and Wilkerson, 1988) ~~and~~as well as the east-west gradient in ~~the~~ oligotrophy~~.~~ ~~Except for~~ (see Fig. 1, panels B and C). Excepting the Liguro-Provençal region, where a large spring bloom takes place, and for some localized spots, most of the basin exhibits very low values (< 0.2 mg m^{-2}) of satellite surface [Chl-a]. Surface [Chl-a] decreases eastward (Bosc et al., 2004; Barale et al., 2008) ~~and displays~~displaying a sharp gradient between the west and east basins (mean [Chl-a] is about 0.4 mg m^{-3} in the west basin and 0.05 mg m^{-3} in the east basin, Bosc et al., 2004~~).~~, Fig. 1, panels B and C). Superimposed on this general pattern, ocean color data ~~provided~~ also provide insights on the occurrence and on the influence of meso and sub-mesoscale structures on [Chl-a] (Taupier-Letage et al., 2003; Navarro et al., 2011, D'Ortenzio et al., 2014).

Satellite observations ~~were~~have also been the primary source of information for the characterization of the [Chl-a] seasonal and interannual variability (D'Ortenzio and Ribera d'Alcalà, 2009; Volpe et al., 2012; Lavigne et al., 2013). At ~~global~~a Global scale, ocean color satellite observations indicate that surface [Chl-a] annual cycles ~~switch~~display different patterns moving from a tropical to a temperate or a polar environment (Yoder et al., 1993) generally following~~ generally~~ latitudinal gradients. Boundaries between large ecological regions have been determined from satellite observations, in the global ocean (Longhurst,

2006) but also at regional ~~scale~~scales (Devred et al., 2007; D'Ortenzio and Ribera d'Alcalà, 2009; Platt et al., 2010). Indeed, ~~in the Mediterranean, a satellite based bioregional approach confirmed previous~~focusing on ocean color observations ~~(~~, D'Ortenzio and Ribera d'Alcalà~~,~~ (2009~~). Authors~~) confirmed the presence, in the Mediterranean Sea, of surface [Chl-a] annual cycles, displaying similarities with subtropical or with temperate regions. The authors demonstrated that a subtropical-like [Chl-a] seasonality (highest [Chl-a] during winter and lowest during summer) encompasses most of the basin whereas a temperate like seasonality, marked by a high peak of surface [Chl-a] in spring (in March/April), is recurrently observed in the North-Western basin and occasionally in other Mediterranean regions. Further analysis (Lavigne et al., 2013) showed that the coexistence of different regimes in the Mediterranean Sea is mainly due to the high variability of the interplay between physical ~~(especially~~forcing, which affects the Mixed Layer Depth~~, –~~ (MLD hereafter~~)~~), and chemical forcing (i.e. ~~nutrients~~nutrient availability).

1.2 The vertical [Chl-a] distribution

~~The vertical~~ Contrary to the horizontal distribution of [Chl-a] ~~is mainly determined by external forcing like the penetration of light in water,~~which, despite the ~~MLD or~~ uncertainties due to the ~~nutrient distribution (~~impact of bio-optical processes (see below), are regularly assessed within the basin, low cloud coverage allowing for high frequency measurements, vertical distributions of [Chl-a] are much less documented due to in situ undersampling and to the intrinsic limits of color remote sensing in the retrieval of information from subsurface layers.

So far, the largest part of the information derives from studies conducted in specific sites (e.g., Dolan et al., 2002; Christaki et al., 2001; Estrada et al., 1993; ~~Ward and Waniec, 2007). From space, however, only a small part of the vertically integrated [Chl-a] content is detected~~Casotti et al., 2003; Marty et al., 2002; Psarra et al., 2000; Krom et al., 1992), generalizations based on large scale cruises (Moutin and ~~the [Chl-a] vertical distribution is missed. In the Mediterranean Sea, which is characterized by a strong oligotrophy~~Raimbault, 2002; Crombet et al, 2011) and synthetic analyses (e.g. Siokou-Frangou et al., 2012), or reconstructions derived from modeling studies (e.g., Macias et al., ~~by the ubiquitous occurrence of a~~2014; Crise et al., 1999). These studies showed that deep chlorophyll maximum (DCM, hereafter~~), this limitation inherent to satellite observation is particularly critical.~~

~~DCMs have been observed everywhere~~) are ubiquitous over the Mediterranean from spring to autumn (Crise et al., 1999; Moutin and Raimbault 2002; Siokou-Frangou et al., 2010). ~~A~~ They display a longitudinal deepening ~~of the DCM has been also documented~~from West to East (see Crise et al., 1999 for a review~~). DCM depths range~~), with their depth ranging from 30 m in the ~~western most~~westernmost area (Dolan et al., 2002) to 70 m in the South Adriatic and ~~to~~even more than 100 m in the Levantine Sea (Christaki et al., 2001). ~~Mediterranean DCMs are also impacted by 3-D processes such as lateral advection, upwelling and eddy transport (Crise et al., 1999; Estrada et al., 1993). Although the photo-adaptation processes (Cullen, 1982; Winn et al., 1995) cannot be totally ignored, previous studies indicated that Mediterranean DCM coincides with biomass maximum (Mignot et al., 2014;~~ During ~~Macias et al., 2014) and thus significantly contributes to vertically integrated primary production (Estrada et al., 1993; Macias et al., 2014).~~

~~Overall, little is known about alternative shapes of the [Chl-a] vertical distribution. Most of the existing observations are obtained for locations where regular sampling provided a seasonal and/or interannual picture of the variability of [Chl-a] (e.g. DYFAMED station, Marty et al., 2002; Cretan Sea, Psarra et al., 2000; Levantine Sea, Krom et al., 1992). DCMs are not observed in the Mediterranean during strong~~ winter ~~mixing episodes (Siokou-Frangou et al., 2010), or, more~~ , DCM generally~~, during winter. During this season, a~~ disappear in the whole basin and the so called "mixed" shape (Morel and Berthon, 1989; Uitz et al., 2006), characterized by a constant [Chl-a] from the surface to the basis of the MLD~~,~~ is often observed~~, in both western and eastern basins~~ (Krom et al., 1992; Marty et al., 2002; Mignot et al., 2014). Alternatively, a [Chl-a] vertical shape marked by a high subsurface maximum close to the surface (less than 10m) ~~have~~has also been documented for the North-Western basin, during the spring bloom period (Marty et al., 2002; Manca et al., 2004). In spite of those focused studies and the compilation of Chl-a climatology provided by the MEDAR/MEDATLAS project (Maillard and Coauthors, 2005), the spatial distribution of [Chl-a] vertical profiles and their yearly patterns are still poorly documented in the basin. Satellite [Chl-a] values may provide additional information using the approach introduced for global assessments of depth integrated Chl-a values (e.g., Morel and Berthon, 1989). In many instances, (e.g., Bosc et al., 2004) their use was implicit and no specific analysis on the vertical distribution *per se* was carried out.

~~The lack of knowledge on the vertical [Chl-a] distribution is mainly due to the costly and difficult in situ [Chl-a] measurements. Standard method requires seawater samples, which are~~

further filtered to concentrate biomass. The filters are then analyzed in laboratory with fluorometric, spectrophotometric or chromatographic methods. A good accuracy in the estimation of [Chl-a] is then obtained, especially when High Performance Liquid Chromatography (HPLC, Gieskes and Kraay, 1983) is used. The associated protocols are, however, expensive, time consuming and it only provides discrete estimations. Consequently, compared to other physical (e.g. temperature and salinity) and even biogeochemical (e.g. oxygen) parameters, [Chl-a] Mediterranean data are very scarce (Manca et al., 2004). However, attempts to group in situ [Chl-a] observations to characterize seasonal and spatial [Chl-a] variability at Mediterranean scale have been realized, resulting in the production of a [Chl-a] climatology (the MEDAR/MEDATLAS project, Maillard and Coauthors, 2005). As expected, however, the vertical resolution of the climatological [Chl-a] field is weak (12 points on the vertical) and only seasonal estimations are available.

As discussed in a recent review by Cullen (2015), there is no unique DCM and its dynamics result from the interactions among external forcing, e.g., the penetration of light in water, the intensity of vertical mixing and subsurface nutrient distribution and biotic processes, e.g., photoacclimation, grazing, phytoplankton composition. To assess which and how many DCMs exist in the Mediterranean sea because of its known geographical and dynamical gradients, a starting step is to produce a quantitative characterization of their shapes and their seasonal evolution, which is one of the main scope of this contribution. In addition, a good appreciation of seasonal changes in vertical [Chl-a] distribution, the other objective of this study, is a first step towards a better understanding of mechanisms controlling seasonal phytoplankton development. It is also essential to better interpret changes in surface [Chl-a] as detected by satellite sensors. This study will allow for the integration of the biogeographical characterization of the basin built on surface [Chl-a] patterns, thus paving the way to focused area studies based on in situ sampling or autonomous vehicles.

1.3 Fluorescence

A way to overcome the scarcity of water sample derived [Chl-a] data, is to use fluorescence observations to increase the number of available profiles.In situ [Chl-a] are obtained on filtered water samples, from which the pigment content was extracted and analyzed. The most accurate results are nowadays obtained by High Performance Liquid Chromatography (HPLC, Gieskes and Kraay, 1983). Their associated protocols are most often expensive, time consuming, and depend on direct sampling with bottles. They hence provide discrete values on a vertical scale with a limited horizontal and temporal resolution. To overcome the above limitations, fluorescence observations can be used. The estimation of [Chl-a] from the fluorescence technique (Lorenzen, 1966) is based on the chlorophyll-a property of absorbing blue light and re-emitting it, as fluorescence, in the red part of the spectrum. The quantity of fluorescence emitted by a water sample is proportional to [Chl-a], which could be then easily derived by measuring emitted radiation at red wavelengths. The fluorescence technique therefore represents ~~then~~ a robust and non-invasive method to observe continuous vertical profiles of [Chl-a]. ~~Because of the simplicity of the in situ fluorescence measurements~~ Nowadays, fluorimeters commonly equip CTDs and ~~the~~can even be built in autonomous profilers. Indeed, an increasing number of profiling floats and gliders are equipped with a ~~fluorometer~~fluorimeter (Johnson~~,~~ et al., 2009~~), the~~) while fluorescence is becoming the main source of data for [Chl-a] vertical profiles ~~(~~. To date, more than 67900 fluorescence profiles are available in the World Ocean Database 2013~~,~~ (Boyer et al., 2013).

~~Fluorescence, however,~~ However, fluorescence is only a proxy for [Chl-a], ~~in the sense~~implying that ~~a calibration of~~ the fluorescence signal ~~is required~~need to ~~obtain~~be calibrated for a [Chl-a] estimation. ~~Generally, calibration~~Calibration coefficients (α and β, see Eq. (1)) ~~as~~ provided by manufacturers~~, do not generally reach the accuracy required for scientific applications. Improved protocols require~~ are only indicative of the response of the sensor to a given Chl-a concentration in an extract or in an algal suspension, and cannot be applied to all in situ conditions. The fluorescence to [Chl-a] ratio is highly variable, since it changes with the taxonomic assemblage or environmental conditions (Kiefer, 1973). For instance, under low light conditions, the chlorophyll content per cell can increase while the fluorescence to [Chl-a] ratio decreases due to the packaging effect (Sosik et al., 1989). In response to supra-optimal light irradiation, phytoplankton triggers photo-protection mechanisms, inducing a drastic decrease in the fluorescence to [Chl-a] ratio (Kolber and Falkowski, 1993; Müller et al., 2001); this mechanism is called Non Photochemical Quenching (NPQ). The main result of NPQ effect is a decrease of fluorescence at the surface, even for constant [Chl-a] (Cullen and Lewis, 1995; Xing et al., 2012).

$$[Chl-a] = \alpha \times (FLUO - \beta) \qquad Eq. (1)$$

~~determination of proper calibration~~Better estimates are obtained by determining the empirical coefficients ~~by comparing~~(i.e. α and β) that fit fluorescence with in situ data~~,~~ for each profile (Morel and Maritorena, 2001) or for each cruise (Sharples et al., 2001; Strass, 1990; Cetinic et al., 2009).

~~$[Chl-a] = \alpha \times (FLUO - \beta) \quad Eq.(1)$~~

However, this calibration method based on the existence of simultaneous in situ samples is not always applicable. Alternative calibration methods, ~~not dependent on~~ independent of concomitant HPLC observations, have ~~been then~~therefore recently been developed (Boss et al., 2008; Xing et al., 2011; Mignot et al., 2011; Lavigne et al., 2012). ~~Using~~They are based on additional information ~~like the~~such as irradiance profiles (Xing et al., 2011), ~~the simultaneous availability of~~ ocean color observations (Boss et al., 2008; Lavigne et al., 2012) or ~~the only knowledge of~~ the shape of the ~~chlorophyll~~ fluorescence profile (Mignot et al., 2011~~) calibration methods were proposed, tested and validated.~~). Although these new calibration methods ~~doesn't attain~~do not reach the accuracy of ~~the~~ HPLC based calibration, they offer an acceptable alternative to ~~calibrate a~~extract reliable estimates of [Chl-a] vertical profiles from large quantity of fluorescence profiles ~~in a unique way~~.

1.4 Outlines

This study aims ~~to improve our~~at improving knowledge ~~of~~on the spatio-temporal variability of the vertical distribution of the [Chl-a] in the Mediterranean Sea, focusing ~~especially~~particularly on [Chl-a] seasonality. ~~In~~For this ~~basin, ocean color observations showed that surface chlorophyll seasonal cycle is characterized by a mid-latitude or a sub-tropical pattern (D'Ortenzio and Ribera d'Alcalà, 2009; Lavigne et al., 2013), although very few is known about~~, all the available proxies of [Chl-a] ~~seasonality in subsurface and deep layers. The~~ were merged to build a new data base. Special attention was paid to the shape of the ~~vertical distribution of~~ [Chl-a] ~~is also accurately analyzed here, as~~ profiles: indeed different ~~forms could be indicative of~~patterns can point to different processes controlling the ~~distribution of~~ phytoplankton~~. The~~ distribution. The spatial and seasonal variability of the DCM, which is one of the most ~~ubiquitous feature of the~~ common features in Mediterranean [Chl-a] vertical ~~shapes~~profiles, will be also specifically investigated. The scope of this paper is essentially restrained to the description of the variability of [Chl-a] vertical profiles, as they result from the interactions between many factors that can be complex as well as poorly documented. This variability will be only discussed with regard to Mediterranean hydrology and light fields.

