In this document we include our replies to Reviewers' comments and the new version of the manuscript, with the corrections reported in red.
The English language has been revised by a professional service and we include the certificate at the end of the document.
Please note that the minor modifications to the English language are not highlighted in red, in order to facilitate the reading of the new manuscript.

In particular, in the new version of the paper we provided a clearer definition of "extreme event" and "extreme event wave (EEW)" (Sect. 2.1.1) and we carefully revised the use of the terms "blooms" and "maxima" throughout the text (please see our reply to Reviewer#1's Overall Comments), with also a further clarification with respect to our previous reply to Reviewer#1's comments posted in the Biogeoscience open discussion.

Moreover, we extended the proposed method to any ecosystem variable (Sect. 2.1) and we revised the Discussion section related to the possible applications of the method (also by reorganizing the order of the arguments). In particular, we explicitly added in the text the possible application to seasonally varying thresholds (as thoroughly discussed in our reply to Reviewer#1's Overall Comments) and we accounted for Reviewer#2's comment #2 about chlorophyll in subsurface layers.

Furthermore, we revised the part of the manuscript concerning the stability of the identified regimes of surface chlorophyll EEWs and we proposed a new version of Fig. 6, that accounts for the "confusion index" computed in the fuzzy clustering analysis (see our reply to Review#2's comment #3).

Finally, we also provided new versions of Fig. 5a (please see our reply to Review#1's comment: P24 – Fig 5a) and Figs. A.2-A.4 (following Review#1's suggestion: P27 - Fig A.2, A.3, A.4) and we modified the format of Figs. 3-4-5-7 and Fig. A.1.

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Reply to Reviewer#1's comments

We sincerely thank Reviewer#1 for his/her comments, which gave us the opportunity to clarify some key points of our paper.
We indicate our reply in blue colour and the corrections of the manuscript text in italic red.
The English language has been revised by an Editing Service, as proved by the certificate at the end of this document. Some comments referred to single English terms were not strictly accepted only because the provided translation reformulated the corresponding sentences.
As regards our previous reply to Reviewer#1's comments posted in the Biogeoscience open discussion, we adopted in this later version an additional revision of the expressions "maxima of local distribution" and "maxima of chlorophyll" to further clarify the terminology. In particular, we dropped the term "maxima" in those cases and we strictly referred to "extreme events" as the values over the 99th percentile threshold in the point, i.e., top 1% values of the local distribution.

== Overall Comments

In this Study, Valeria Di Baggio et al. use an extreme event identification method to track the late winter-early spring blooms in the Mediterranean sea. Their method enable to identify and follow day by day the bloom propagation, and characterize the event with different indexes.
Although the method is shown to be powerful and useful, I have some questions/concern with the application done here with the Mediterranean surface chlorophyll, as I am not sure what we are looking for, and getting in the end... Are we looking for extremes ? blooms ? strong blooms ? blooms maxima ? maxima of surface chl maximum ? we are not sure, and the way it is done probably allow all of those. But then... Are blooms considered as extreme events ?

This study aims to propose a methodology for the analysis of "extreme event waves" (EEWs), defined as a set of "extreme events" which are contiguous in space and time.
We defined statistically an "extreme event" in each point (x,y) as a value of the variable which is over a given threshold. In our case, the threshold is set as the 99th percentile of the time series recorded at that specific point (i.e., the threshold is site specific: p99 = p99(x,y)).
Extreme events are thus represented by the top 1% values of the variable distribution in that point (i.e., upper tail of the local distribution). They are "rare" events (i.e., their number is equal to 1% of the total records; right panels in Fig. R.1.1 and R1.2), selected independently from their distribution over the years. In fact, the temporal regularity over the years (i.e., the inter-annual variability) is one of the features which, in retrospect, can be quantified in the analysis of the "extreme event waves" by means of our "anomaly" index.

In our specific application focused on surface chlorophyll, the "extreme events" are strictly identified by the values of the local distribution of surface chlorophyll that are above the 99th percentile threshold, i.e., the top 1% values of the surface chlorophyll distribution. The occurrence of these values can be distributed quite regularly over the years and thus correspond to annual maxima (i.e., in the seasonal cycle), or can spread among a few years, as in case of the northern Ionian Sea (as shown in Fig. R1.1, below). In the latter case, such high inter-annual variability has been detected in the EEWs covering that area, by means of high values of the anomaly index.

On the other hand, the extreme events of surface chlorophyll can correspond to blooms (e.g., in the Gulf of Lion), but also to chlorophyll values which are too low to be properly considered as "blooms" (e.g., in the southern Levantine Sea). Our method is able to distinguish between these two cases, by means of high and low values of the severity index of the EEWs, respectively.