In the ~~next~~following section, the fluorescence database ~~used~~ is presented ~~as well as~~, including the quality control and ~~the~~ calibration procedures that were applied. In the ~~result~~results section, the seasonal and spatial variability of climatological [Chl-a] vertical profiles ~~are~~, derived from fluorescence-based reconstructed [Chl-a] profiles is presented. Climatological results are completed by the analysis of the shape of the [Chl-a] profiles. Contrary to the climatology of [Chl-a] vertical profiles, the shape analysis is based on normalized [Chl-a] profiles and does not account for the [Chl-a] values. The seasonal variability ~~of~~ in occurrences of ~~the main observed~~principal [Chl-a] vertical shapes ~~for [Chl-a] vertical profiles is~~ is also investigated ~~-~~here. In the ~~Sect. 4, some~~fourth section, certain methodological points related to the production of climatological patterns are addressed. Results presented in ~~the previous~~above mentioned section are also ~~discussed against~~ compared with previous remote sensing based observations ~~and finally,~~. Finally, the diversity in Mediterranean ~~diversity in~~ [Chl-a] patterns is highlighted ~~with~~in a comparison ~~to~~with the Global Ocean.

2 Data and Methods

2.1 Data set of fluorescence chlorophyll profiles

More than 6000 chlorophyll fluorescence profiles, and their corresponding temperature and salinity profiles, ~~obtained in~~from the ~~open ocean~~ Mediterranean Sea ~~(regions~~in areas where bathymetry exceeds 100m depth~~)~~, were collected from various data ~~sources~~source (Table 1~~)~~ ~~which~~). These comprise online databases (986 profiles), French cruises (2670 profiles), the MEDAR (228 profiles) and the SESAME programs data base (1815 profiles) and, finally, fluorescence profiles derived from Bio-Argo floats (1091 profiles). ~~Profiles~~The density of profiles covers the whole Mediterranean Basin, although some areas are better represented than others (Fig. 1). Many profiles are available in the North-Western Mediterranean Sea, whereas the South-Western Mediterranean Sea and the Levantine Sea are poorly represented. Available profiles ~~spread over the~~ range between 1994~~-2014 period~~ and 2014, all seasons ~~are~~being equally represented (winter 30% of data, spring 21%, summer 25% and autumn 24%). Although only 16% of the database are Bio-Argo profiles, they represent half of available profiles for the 2008-2014 period.

2.2 Data processing and calibration

~~Before~~Prior to calibration, a quality control procedure was applied to fluorescence profiles. It comprises a test of uniqueness (to eliminate repetitions of a same profile), the identification of ~~the double profiles, of the~~ spikes (see D’Ortenzio et al., 2010) and of the signs of fluorometer failure (portion of profile with exactly the same value or jumps in the fluorescence profile).

After ~~the application of~~this quality control step, 593 profiles were removed from the database. Then, ~~too shallow~~incomplete profiles (i.e. profiles for which the acquisition was not deep enough to display the whole fluorescence shape) were also removed. ~~Practically, profiles~~Profiles with a surface fluorescence value lower than the bottom value were removed from the database (202 profiles removed). In addition, the profiles ~~achieved in the Ionian Sea~~obtained during the three “Long Duration” ~~station B~~stations of the BOUM cruise (Moutin et al., 2012) were removed from ~~our~~the dataset~~ as~~, because they had been sampled at very high temporal frequency ~~an~~within anticyclonic eddy (Moutin and Prieur, 2012). ~~We considered then these~~These 404 profiles~~ (121)~~, which are therefore not ~~really representative of the Ionian Sea and they were eliminated from the database~~independent, would have over-represented specific environments in the dataset.

The remaining fluorescence profiles (5571 profiles) were calibrated using satellite ocean color matchups as surface ~~reference~~references (Lavigne et al., 2012). This method has been validated in the Mediterranean Sea, by comparing satellite calibrated profiles and in situ HPLC [Chl-a] data. In the Mediterranean Sea, the calibrated profiles are unbiased and present a median error of 41%, which is reduced to 34% when compared to climatological averages ~~are compared. To summarize~~. In summary, (see Lavigne et al., 2012, ~~to~~for a comprehensive description and validation of the procedure) the method consists in (step 1) a correction for the ~~non-photochemical quenching (~~NPQ~~)~~ effect, (step 2) ~~an~~the adjustment to a zero value of the fluorescence profile at depth and (step 3) ~~an~~the application of a calibration coefficient obtained from ocean color satellite matchups. The last step has only been applied ~~only~~ to the fluorescence profiles available for the ~~period~~ 1998-2014 period (i.e. ~~period~~time during which the SeaWiFS or MODIS Aqua data ~~are~~were available and ~~can~~could be used to calculate the matchups).

~~The step~~Step 1 provides a systematic correction of the NPQ effect~~. NPQ occurs when, in response to supra-optimal light irradiation, phytoplankton triggers photo-protection mechanisms, inducing a drastic decrease of the fluorescence to [Chl-a] ratio (Kolber and Falkowski, 1993; Müller et al., 2001). The main result of NPQ effect is a decrease of fluorescence at the surface, not paralleled by a diminution of the [Chl-a] (Cullen and Lewis, 1995; Xing et al., 2012). Step 1 corrects systematically the NPQ effect~~ by extrapolating ~~up to the surface~~ the maximum fluorescence value observed in the mixed layer ~~(Xing et al. 2012). The~~ up to the surface (Xing et al. 2012). Although Biermann et al. (2014) proposed an improvement of the method for profiles with euphotic depth above MLD, we preferred to use a unique data processing procedure, to avoid the introduction of an artificial bias due to a heterogenic data treatment. The MLD was evaluated from potential density profiles using a density criterion of 0.03 kg m^{-3} (de Boyer Montegut et al., 2004; D'Ortenzio et al., 2005). This method revealed to be an efficient NPQ correction in most of conditions (Xing et al., 2012; Lavigne et al., 2012), although it presented limitations for shallow MLD and stratified water columns. By applying the equation proposed by Sackmann et al. (2008) on monthly averaged light fields, the impact of NPQ was observed to be significant only above 60m, thus leading a two-fold underestimation of surface [Chl-a]. Considering this result, the weak efficiency of the NPQ correction method in stratified conditions should not have major consequences on the present study. Only the analysis of the surface to integrated content chlorophyll ratio (see Table 3) should be considered with caution.

Step 2 corrects the systematic instrumental offset, which impacts on the whole profile, although it ~~could~~can only be detected at depth. Except for very specific cases, [Chl-a] is ~~supposed to be~~ considered reach a zero value at depths where ~~depth~~there is ~~deep enough to prevent~~no more light availability. If it is not the case, a correction factor (i.e. β on Eq. (1)) is subtracted ~~to~~from the whole fluorescence profile ~~to impose~~, considering that the median of the ten deepest observations is equal to zero. Profiles in which MLD was ~~deepest~~deeper than the deepest fluorescence observation were not ~~treated~~processed but not remove of the database (1.1% of data set). After step 1 and step 2 procedures, ~~5854~~5571 profiles were successfully corrected and stored in the so-called "1994-2014 database". These fluorescence profiles were used later for the shape analysis (see Sect. 2.3 and Sect. 3.2~~.~~).

In step 3, fluorescence profiles ~~achieved~~collected after 1998 were converted into [Chl-a] units using a transformation based on ~~the~~ ocean color satellite observations (Lavigne et al., 2012). ~~The~~ 8-day Level 3 standard mapped images of SeaWiFS and MODIS Aqua surface chlorophyll at 9km resolution were obtained from the NASA web site (http://oceancolor.gsfc.nasa.gov/) for the 1998-2014 period (1998-2007 for SeaWiFS and 2008-2014 for MODIS Aqua). The use of NASA [Chl-a] standard products allows for a good consistency between SeaWiFS and MODIS datasets ~~and avoids~~thus avoiding the introduction of any bias between the two time-series (Franz et al., 2005). For each fluorescence profile, the satellite image matching the ~~date of~~ profile date was selected. The corresponding surface [Chl-a] values over a 0.1° x 0.1° box centered on the geographical position of the profile were extracted and averaged. The integrated chlorophyll content over $1.5Z_e$ (where Z_e is the euphotic depth) is then estimated from satellite [Chl-a] using empirical relationships (Uitz et al., 2006). A multiplicative coefficient (α coefficient in Eq. (1)) is applied to the fluorescence profile, imposing that the integrated fluorescence content matches the valueintegrated chlorophyll content derived from satellite. At the end, 41503867 fluorescence profiles were successfully transformed into [Chl-a]. These [Chl-a] profiles formed the “1998-2014 database” and similarly to fluorescence profiles of the “1994-2014 database”, they are available upon request tofrom the first author.

2.3 Determination of the shape of fluorescence profiles

On the basis of a visual analysis of the whole database, five general types of fluorescence vertical shapeshapes were identified. TheThese five categories, which represent the most frequent shapes of vertical distribution observed in the Mediterranean, also reflect the their conditioning by physical-biological processes determining them.. These categories are referred to as “DCM”, “homogeneous”, “bloom”,HSC” (for High Surface Chlorophyll), “complex” and “modified DCM erosion” on the basis of their general characteristics (Fig. 2). The “DCM” and “homogeneous” shapes arehave been commonly used to describe chlorophyll[Chl-a] vertical profiles (Morel and Berthon, 1989; Uitz et al., 2006; Mignot et al., 2011). They are referred to as “stratified” and “mixed”, respectively, and are discriminated according to the relative position of Ze and MLD. The “DCM” shape corresponds to the typical “stratified shape” (Cullen, 1982),is characterized by a subsurface DCM, whileand the “homogeneous” shape, corresponds to the already identified “mixed shape” (Morel and Berthon, 1989; Uitz et al. 2006), characterized by a positive homogeneous [Chl-a] in the mixed layer. ExaminingAfter examination of the database, three other standard shapes have been introduced (i.e. “bloom”, ““HSC”, “modified DCM erosion” and “complex” shapes) to better describe the observed variability observed. The “bloomHSC” standard shape was defined for profiles displaying a steady decrease of [Chl-a] from surface to depth (~100m) as previouslygenerally observed during phytoplankton bloomblooms (Chiswell, 2011). The “modified DCM erosion” shape describes profiles with relatively high values in the mixed layer and with a peak of [Chl-a] just below the MLD. It represents an intermediate condition between the “DCM” and “homogeneous” situations. Finally, profiles with a complex shape, often displaying several peaks and a relatively high surface [Chl-a] in surface were referred to the classed as standard “complex” standard shapeshapes.

To automatically categorize the profileseach profile of the 1994-2014 database ininto one of the five standard shapesshape classes, a simple algorithm has been used, computing for each

~~profile~~ the following metrics for each profile: the depth of fluorescence maxima (D_{max}, see Fig. 2 panels A and ~~F~~D), the MLD, the fluorescence integrated content in a 20m layer centered on D_{max} (F_{max}, see Fig. 2, panel A), the fluorescence integrated content in the 0-20m surface layer (F_{surf}, see Fig. 2 panel A), the fluorescence integrated content in the mixed layer (F_{MLD}, see Fig. 2 panel ~~F~~D) and the total fluorescence content (F_T, see Fig. 2 panel B).

The algorithm was applied ~~on~~to each profile. ~~First, it~~It first tests ~~for~~the "HSC" shape. The "HSC" shape is assigned to a profile, if its fluorescence averaged over layers of 10m width decreases from surface to 100m. Secondly, the "DCM" shape is tested. If MLD is above D_{max} and if F_{max} is twice superior to F_{surf}, the profile is classed in the "DCM" category. If not, the "homogeneous" shape is tested. The profile is classed in the "homogeneous" category if F_{MLD}/F_T is superior to 0.85 (more than 85% of biomass ~~is~~ contained in the mixed layer). ~~Then, the "bloom" shape is tested. The "bloom" shape is assigned to a profile if its fluorescence averaged over layers of 10m width decreases from surface to 100m.~~ Finally, if the fluorescence profile does not meet any of the previous criteria, it is either classed in the "modified DCM~~-erosion~~" category, if ~~its~~the corresponding MLD is above D_{max} or in the "complex" category ~~otherwise~~.

Overall, ~~3063~~2780 profiles were classed in the "DCM" category, 751 in the "homogeneous" category, 413 in the "~~bloom~~HSC" category, 637 in the "modified DCM~~-erosion~~" category and 990 in the "complex" category.

3 Results

3.1 Some climatological behaviors

Although the availability of the calibrated profiles (1998-2014 database) should allow ~~generating~~to generate interpolated products on a regular mesh grid (as, for example, the ~~Global~~World Ocean Atlas, Conkright et al., 2002), we preferred to avoid any ~~hard~~large interpolation and only present Mediterranean patterns for locations well represented in our database. Hence, monthly climatologies of [Chl-a] vertical profiles were computed for four geographical points ~~around which~~where the data density was high. These points were also placed in four main Mediterranean sub-basins (i.e. 42°N/5°E in the North~~-~~-Western basin, 38°N/5°E in the South-Western basin, 36°N/17°E in the Ionian Sea and ~~33.5~~34°N/~~33~~30°E in the Levantine Sea, see yellow diamonds on Fig. 1). The monthly ~~climatological~~ time-series are presented in the next section (Sect. 3.1.1). ~~Then,~~Although, in the following, we refer to these time-series as “climatological”, certain average profiles result from a low number of fluorescence profiles (sometimes less than 10, see numbers on Fig. 3) and therefore do not strictly represent a climatological pattern. To better identify spatial changes in [Chl-a] fields, we also present climatological transects (Sect. 3.1.2). ~~The~~Due to the weak density of data in the eastern basin, ~~only allows us to analyze~~the [Chl-a] distribution could only be analyzed along a 5°E north-south transect in the western basin (see dotted line on Fig. 1). ~~As~~Nevertheless, this transect encompasses regions with different biological dynamics (D’Ortenzio and Ribera d’Alcalà, 2009~~), it represents a great interest.~~) and it is representative of the main patterns of the Western Mediterranean.

3.1.1 Seasonality in four geographic points

For each of the four selected geographic points (see above), all available profiles in a 4°x4° side box centered on the chosen geographical position were averaged on a 1-meter vertical scale and on a monthly basis to produce climatological profiles. The resulting monthly climatologies are displayed on Fig. 3.

Overall, the climatological time-series representing the South-Western basin, the Ionian Sea and the Levantine Sea (Fig. 3, panels B, C and D) display a similar evolution of the vertical [Chl-a] distribution. From December to March, [Chl-a] is greater in the surface ~~layers~~layer: from surface to the base of pycnocline (Fig. 2, panel B), while the April to November months are characterized by the occurrence of a DCM~~.~~, concurrent with the development of the seasonal pycnocline close to surface. In the South-Western region, winter profiles present relatively high [Chl-a] in the upper ~~70~~ meters ([Chl-a] > 0.5 mg m^{-3}), ~~-~~whereas in the Ionian, and even more in the Levantine, upper layer [Chl-a] is lower and the ~~depth~~base of the ~~layer in which [Chl-a] is not zero~~pycnocline is deeper (about 150 m in the Ionian Sea and more than 200 m in the Levantine Sea). DCM, when occurring, is deeper in the Levantine and Ionian seas than in the South-Western region. The climatological time-series in the North-Western basin (Fig. 3, panel A) displays a different succession. ~~The presence of [Chl-a] accumulation in surface and subsurface layers (Fig. 2, panel C) is observed in March and April, and, in a minor extent from November to February. DCM occurs from May to October.~~DCM occurs from May to October, when surface stratification of the water column can be observed. In November and December, [Chl-a] vertical profiles display homogeneous concentrations from the surface to the upper limit of the pycnocline, which deepens through mixing processes. In January and February, the water density profiles are nearly constant and [Chl-a] profiles display low and homogeneous concentrations up to 100m. In March and April, although surface water density slightly decreases, pointing to water column stabilization and/or stratification, surface [Chl-a] considerably increases. Finally, all time-series are characterized by a deepening of the DCM from May to July and a shallowing from August to September. It appears that in the North-West region, the deepening of the DCM coincides with the deepening of the pycnocline. In the other areas, the pycnocline is much shallower than the DCM and their dynamics seem to be uncoupled until September. In October and November, the base of the surface mixed layer seems to be correlated with DCM.

Regarding [Chl-a] values, regional differences are visible~~ and confirm~~, confirming previous observations ~~about~~on the eastward increase of ~~the oligotrophy from west to east.~~oligotrophic conditions. The highest [Chl-a] value is observed in April, in the North-Western climatology (Fig. 3, panel A~~) and it reaches~~), reaching 1.2 mg m^{-3}. ~~Note however, that~~However, this mean value is derived from extremely variable observations ~~in the range~~ranging between 0.3 and 4.2 mg m^{-3}. The South-Western time-series shows [Chl-a] values up to 0.5 mg m^{-3}, observed in the surface during winter and at the DCM during summer. In the Ionian climatology, highest [Chl-a] values can be observed at the DCM, ~~they reach~~reaching 0.3 mg m^{-3}. Finally, the Levantine climatology displays the lowest [Chl-a], with values rarely exceeding 0.25 mg m^{-3}.

Table 2 ~~indicates on the~~ presents averaged [Chl-a] values at the DCM depth, for ~~each of~~ the four geographic points analyzed here. Contrary to the DCM [Chl-a] values visible ~~on~~in Fig. 3, the values reported ~~on~~in Table 2 are derived from the ~~averaging of the~~mean DCM [Chl-a] values extracted individually ~~on~~from each fluorescence profile presenting a DCM. In the North-Western region, [Chl-a] at DCM is often around 1 mg m^{-3} ~~but~~, though it ranges between 0.65 mg m^{-3} in September and 1.22 mg m^{-3} in April. At the South-Western point, the averaged [Chl-a] at DCM is 0.87 mg m^{-3}. In the Eastern basin, values are twice lower (about 0.55 mg m^{-3} at the Ionian point and 0.45 mg m^{-3} at the Levantine point). A seasonal pattern does not clearly emerge from the analysis of the DCM statistics, except that [Chl-a] at DCM is generally higher during spring and summer and lower during autumn. Note that averaged DCM depth [Chl-a] values (Table 2) are ~~highest~~higher than the DCM depth [Chl-a] values observed on climatological profiles (Fig. 3) because the averaging process on the latter tends to flat DCMs (see discussion on Sect. 4.1.2, Lavigne et al., 2012).

3.2.1 North-South transect

All the data located ~~in a surface of~~within ±2° from the 5°E meridian were selected to produce a climatological pictures of [Chl-a] ~~field at~~fields in spring (March to May, Fig. 4, panel A) and in summer (June to September, Fig. 4, panel B).

The spring situation (Fig. 4, panel A) displays various types of profiles and a large range of [Chl-a] values. North of 41°N, [Chl-a] values are high (> 1 mg m^{-3}) ~~in~~at surface and decrease with depth. Highest [Chl-a] values (~3 mg m^{-3}) are observed around 42°N in surface (up to 30m depth). Between 40°N and 41°N, surface [Chl-a] is around 0.5 mg m^{-3} and a DCM is visible at 50m depth. ~~Southward~~Further south, the climatological transect displays a deeper DCM (around 75m depth) and very low surface [Chl-a] values (<0.3 mg m^{-3}).

In the summer transect (Fig. 4, panel B), the presence of a DCM is ubiquitous, ~~though~~although its position in the water column and its [Chl-a] values vary throughout the transect. A steady deepening of the DCM is observed from 43°N (DCM depth around 50 m) to 39°N (DCM depth around 85 m). A southward decrease of [Chl-a] at DCM is also observed~~ southward~~. It ranges from 0.8 mg m^{-3} to 0.4 mg m^{-3}. South of 39°N, a shallowing of the DCM depth and an increase of the [Chl-a] at DCM are observed.

3.2 Analysis of the profile shapes

3.2.1 ~~Seasonal distribution~~Characteristics of ~~the profile~~standard shapes

As a procedure was established to classify the shapes of the [Chl-a] profiles included in the 1994-2014 database (Sect. ~~2.3), an objective study of their seasonal and spatial distributions is possible (Fig. 5). Boundaries of main Mediterranean regions are drawn in the Fig. 1.~~2.3), certain characteristics related to [Chl-a] profiles could be computed. They are summarized in Table 3.

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unsurprisingly, MLD is shallowest when the standard vertical fluorescence shape is “DCM”. Additionally, the MLD is deepest when the standard florescence shape is “homogeneous”. In these 2 cases, the relative position of MLD and Ze confirm therefore that the “homogeneous” and “DCM” shapes can be compared with the well-known “stratified” and “mixed” shapes introduced by Morel and Berthon (1989). Profiles shapes categorized as “modified DCM”, “complex” and “HSC”, display intermediate values for MLD. For profiles of the “modified DCM” shape, the average distance between MLD and chlorophyll maxima is 22m. This relatively short distance may indicate that the “modified DCM” shape derives from erosion by deeper mixing of the DCM structure. For the “HSC” standard shape, MLD can be relatively deep (ranging between 13m and 95m). A [Chl-a] gradient could therefore develop in both, stratified and mixed conditions. According to Huisman et al., (1999), the development of a [Chl-a] gradient in the mixed layer would be possible if mixed layer turbulence were low thus allowing for the accumulation of phytoplankton cells near the surface.

According to the results presented in Table 3, surface [Chl-a] values are related to the shape of the vertical profile. Lowest surface [Chl-a] values are observed for “DCM” shape profiles while highest (1.22 mg m^{-3}) values are observed for “HSC” shape profiles. In spite of its variability, this high value suggests that the “HSC” shape could result from the exponential growth of phytoplankton at surface in unlimited nutrient condition associated to a stable water column. Hence, “HSC” profiles would typically correspond to bloom conditions. A very high variability, with surface [Chl-a] values ranging from 0.13 mg m^{-3} to1.19 mg m^{-3}, is observed for profiles of the standard “homogenous” shape. This variability likely results from the interactions between the high variability of MLD and the recent development of phytoplankton biomass.

The F_{surf}/F_T ratio changes with the shape of the [Chl-a] profile. The lowest ratio (6%) is observed for the “DCM” shape, even though this value is likely to be underestimated by a factor of 2.5 because of NPQ. The standard “homogeneous”, “complex” and “HSC” shapes display similar averaged ratios, 32%, 30% and 35%, respectively. Once again, there is a large variability for “homogeneous” shape profiles that which can be explained by the variability of the MLD. Finally, in the “HSC” situation, the upper 20m can accumulate up to 50% of the chlorophyll content.

3.2.2 Seasonal distribution of the profile shapes

An objective study of the seasonal distributions of standard shapes was performed for the main Mediterranean regions (Fig. 5, boundaries of the Mediterranean regions are drawn in the Fig. 1). During summer, all the regions are dominated by the “DCM” shape, with occurrences exceeding 90%. The “DCM ~~definitively~~” shape disappears in November everywhere, ~~although~~ the ~~start~~time of its ~~formation varies with regions: in~~onset depends on the region: April for the Ionian, Levantine and Tyrrhenian regions, ~~in~~ May for the South-West region and ~~in~~ June for the North-West region. During the autumn/winter period, all the categories of shapes ~~are~~can be observed in ~~a~~one same region and ~~in~~during a same month. Nevertheless, profiles ~~with the “~~shapes classed as “modified DCM ~~erosion” shape~~” are more frequent in early winter (~~see for instance~~i.e. the Ionian region where the "modified DCM~~ erosion~~" shape represents more than 60% of profiles in December and January~~).~~), which reinforces the intuition that this shape might be generated by deeper mixing eroding the DCM structure. Profiles with the "homogeneous" shape are observed from November to March everywhere, except in the Ionian region. Similarly, the "complex" shape is ~~presented~~present everywhere from November to March. Profiles displaying a "~~bloom~~HSC" shape are absent, or nearly absent, ~~of~~in the Ionian and Levantine regions. In the Tyrrhenian and South-West regions, "~~bloom~~HSC" profiles can be observed between November and March and are ~~the~~ most abundant in February. In the North-West region, although "~~bloom~~HSC" profiles are observed in winter, from November to February, they peak ~~at~~in spring (March – April) with occurrences exceeding 60%. Assuming that the "HSC" profiles denote bloom events, this result suggests that bloom events may occur during winter in the whole Western Mediterranean although they only peak in the North-West region during spring.

3.2.~~2.~~3 Longitudinal and seasonal distribution of the DCM depth

The DCM~~ shape~~ is confirmed to be a dominant feature of the [Chl-a] distribution in the Mediterranean, although its characteristics change from ~~a~~one region to another and with time. A deepening of the DCM depth with~~ the~~ longitude is generally observed (Fig. 6), confirming previous findings (Crise et al., 1999). A linear model applied to DCM depth data indicates that, on average, DCM depth deepens by 1.6 m for 1° of longitude. However, a large variability exists, especially in the Ionian and Levantine seas. Superimposed to this general deepening of DCM with longitude, regional differences can be observed between the main Mediterranean sub-basins. Considering profiles at the same range of longitude, the averaged DCM depth is deeper and more variable in the South-West region ~~(mean=73m, standard deviation (sd) = 18.7m)~~ than in the North-West region (~~mean=52m, sd=12.5m).~~see Table 4). In the eastern basin, the Adriatic region displays shallow and stable DCM depths~~ (mean= 56m, sd=10.1m)~~, whereas the Ionian and Levantine regions display deeper and more variable DCM depths (~~mean=75m, sd=21.5m for Ionian, mean=102m, sd=16.9m for Levantine~~Table 4).

~~The~~Part of the variability observed in the different Mediterranean regions can be ~~partially~~ explained by ~~the~~ seasonality. All the Mediterranean regions have a seasonal variability in the DCM depth (Fig. 7~~)~~), which is characterized by a widespread deepening from March to mid-summer, and a shallowing from mid-summer to November. In all the Mediterranean regions,

Formattato: Motivo: Trasparente (Bianco) except the North-West region, ~~the spring to summer~~ there is 40% deepening of the DCM ~~is of 40% (~~between spring and summer (33% in the North-West ~~region it is of 33%).~~).

4 Discussion

4.1 ~~Discussion on method~~Methodological discussion

4.1.1 Comparison with MEDATLAS

The climatological profiles for each of the four geographical points analyzed in the Sect. 3.1 have been computed from the MEDATLAS climatology and compared ~~with~~to their fluorescence based counterparts evaluated here (Fig. 8). For each geographical point, the two versions of [Chl-a] vertical profiles (fluorescence based and MEDATLAS) ~~display~~displayed similar ranges of values, although differences are observed in the form of [Chl-a] vertical profiles. The fluorescence based profiles often display thinner DCMs with higher [Chl-a] values than in the MEDATLAS climatology (see for instance Fig. 8, panel B summer, panel C autumn and panel D summer). Moreover, in the MEDATLAS climatology, very weak seasonal changes of the DCM depth are visible. These divergences can be explained by the use of discrete data and of interpolation in the MEDATLAS climatology, which prevents the proper characterization of vertical structures ~~like DCMs~~. In winter, the MEDATLAS climatology, and sometimes the fluorescence based climatology, ~~shows~~show profiles with subsurface maxima (Fig. 8, panels A, B, C, winter), which ~~are~~have not been observed in the monthly fluorescence based time-series (Fig. 3). We hypothesize that these winter subsurface maxima could be an artifact caused by the large averaging ~~period (from December to March), which drive to merge [Chl-a] profiles with highly different vertical distributions (see Fig. 5).~~timescale (from December to March), leading to the combination of [Chl-a] profiles with highly different vertical distributions (see Fig. 5). Another particular feature of the MEDATLAS climatology that does not show in the fluorescence-based climatology are the rises in summer and autumn surface [Chl-a] above DCM (Fig. 8, panels A, B and D). We suggest that this feature could result from the propagation by interpolation of the high surface [Chl-a] observed on coastal regions (see also Bosc et al., 2004). In addition, considering the geographical positions of the available MEDAR observations, in almost all the studied sub-basin (except Ionian) coastal observations are included in the database. They might therefore be responsible for the observed difference with the fluorescence-based climatology.

In summary, the results of this comparison demonstrate that, although the MEDATLAS database is extremely valuable, the derived MEDATLAS fields for [Chl-a] present serious limitations and they need to be updated.

4.1.2 Methodological approaches

In the present study, two different approaches have been used to describe the monthly variability of [Chl-a] profiles. On one hand, the "standard" method~~, consisting~~ consists in averaging [Chl-a] values for ~~some~~a number of defined standard depths (i.e. Conkright et al., 2002, Sect. 3.1). On the other hand, a "probabilistic" method (Sect. 3.2), ~~where~~for which each [Chl-a] profile ~~was~~is considered as a whole, ~~focusing~~focuses the analysis on its general shape and on specific features (e.g. DCM depth). The second approach requires ~~the~~an *a priori* knowledge of the ~~main shapes of~~different profile ~~existing~~shapes found in the database ~~and~~as well as the definition of an efficient and automatic procedure to categorize the profiles. In this study, the main standard shapes and the classification procedure ~~have been~~were defined after ~~the~~ individual visualization of all the fluorescence profiles ~~of~~in the database ~~as well as~~ and determination of their characteristics (i.e. D_{max}, F_{MLD}/F_T, F_{max}/F_{surf}, see Sect. 2.3 for details).

The two approaches are complementary. The "standard" method highlights the average pattern of the [Chl-a] profile and ~~informs about~~provides the ranges of [Chl-a] values ~~for [Chl-a]~~. However, [Chl-a] values ~~has to~~must be considered independently for each depth and the shape of the resulting climatological profile has to be interpreted carefully because it is a composite. A typical artifact of this method is the tendency of the DCM to be flattened (compare DCM of Fig. 3 and values of Table 2). In these cases (i.e. [Chl-a] profile extremely stable, as during summer, or very dynamic, as during winter), the "probabilistic" analysis of the shape of the [Chl-a] profile appears more pertinent. ~~It showed that seasonal changes in [Chl-a] profiles are not smooth and steady, like the climatological analysis may suggest, but highly dynamic. This approach reveals then the complexity and variability of factors influencing the vertical distribution of biomass (i.e.~~In addition, the "probabilistic" analysis provides information on the environmental processes that lead to the observed [Chl-a] shape. As mentioned in Sect. 3.2.1, the "modified DCM" shape likely results from the erosion by upper vertical mixing of the DCM structure while the "homogenous" standard shape is likely driven by vertical mixing, which encompasses the whole [Chl-a] profile. Similarly, the "HSC" profiles, associated to high surface [Chl-a] values (see Table 3), could be collected (and then associated) to surface phytoplankton bloom conditions. Under these conditions, if there is no

Formattato: Tipo di carattere: Corsivo nutrient limitation, growth rate is essentially affected by light availability and then decreases with depth. This can account for the derived decrease in the [Chl-a] gradient from surface to depth. Nevertheless, these conjectures have to be considered on a statistical basis. Indeed, each individual profile is affected by complex and variable factors (i.e. vertical mixing, 3D dynamic structures, light distribution, grazing pressure, Longhurst and Harrison, 1989, see also discussion below~~).~~), which sometimes lead to erratic [Chl-a] vertical distributions that become difficult to explain (17% of profiles have been classed as "complex" standard shapes). Finally, the "probabilistic" analysis also revealed that seasonal changes in [Chl-a] profiles are not smooth and steady, as the climatological analysis may suggest, but are rather strongly dynamic.

4.2 A new vision of the [Chl-a] in the Mediterranean Sea

4.2.1 Comparison ~~to previous~~with satellite ocean color observations

The main feature that emerges from the analysis of annual cycles of surface [Chl-a] from ocean color data over the Mediterranean sea is the coexistence of two main types of cycle (Bosc et al., 2004; D'Ortenzio and Ribera 2009; Lavigne et al., 2013). The two cycles ("NO BLOOM" and "BLOOM", following the definition of D'Ortenzio and Ribera d'Alcalà, 2009) ~~are~~can be characterized, ~~the first~~firstly, by ~~an~~a two-fold increase ~~of normalized [Chl-a] by a factor up to 2~~ from summer to winter ~~(~~in the normalized [Chl-a] (so-called NO BLOOM annual cycle) and~~, the second~~ secondly, by a moderate (two-fold) increase ~~of~~in normalized [Chl-a] ~~(factor 2)~~ from summer to winter, followed by an exponential increase (~~factor 3~~three-fold) in early spring (so-called BLOOM annual cycle). ~~Although these~~These previous findings are based on satellite surface [Chl-a] and result from a complex statistical analysis (i.e. normalization of the seasonal cycles, clustering analysis), but they ~~are~~have also been confirmed by~~ some of~~ the climatological time-series presented here (see Sect. 3.1). Climatologies of [Chl-a] profiles (Fig. 3) for the South-Western region (panel B), the Ionian region (panel C) and the Levantine region (panel D~~)~~), which correspond to the NO BLOOM regions identified by D'Ortenzio and Ribera d'Alcalà (2009~~) not only~~), display similarities in the seasonal variations of surface [Chl-a] ~~but~~and they also showed ~~the same~~a similar succession of winter homogeneous profiles and summer profiles with DCM. In contrast, the time-series corresponding to the North-Western region (Fig. 3, panel A) presents, in March and April, [Chl-a] vertical profiles characterized by high surface concentrations (i.e. ~~Bloom profiles) and confirm the special feature of the North-Western region in the Mediterranean~~

~~Sea.~~HSC profiles), confirming the specific feature of the North-Western region in the Mediterranean Sea. Unlike NO BLOOM Mediterranean regions, in the North-West region, the average winter MLD is deeper than the DCM and the nitracline depth (see Table 4). This particularity explains the March-April bloom, which could be supported by large winter nutrient supplies. It also indicates that winter vertical mixing fully destroys the nitracline, pycnocline and DCM, which have to be restored each year. The annual renewal of these structures contributes to their tight coupling (see Fig. 3 panel A and Table 4), which is not observed in NO BLOOM Mediterranean regions (based on Fig. 3 results, DCM and pycnocline are uncoupled). In NO BLOOM regions, DCM and nitracline are not reached by the average winter MLD (see Table 4) except for extreme MLD events (Lavigne et al., 2013).

Beyond the bimodal conception (i.e. BLOOM / NO BLOOM) of annual ~~biomass~~[Chl-a] cycles in the Mediterranean Sea, there is an important and unresolved complexity marked by the presence of regional differences ~~inside of~~within the two main biomass annual cycles. ~~One of the best~~A good illustration of this complexity is the identification by D'Ortenzio and Ribera d'Alcalà (2009) of three different annual cycles (i.e. 3 bioregions) for the NO BLOOM ~~dynamic~~dynamics. The probabilistic analysis of the general shape of the [Chl-a] profiles achieved in this paper also contributes to refine the basic BLOOM / NO BLOOM scheme and should help to explain the complex patterns observed from the surface. In Fig. 5, regional differences in the distribution of the standard shapes for [Chl-a] vertical profiles are observed among the NO BLOOM regions (i.e. South-West, Levantine and Ionian regions). The main difference is ~~probably~~ the significant proportion of "~~bloom~~HSC" like profiles during winter months (i.e. January, February and March) in the South-West region, whereas this proportion is very small (less than 10%) in the Ionian sea, and even zero in the Levantine Sea. The observation of "~~bloom~~HSC" like profiles in the South-West region suggests that, during winter, mixing is able to supply enough nutrients ~~in~~at the surface to ~~allow for~~support episodic developments of phytoplankton close to the surface, when water column ~~begin~~begins to stabilize. ~~That~~This could also explain the higher [Chl-a] observed in the South-West region and the difference between the South-Western ~~[Chl-a] normalized annual cycle and the Eastern ones (D'Ortenzio and Ribera d'Alcalà, 2009).~~and Eastern normalized [Chl-a] annual cycles (D'Ortenzio and Ribera d'Alcalà, 2009). Compared to the Eastern Mediterranean Sea, DCM and nitracline depths are shallow in the South-West region (Table 4). However, winter mixing is constrained, in the Algerian basin, by the strong halocline associated to the spreading of Atlantic Water, and barely reaches the nitracline depth (D'Ortenzio and Prieur, 2010; Lavigne et al., 2013). Therefore, the spatial divergences in the occurrence of “HSC” profiles might originate in the regional differences in nutrient stocks below the nitracline. Indeed, for the intermediate layer, the nitrate concentration is much higher in the Western than in the Eastern basin (Ribera d’Alcalà et al., 2003). In addition, the nitrate to phosphate ratio increases eastward, suggesting that phytoplankton growth is mainly limited by phosphate in the Eastern Mediterranean Sea (Ribera d’Alcalà et al., 2003, Bethoux et al., 2002; Krom et al., 1991). Hence, the absence of “HSC” profiles in the Eastern Mediterranean Sea could be due to a too weak mixing efficiency to supply sufficient amounts of nitrate and phosphate for supporting a phytoplankton bloom.

4.2.2 High diversity of the Mediterranean [Chl-a]

Although the Mediterranean Sea ~~spreads over~~covers a relatively small latitudinal range (from 30°N to 45°N), previous findings, essentially based on satellite observations, have shown that in this basin, the annual phytoplankton cycles representative of subtropical and mid-latitude regions of the global ocean coexist (D’Ortenzio and Ribera d’Alcalà 2009, Lavigne et al., 2013). Present results, which focus on the seasonal variability of the whole [Chl-a] vertical distribution, confirm these previous statements. The climatological time-series of [Chl-a] profiles (Fig. 3) for the South-Western region (panel B), the Ionian region (panel C) and the Levantine region (panel D) are very close to typical subtropical behavior marked by the quasi-permanent existence of the DCM (Letelier et al., 2004; Mignot et al., 2014). In particular, the [Chl-a] climatology of the BATS station ~~BATS~~ in the subtropical North Atlantic gyre (Steinberg et al., 2001; Lavigne et al., 2012) displays many similarities, in terms of ranges of values for [Chl-a], DCM depths and ~~depths of~~ winter mixing depths, with the climatological time-series built in the Levantine Sea (Fig. 3, panel D). The only main difference is that the “homogeneous” climatological profiles ~~are observed from~~begin in December in the Mediterranean regions and only ~~from~~in January at the BATS station (Lavigne et al., 2012). Regarding seasonal cycles obtained for the North-Western Mediterranean Sea, ~~we~~they can be easily compared ~~them~~ to mid-latitude (40°-60°) regions marked by an intense spring bloom ~~like~~as in the North Atlantic (Siegel et al., 2002) or in certain regions of the Southern Ocean (Thomalla et al., 2011). Similarly to our northwestern Mediterranean ~~North-West~~ observations, the seasonal cycles for [Chl-a] vertical profiles presented by Boss et al. (2008) in the Western North-Atlantic (about 50°N) and by Chiswell (2011) in the waters east of New Zealand (about 40°S) display a majority of profiles with ~~an~~a “homogeneous” shape during winter and, ~~at~~in spring, a predominance of profiles displaying a “~~bloom~~HSC” shape or an "homogeneous" shape with high [Chl-a] values. The coexistence of profiles with "homogeneous" ~~like~~ and "~~bloom" like profiles~~HSC" shapes during spring could be explained by the intermittent feature of mixing, which continuously modifies the vertical distribution of [Chl-a] during the spring bloom (Chiswell, 2011). Finally, it is important to mention that the summer situation is very different between the North-Atlantic region studied by Boss et al. (2008) and the North-Western Mediterranean Sea. Although, DCM like profiles are nearly permanent in the North-Western Mediterranean from May/June, Boss et al. (2008) only observed them ~~only from~~to start in late summer.

~~Our analysis~~ The present study also ~~showed~~shows that in the Mediterranean Sea, the specific features of the ~~"DCM" like~~ [Chl-a] profiles with a "DCM" shape have a large variability~~.~~, comparable to those observed in the Global ocean, although occurring on shorter spatial scales. The most relevant indicator is certainly the DCM depth, which was observed to range between 30m and more than 150m. As expected (e.g. Cullen, 2015), the depth of the Mediterranean DCM is inversely related to the surface [Ch-a] (Fig. 9). In addition, the relationship between the DCM depth and surface [Chl-a] (blue curve on Fig. 9) is similar to the relationship reported for the Global ocean (red curve on Fig. 9, Mignot et al., 2011). ~~Its~~ This observation suggests that certain DCM properties in the Mediterranean Sea conform to the same generic properties established for the Global Ocean.

At the first order, the DCM depth variability ~~is partly explained by a seasonal and a spatial (~~in the Mediterranean Sea is related to the spatial component and, in particular, longitude. The deepening of the DCM along a longitudinal~~) component (Fig. 6 and Fig. 7). This seasonality of DCM~~ gradient (in the present study, DCM deepens by 1.6m per 1 degree of longitude east) agrees with the previous review, also based on observations, by Crise et al. (1999). This general deepening of the DCM with longitude covaries with the eastward increase of oligotrophy in the Mediterranean Sea (Béthoux et al., 1998). This pattern is generally attributed to anti-estuarine circulations in the Straits of Gibraltar and Sicily, which generate an eastward inflow of surface nutrient depleted waters and a westward outflow of deep nutrient rich waters. In the Eastern Mediterranean Sea, oligotrophy is also maintained by poor nutrient inputs from the boundaries (atmosphere and coasts) and by the formation of Levantine Intermediate Water, which is not the product of deep convection but of the subduction of surface water into intermediate water layers (Robinson and Golnaraghi). As revealed by Table 4, regional changes in DCM depth, nitracline depth and averaged daily PAR at DCM are correlated in the Mediterranean Sea. The eastward deepening of the DCM depth and of the nitracline depth is accompanied by a decrease in the mean daily averaged PAR at DCM (values ranging from 1 mol quanta m^{-2} day^{-1} in the North-West Mediterranean to 0.16 mol quanta m^{-2} day^{-1} in the Levantine Sea). This trend concurs with the "general rule" that states that the DCM builds-up where there is an optimal balance between the upward nutrient flux and the downward photon flux and lies on top of the nutricline (Cullen, 2015). The large distance between DCM depth and nitracline depth in the Ionian (36m) and the Levantine (83m) basins may be considered as contradictory with the previous theory. However, according to Table 4, the estimations of nitracline depths are not likely to be good estimators of the top of the nitracline, if the nitrate gradient is not a enough sharp feature, as is it the case, for example in the Eastern Mediterranean Sea. Indeed, nitracline depths have been computed from discrete vertical profiles, using the 1µM isoline (Lavigne et al., 2013).

Results from Fig. 10 also show that a seasonal component contributes to explain DCM variability in the Mediterranean regions. The observed seasonal pattern of the DCM depth (i.e. deepening from spring to summer and shallowing from summer to autumn) is consistent with previous model results (Macias et al., 2014~~)~~), and with individual Bio-Argo float observations (Mignot et al., 2014). ~~The observed pattern in the seasonality of the DCM depth (i.e. deepening from spring to summer and shallowing from summer to autumn) was explained by~~ Letelier et al. (2004) and Mignot et al. (2014~~). Authors supposed~~) explain this seasonal pattern by considering that the DCM depth ~~is~~might be driven by the light availability and ~~follows~~that it would follow the depth of an isolume. ~~The characterization of the deepening of the DCM with longitude (DCM deepens by 1.6m per 1 degree of longitude east) obtained in the presented database is in agreement with previous review (Crise et al. 1999). However, it is not consistent with model results of Macias et al. (2014), which underestimate DCM depth in the Eastern Mediterranean Sea. Seasonal and longitudinal effects explain a part of the Mediterranean DCM variability but the "unexplained" part of DCM variability is significant. It could be ascribed to the interannual variability, especially in the North Ionian Sea which undergoes interannual reversals of its circulation (Civitarese et al., 2010) or to the numerous meso and sub-mesoscale structures (i.e. gyres, fronts and jets) observed in the Mediterranean Sea (Hamad et al., 2005; Rio et al., 2007).~~

~~Finally, the large variability of Mediterranean DCM like profiles allow us to analyze relationships between DCM characteristics and to compared them with the relationships determined from global ocean datasets (Mignot et al., 2011). The DCM characteristics analyzed here are the DCM depth, the width of the DCM (dz, see caption of Fig. 9 for~~

details), the surface [Chl-a] ([Chl-a]$_{SURF}$) and the [Chl-a] at DCM ([Chl-a]$_{DCM}$). Scatter plots of [Chl-a]$_{SURF}$ versus DCM depth, [Chl-a]$_{DCM}$ versus DCM depth and dz versus [Chl-a]$_{DCM}$ are displayed on Fig. 9, panels A, B and C respectively. A second order polynomial model has been computed (blue lines on Fig. 9) on log transformed Mediterranean data and compared with the relationships obtained from a global ocean dataset (red lines on Fig. This observation is confirmed here by the analysis of the vertical [Chl-a] profile as a function of irradiance for the spring, summer and autumn periods (Fig. 10). For all regions, from spring to summer, PAR at DCM depth remains unchanged although [Chl-a] decreases. Accordingly to Letelier et al. (2004), higher spring [Chl-a] may be explained by the temporal erosion of the upper nitracline from spring to summer, supporting the hypothesis of deep biomass maxima. From summer to autumn, the magnitude of DCMs remains roughly unchanged, similarly to the PAR at DCM.

9, Mignot et al., 2011). Although, for each case, similarities (at least in the sign of the slope) are observed, several differences, especially in the value of the slope, exists for the models [Chl-a]$_{DCM}$ versus DCM depth (Fig. 9, panel B) and dz versus [Chl-a]$_{DCM}$ (Fig. 9, panel C). For a same DCM depth, [Chl-a]$_{DCM}$ in the Mediterranean tends to be higher than in the global ocean and this trend is reinforced when DCM depth is shallow. This result may suggest that, in the Mediterranean Sea, production rate and biomass are particularly high at DCM when it ranges between 60 and 30m. Regarding the relationship between dz and [Chl-a]$_{DCM}$, in the Mediterranean Sea, like in the global ocean, the width of the DCM is inversely related to its [Chl-a]. However, this trend is reduced in the Mediterranean Sea compared to the global ocean. In the Mediterranean Sea, large DCMs have higher [Chl-a]$_{DCM}$ than in global ocean and narrow DCMs have lower [Chl-a]$_{DCM}$. It appears that for a same range of DCM widths the corresponding range of [Chl-a]$_{DCM}$ is smaller in the Mediterranean Sea than in the global ocean.

5 Conclusion

Since the initial work of the MEDAR/MEDATLAS group (Maillard and coauthors, 2005) renewed by; Manca et al. (., 2004), the proposed study represents the first attempt to analyze the seasonal variations of the [Chl-a] vertical distribution over the Mediterranean Sea. We updated here theThe picture of the [Chl-a] field in the basin, which was has been updated here, as it had been mainly derived from surface satellite data or from limited and scarce in situ observations. Chlorophyll-a fluorescence data (specifically calibrated and homogenized with a dedicated method) ~~allowed for the production of a~~provided a significantly larger database than the commonly used in situ bottle estimations. Additionally, a better description of the vertical distribution was made possible. 6790 profiles of fluorescence were gathered and processed to carry out a comprehensive analysis of the seasonal variability of the vertical [Chl-a] profiles within the main Mediterranean sub-basins. ~~The comparison of our [Chl-a] database with the MEDATLAS climatology allowed to validate our fluorescence based [Chl-a] data with in situ data derived from water samples but also to demonstrate that the characteristics of our new database highly contribute to improve our knowledge of [Chl-a] vertical distribution in the Mediterranean Sea. Two complementary approaches have been used to analyze the database: the traditional construction of monthly mean [Chl-a] profiles (Conkright et al., 2002) and an innovative approach which is based on the identification of the general shape of the fluorescence profile. The association of these two approaches allowed to stress the mean seasonal behavior as well as its variability and its stability. The use of this two complementary approaches was essential in the Mediterranean Sea where the shape of the [Chl-a] is very dynamic, especially during winter. DCM appears as an important characteristic of [Chl-a] vertical profile, as it is dominant in the Mediterranean Sea (53% of available [Chl-a] profiles). Our results also showed that different types of phytoplankton biomass annual dynamics co-exist in the Mediterranean Sea which confirms previous surface limited satellite findings (D'Ortenzio and Ribera d'Alcalà, 2009). Overall, from the phytoplankton dynamics point of view, Mediterranean Sea can be compared to some large regions of the global ocean.~~The present analysis, in agreement with previous satellite results (D'Ortenzio and Ribera d'Alcalà, 2009), demonstrates the coexistence of two main types of dynamics (i.e. subtropical and mid-latitude dynamics) in the Mediterranean Sea. Mid-latitude dynamics are observed in the North-Western basin. Their main specificity is the high occurrence of "HSC" profiles in March and April, whereas this type of shape, associated to bloom conditions, is nearly absent elsewhere during this season. The subtropical dynamics encompass most of the remaining basin. It is characterized by an omnipresent DCM from spring to autumn and by a large variety of [Chl-a] vertical shapes during winter. The present analysis also demonstrated that the [Chl-a] pattern in the Mediterranean Sea is not uniform. Even among regions with subtropical dynamics, a strong variability was observed in [Chl-a] values or DCM characteristics. At the basin scale, this variability follows an eastward oligotrophic pattern.

The present study was often limited by the quantity of data, which did not allow ~~to analyze every regions~~for the analysis of each region of the Mediterranean Sea (e.g. the Adriatic Sea).

We ~~deplore~~regret the singular absence of fluorescence profiles in oceanographic databases compared to other parameters. For instance, in the MEDAR database, there are 118009 ~~profiles of~~ salinity profiles, 44928 oxygen profiles ~~of oxygen~~ and only 1984 ~~profiles of~~ chlorophyll-a fluorescence profiles. Finally, in this study we were only able to present climatological behaviors. ~~To~~Although it is a first and necessary step for a better ~~understand~~ understanding of processes which impact ~~on~~ seasonal variability of ~~the~~ [Chl-a] vertical ~~profile~~profiles, it would be ~~necessary~~interesting to further study ~~some~~certain particular cases showing, with a high frequency, annual series of vertical [Chl-a] profiles. These data ~~are~~have now become available with the development of Bio-Argo floats (~~Jonhson~~Johnson et al., 2009) and some studies have already demonstrated their potential for such applications (Boss and Behrenfeld, 2010; Mignot et al., 2014).

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Table 1. Description of sources for fluorescence profiles. In this table, only fluorescence profiles ~~achieved~~obtained in Mediterranean regions where bathymetry is superior to 100m are counted. Coastal regions have been neglected.

	Data source	Number of profiles
Online databases	PANGAEA (http://www.pangaea.de/)	93
	SISMER (http://www.ifremer.fr/sismer/index_FR.htm)	110
	WOD09 (http://www.nodc.noaa.gov/)	94
	OGS database (http://nodc.ogs.trieste.it/cocoon/data/dataset)	689
	SUB-TOTAL	**986**
French cruises	PROSOPE (Claustre et al., 2004)	96
	DYNAPROC (Andersen and Prieur, 2000)	251
	BOUM (Moutin et al., 2012)	573
	ALMOFRONT (Claustre at al., 2000)	1046
	DYFAMED (Marty et al., 2002)	191
	MOOSE-GE (http://hermes.dt.insu.cnrs.fr/moose/)	285
	DEWEX (Durrieu de Madron et al., 2011)	228
	SUB-TOTAL	**2670**
SESAME Program (http://www.sesame-ip.eu/)		1815
MEDAR Program (MEDAR Group, 2002)		228
Bio-Argo (Xing et al.. 2011; http://www.oao.obs-vlfr.fr/web/index.php)		1091
	TOTAL	**6790**

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Table 2. Averaged [Chl-a] at DCM for each geographical point analyzed on Fig. 3 (i.e. yellow diamonds on Fig. 1). Averaged [Chl-a] values were computed by averaging all the DCM depth [Chl-a] estimations extracted from available "DCM" like profiles.

	Point: 42°N 5°E (North-West)			Point: 38°N 5°E (South-West)			Point: 36°N 17°E (Ionian)			Point: 33.5°N 33°E (Levantine)		
	MEAN	SD	N	MEAN	SD	N	MEAN	SD	N	MEAN	SD	N
April	1.22	0.66	26				0.73	0.24	107	0.50	0.07	6
May	0.86	0.20	38	0.93	0.18	9	0.73	0.24	37	0.50	0.09	6
June	0.99	0.28	129	1.24	0.76	6	0.90	0.23	17	0.47	0.09	154
July	0.98	0.40	67	0.86	0.17	160	0.47	0.15	9	0.46	0.15	10
August	0.69	0.32	45	0.84	0.40	7	0.44	0.14	22	0.44	0.12	11
September	0.65	0.26	41	0.99	0.98	9	0.34	0.11	23	0.34	0.07	23
October	0.90	0.45	33	1.06	0.10	6	0.48	0.24	81	0.31	0.04	10

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Table 3. Average value (bold) and inter-decile range for parameters: MLD, euphotic depth (Z_e), surface [Chl-a] observed by satellite (Chl_{SAT}) and percentage of chlorophyll content in the upper 20m layer compared to the whole integrated content (F_{surf}/F_T).

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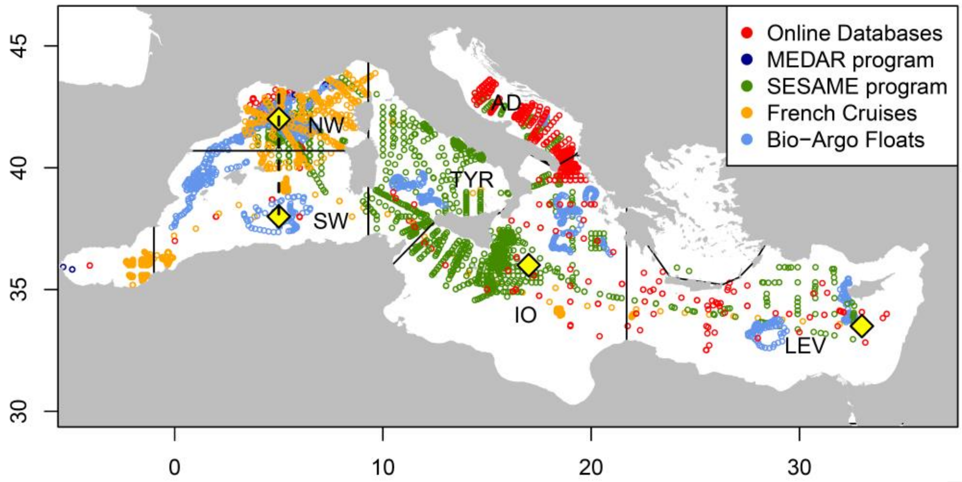


	MLD (m)	Z_e (m)	Chl_{SAT} (mg m^{-3})	F_{surf}/F_T (%)
DCM	**17** 11-27	**72** 57-90	**0.15** 0.05-0.27	**6%** 2-11
Modified DCM	**30** 13-52	**52** 37-66	**0.39** 0.16-0.63	**22%** 13-32
Homogeneous	**186** 27-596	**51** 29-71	**0.53** 0.13-1.19	**32%** 11-43
Complex	**39** 17-63	**48** 33-62	**0.52** 0.18-0.80	**30%** 18-47
HSC	**57** 13-95	**36** 17-57	**1.22** 0.25-2.76	**35%** 20-53

Table 4. Regional average values and standard deviations (numbers in brackets) for a set of parameters. Winter MLD was computed with January and February MLDs. The DCM depth and the PAR at DCM has been computed only for profiles belonging to the "DCM" standard shape category. PAR at DCM has been determined for each fully calibrated (i.e. 1998-2014 database) [Chl-a] vertical profiles. The vertical profile of the PAR attenuation coefficient was computed from [Chl-a] vertical profile and applied to surface PAR estimates derived from the monthly SeaWiFS PAR climatology. For the nitracline depth, the isoline 1µM was computed on a large set of nitrates profiles derived from MEDAR and SESAME programs (see Lavigne et al., 2013 for details about this database).

	Winter MLD (m)	Nitracline depth (m)	DCM depth (m)	PAR at DCM (mol photons m^{-2} day^{-1})
North-West	342 (623)	62 (38)	51.7 (12.5)	1.03 (0.86)
South-West	47 (63)	78 (24)	73 (17)	0.77 (0.77)
Tyrrhenian	45 (38)	97 (23)	73 (13)	0.57 (0.19)
Adriatic	126 (181)	56 (24)	56 (10)	--
Ionian	67 (46)	119 (46)	83 (29)	0.51 (0.64)
Levantine	122 (122)	185 (47)	102 (17)	0.16 (0.16)

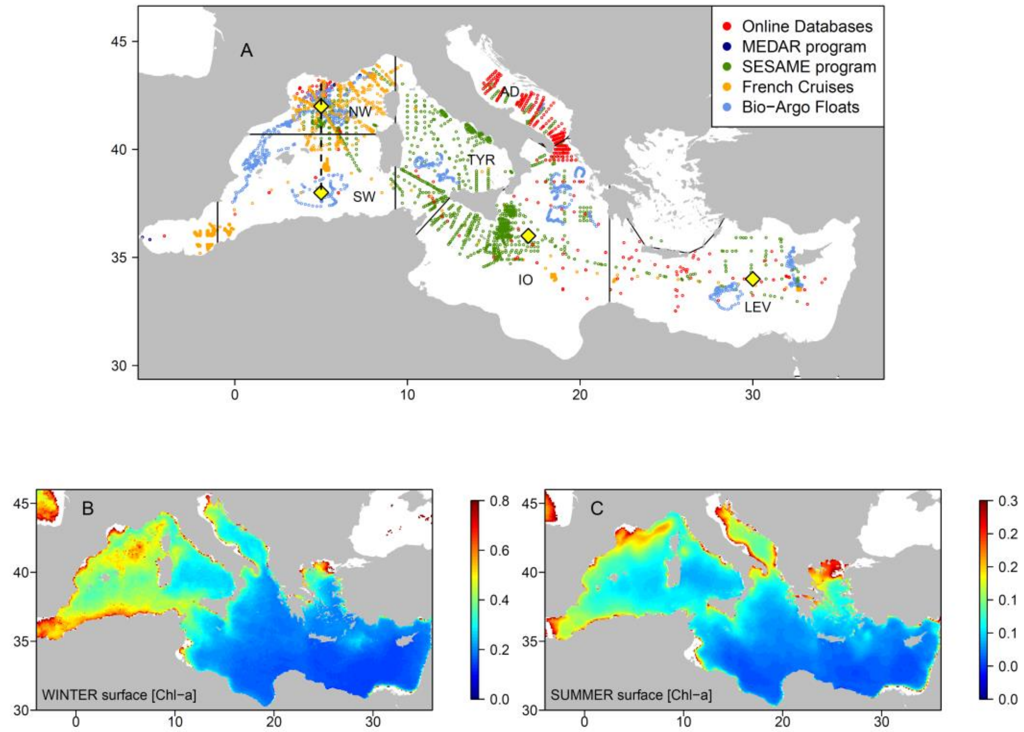
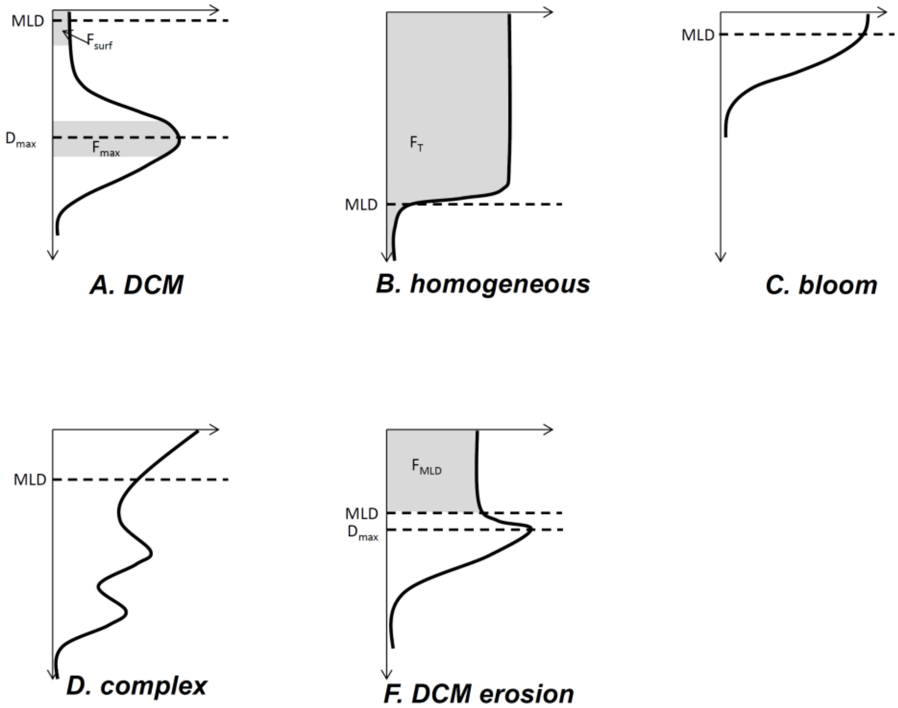


Figure 1. ~~Spatial~~Panel A: spatial distribution of fluorescence profiles available in the database. Colors indicate the source of data. Black lines delineate large Mediterranean regions: they are referred by NW for “North-West”, SW for “South-West”, TYR for “Tyrrhenian”, AD for “Adriatic”, IO for “Ionian” and LEV for “Levantine”. Yellow diamonds refer to the center of region for which a climatology of [Chl-a] vertical profile has been computed (see Fig. 3) and the dashed black line shows the center of the North-West transect (see Fig. 4).

Panels B and C: SeaWiFS climatology of surface [Chl-a] for winter (panel B) and summer (panel C). Note that color scales are not the same.



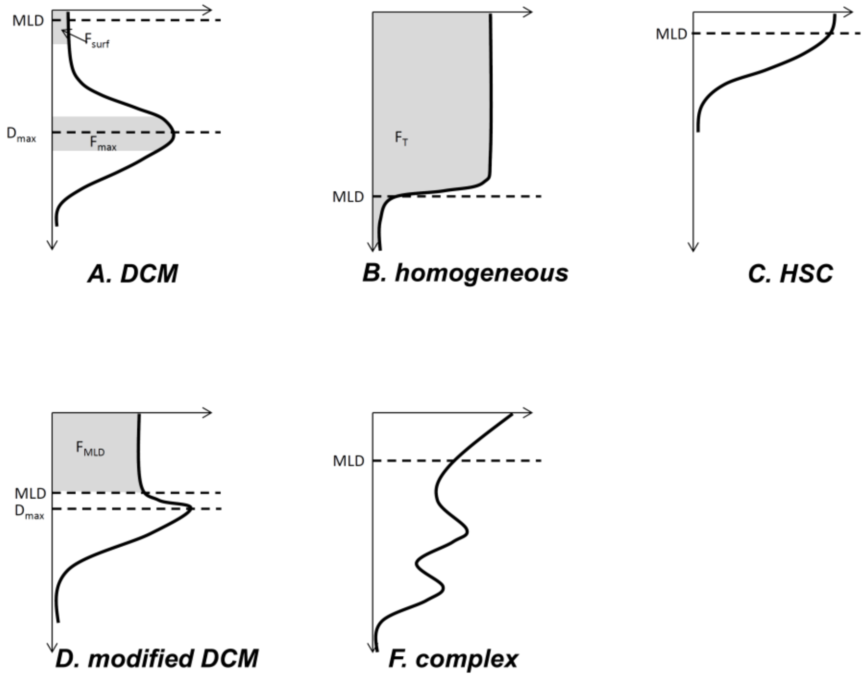


Figure 2. The five standard shapes for [Chl-a] vertical profiles identified in our dataset. See Sect. 2.3 of the text for more details about these shapes and for a description of the algorithm used to identify them. Black solid lines represent the normalized [Chl-a] vertical profile. Metrics used for the determination of the profile standard shape (i.e. MLD, D_{max}, F_{surf}, F_{max}, F_T, see text Sect. 2.3 for definitions) are represented on standard profiles. Although all of these metrics have –been computed ~~for~~on each fluorescence profile, they could not be represented on a same profile for practical reasons.

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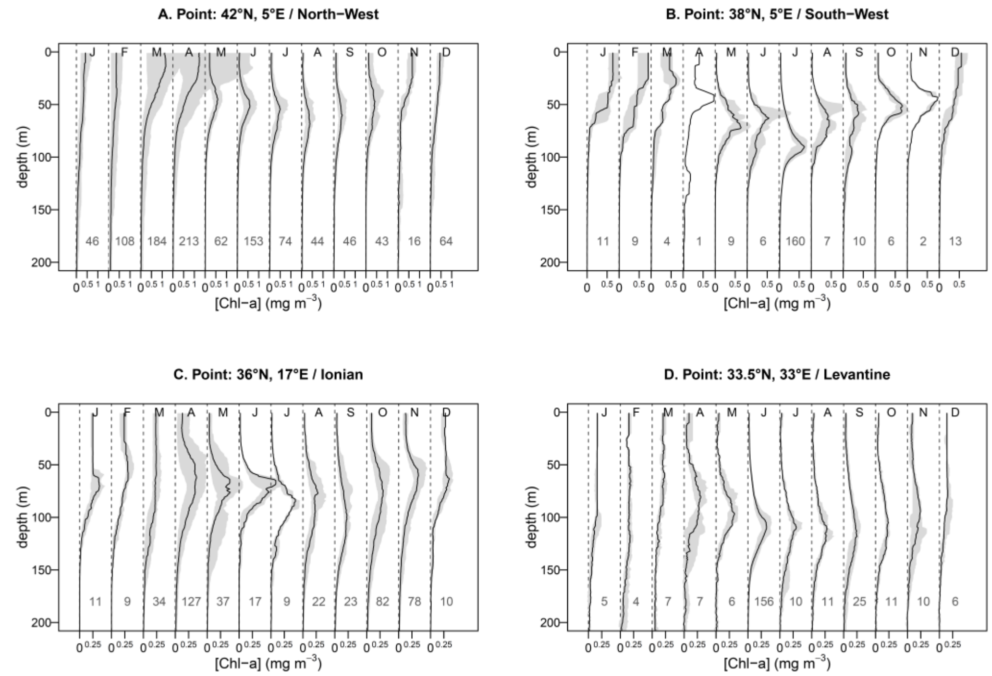
A. Point: 42°N, 5°E / North−West
B. Point: 38°N, 5°E / South−West
C. Point: 36°N, 17°E / Ionian
D. Point: 33.5°N, 33°E / Levantine
J F M A M J J A S O N D
depth (m)
0 50 100 150 200
46 108 184 213 62 153 74 44 46 43 16 64
11 9 4 1 9 6 160 7 10 6 2 13
11 9 34 127 37 17 9 22 23 82 78 10
5 4 7 7 6 156 10 11 25 11 10 6
[Chl−a] (mg m−3)

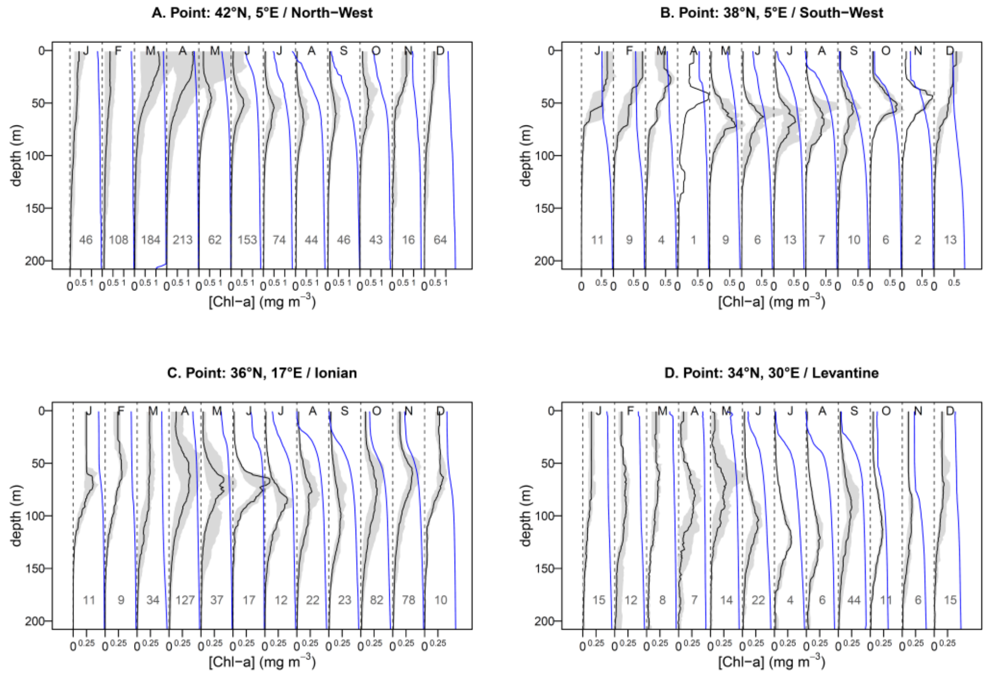

Figure 3. Climatology of [Chl-a] vertical profiles (black lines) for 4 points of the Mediterranean Sea (see yellow diamonds on Fig. 1). All profiles located within a 4°x4° box centered on indicated positions were retained. The median value for each month is the black line. The grey zone indicates the 0.1 quantile – 0.9 quantile range. Numbers below climatological profiles indicate on the number of available data profiles used to compute them.

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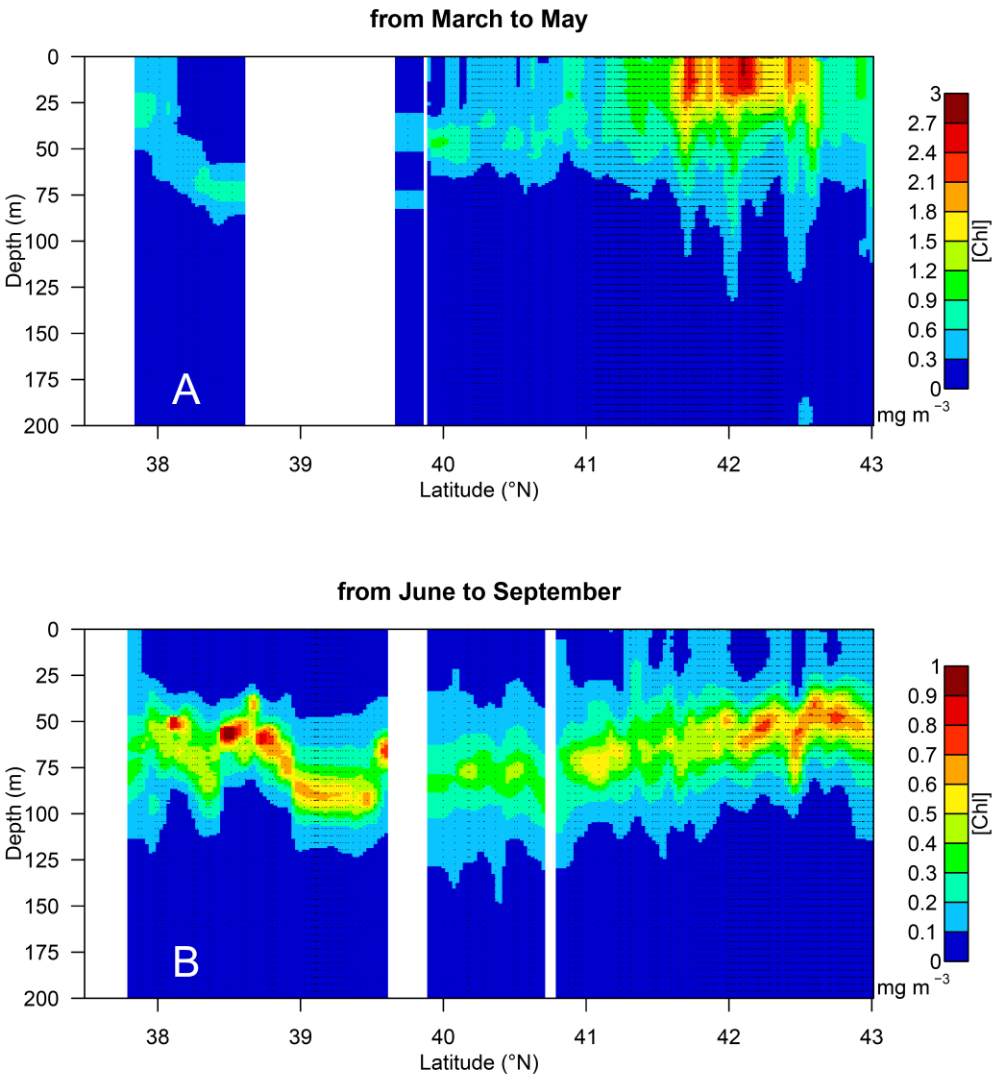
Normalized average water density profiles are superimposed (blue lines).



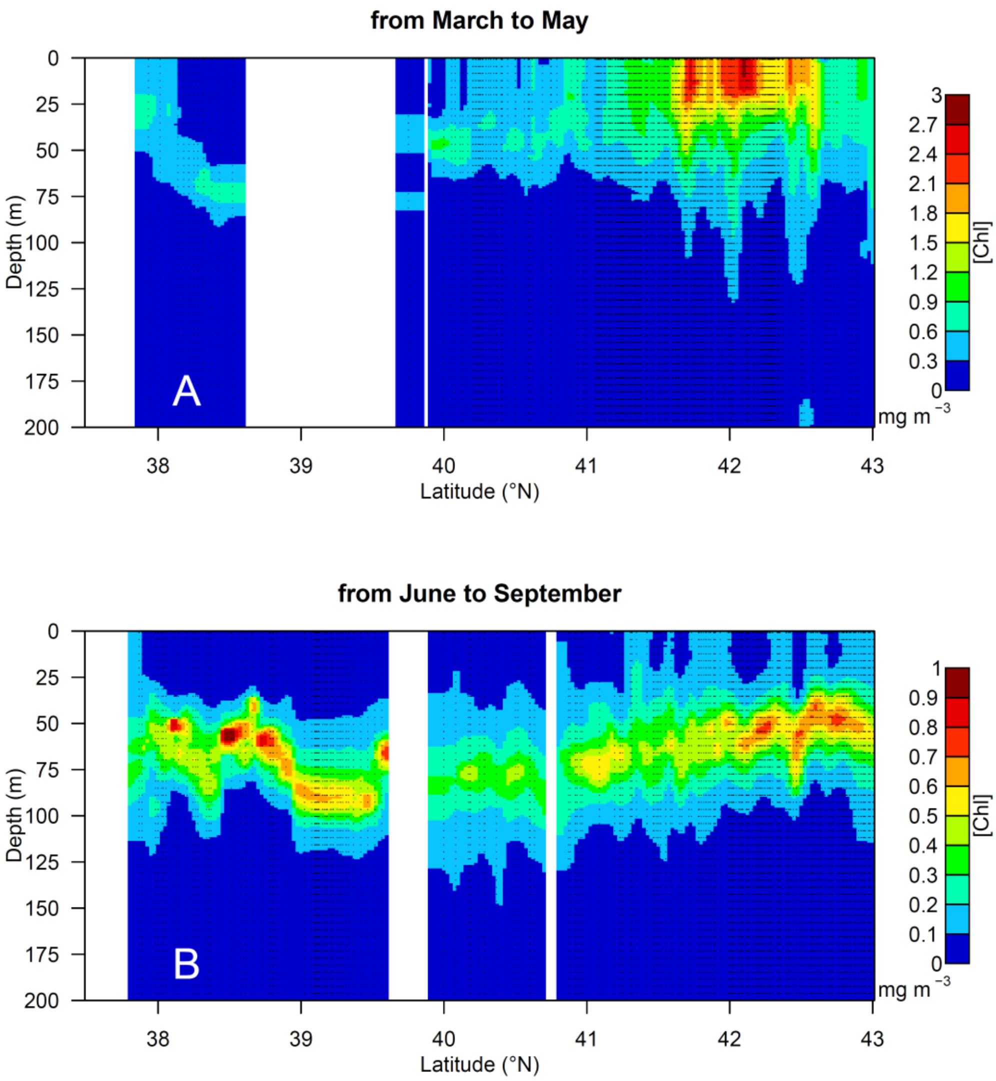
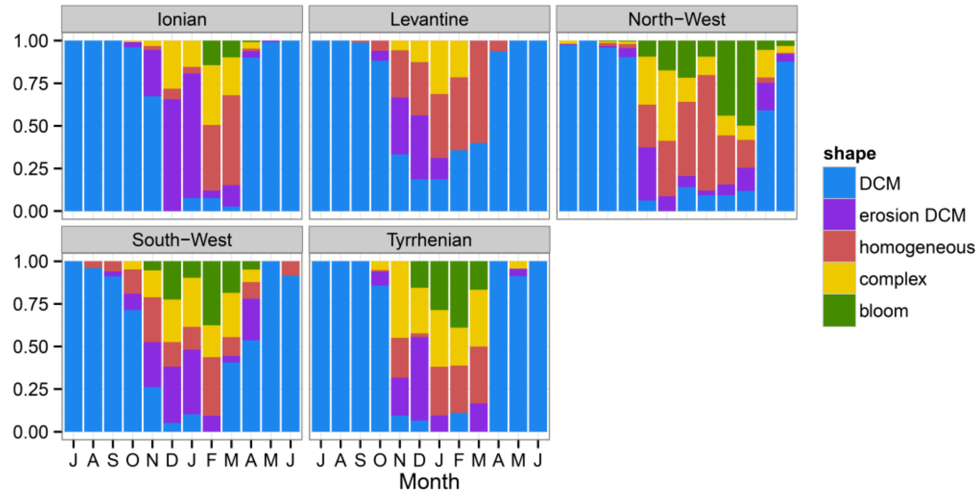


Figure 4. North-South climatological transect of [Chl-a] along the 5°W meridian (see the black dotted line on Fig. 1). Panel A represents the averaged situation for the March to May period and panel B for the June to September period. Note that color scales are different between panels A and B. For each available data profile, a vertical dotted line was superimposed to the graphic.

Formattato: Tipo di carattere: Non Grassetto

Formattato: stile texte

Formattato: SpazioDopo: 0 pt, Interlinea singola



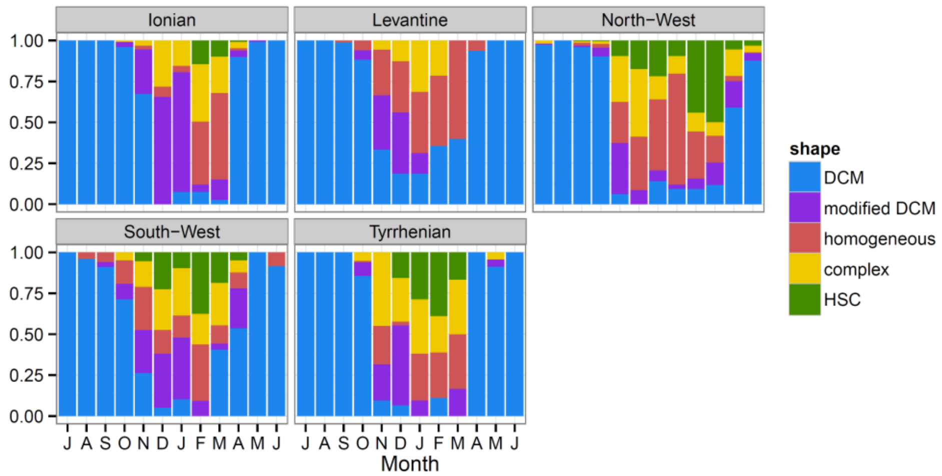
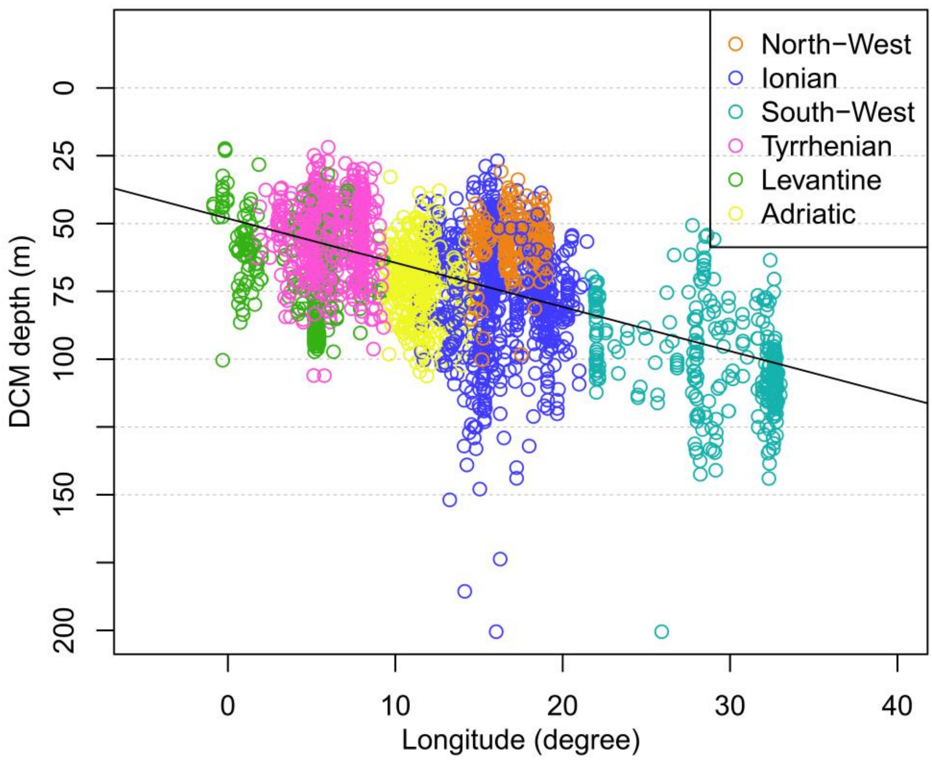
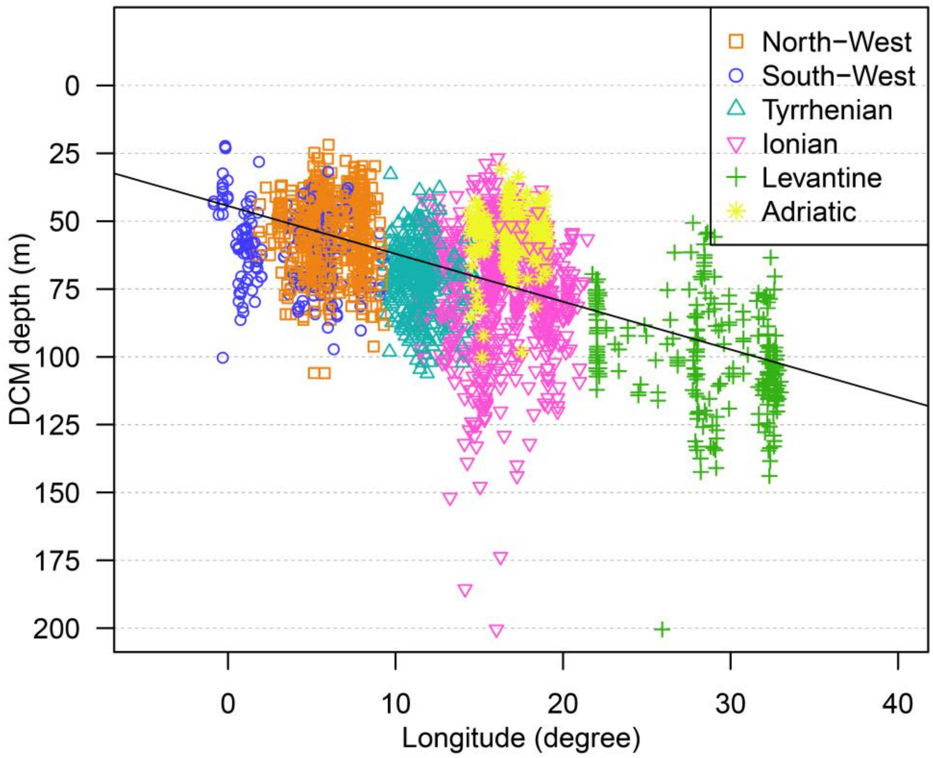


Figure 5. Histograms indicating for each month and each Mediterranean region, the proportion of each type of standard shape observed in the 1994-2014 database (i.e. “DCM”, “homogeneous”, “~~bloom”, “~~<u>HSC”, “modified </u>DCM~~ erosion~~” and “complex” see Fig. 2 and Sect. 2.3). The height of color bars indicates~~ on~~ the proportion of profiles which were classed in each category of standard shapes. Note that months ~~are ranging~~<u>range</u> from July to ~~August.~~

June.

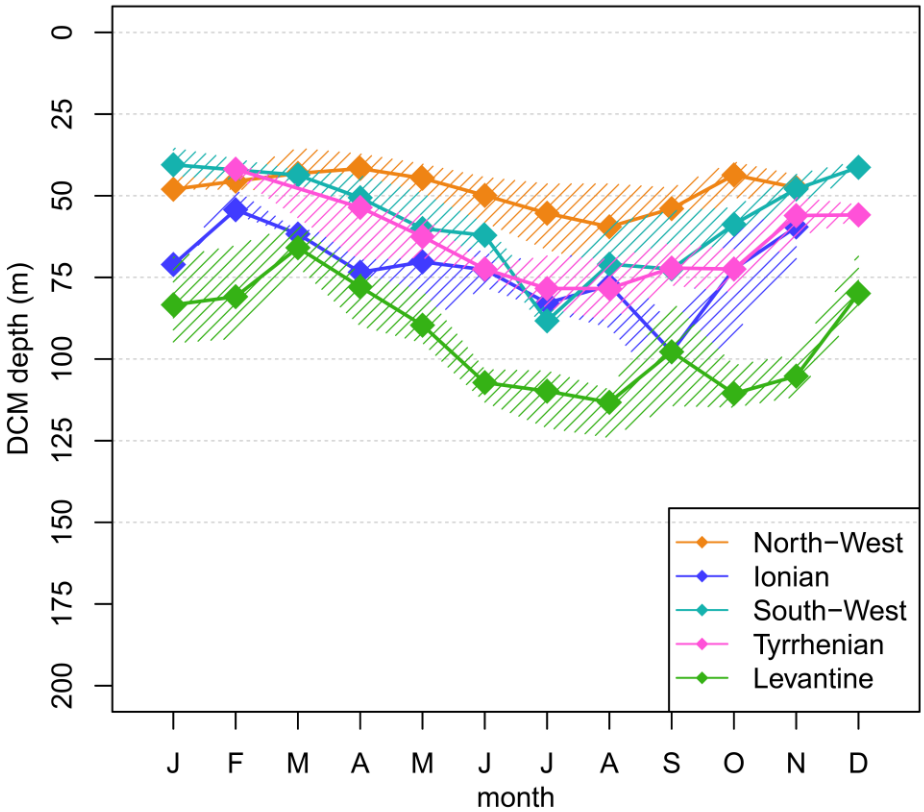
Formattato: stile texte

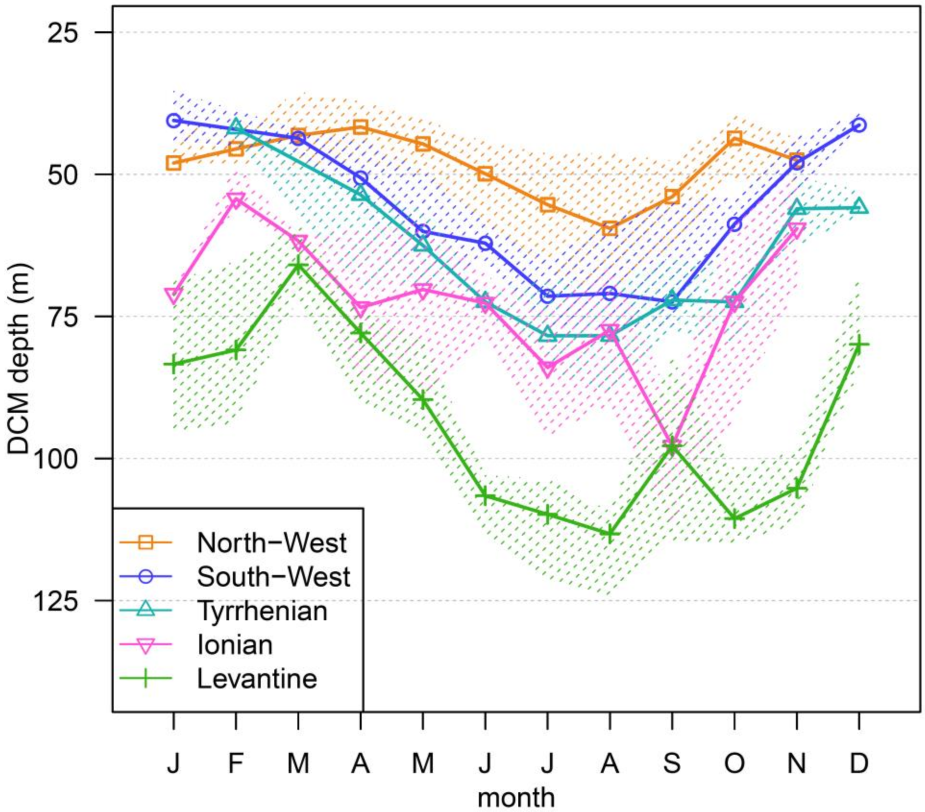




Formattato: stile texte

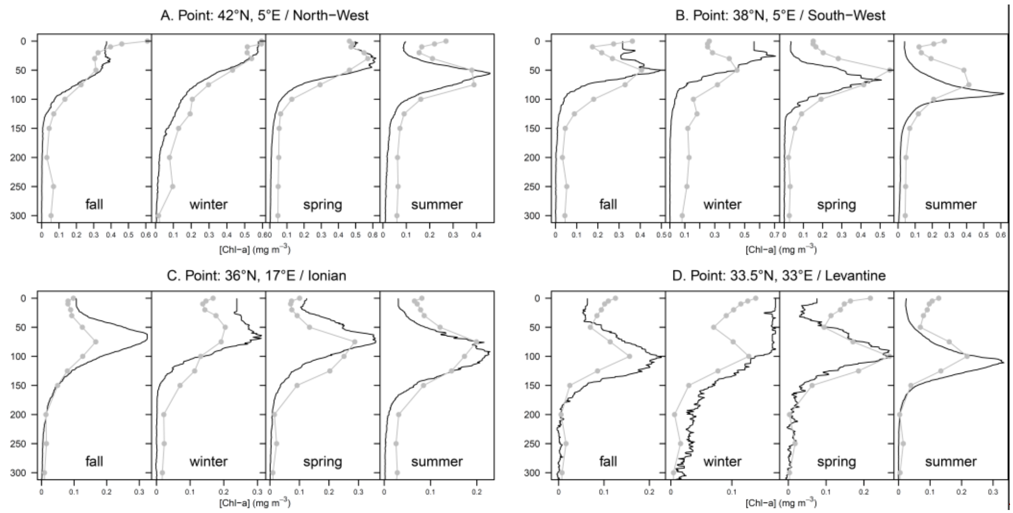
Figure 6. DCM depth as a function of longitude. DCM depths were computed only on "DCM" like ~~profils~~profiles (see Sect. 2.3 for an objective definition of "DCM" like profile). Black line represents the linear model between the DCM depth and the longitude. Its slope is 1.6 m per degree of longitude.


DCM depth (m)
0
25
50
75
100
125
150
175
200
J
F
M
A
M
J
J
A
S
O
N
D
month
North−West
Ionian
South−West
Tyrrhenian
Levantine



Formattato: stile texte

Figure 7. Seasonal evolution of the DCM depth. DCM depths were computed only on "DCM" like profiles (see Sect. 2.3 for an objective definition of "DCM" like profile). ~~Diamonds~~Symbols refer to monthly median whereas ~~hatched zones~~dotted areas indicate the inter-quartile range.


A. Point: 42°N, 5°E / North−West
B. Point: 38°N, 5°E / South−West
C. Point: 36°N, 17°E / Ionian
D. Point: 33.5°N, 33°E / Levantine
fall
winter
spring
summer
[Chl−a] (mg m^{-3})

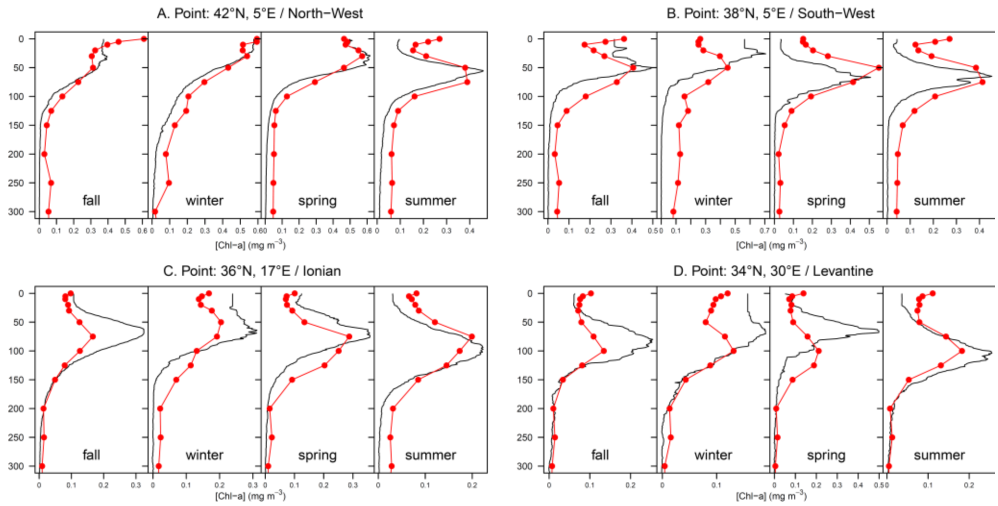


Figure 8. [Chl-a] profiles obtained from the MEDATLAS climatology for the four locations analyzed on Fig. 3 (~~grey~~red lines and ~~grey~~red points). MEDATLAS climatology was ~~download on~~downloaded from http://modb.oce.ulg.ac.be/backup/medar/medar_med.html. For comparison, corresponding seasonally averaged profiles were computed from the 1998-2014 [Chl-a] fluorescence database (black lines).

Formattato: Tipo di carattere: Non Grassetto

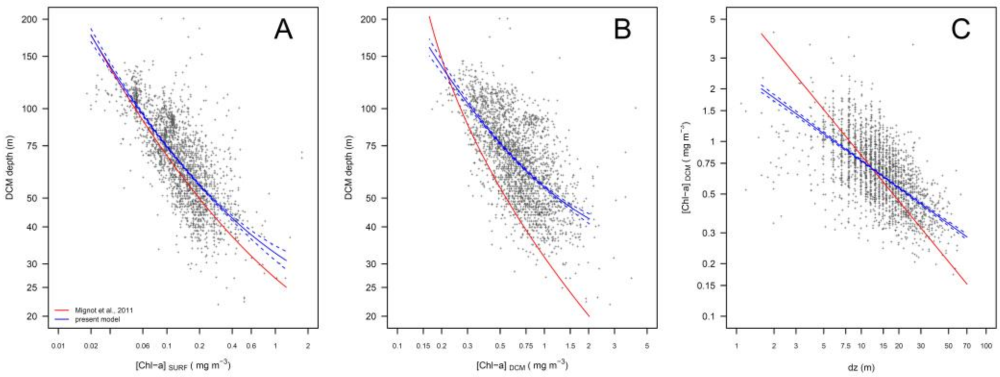
Formattato: stile texte, Interlinea singola

Formattato: stile texte

Formattato: Collegamento ipertestuale, Nessuna sottolineatura, Colore carattere: Automatico

Seasons are calendar-based seasons.

Formattato: Tipo di carattere: Grassetto



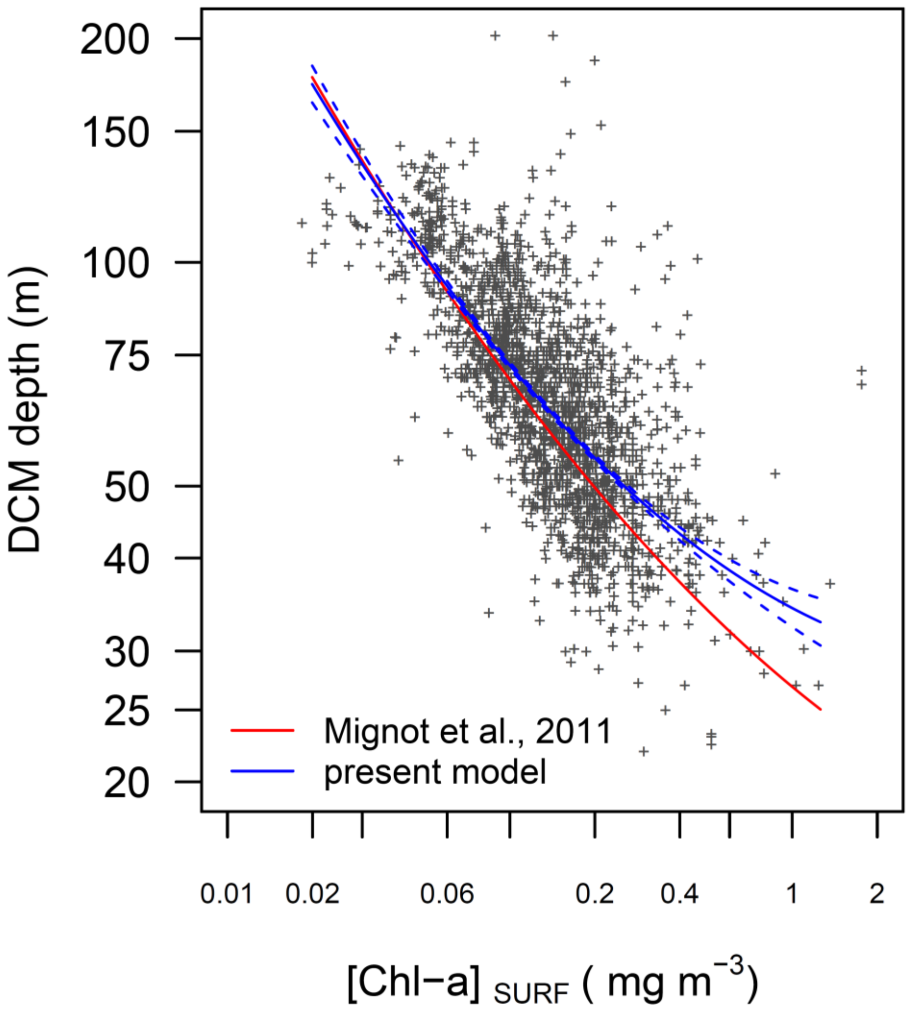


Figure 9. Scatter plots of the DCM depth as a function of surface [Chl-a~~] (panel A), of the DCM depth as a function of [Chl-a] at DCM (panel B) and of the width of the DCM (dz) as a function of the [Chl-a] at DCM (panel C).~~]. Only “DCM” like profiles were used for this analysis. ~~Similarly to Mignot et al. (2011), dz was determined by applying a Gaussian model on the [Chl-a] profiles.~~ Surface [Chl-a] ~~comes~~were obtained from satellite ocean color data ~~and the [Chl-a] at DCM was extracted from satellite calibrated profiles. On each panel, the~~.

The blue solid line refers to a second order polynomial model determined from present data with its confidence intervals (blue dotted lines). The red lines represent) and the modelsred line represents model computed by Mignot et al. (2011) from a global ocean dataset.

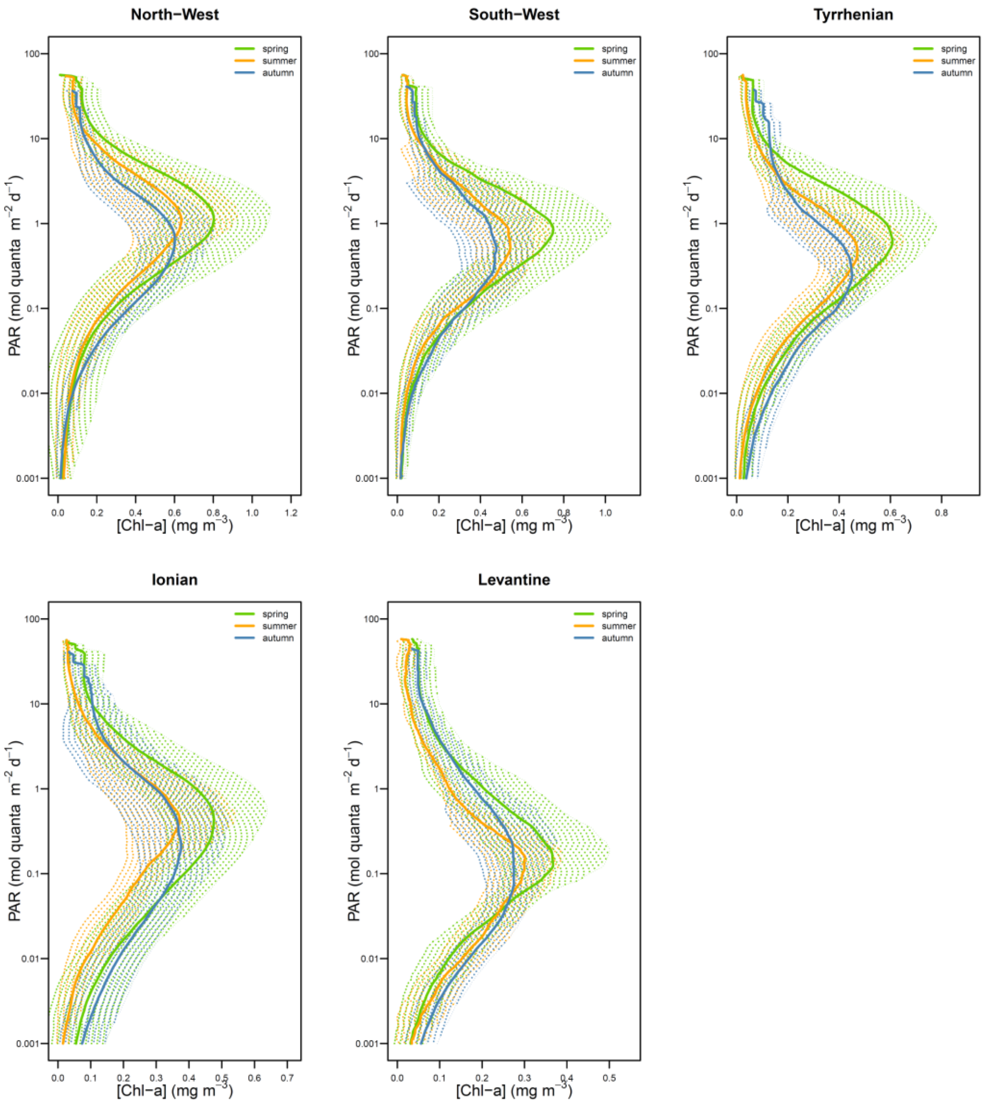


Figure 10. Averaged vertical distribution of [Chl-a] as a function of PAR with standard deviation (dotted area). Spring refers to the April-June period, summer to July and August and autumn to the September-November period.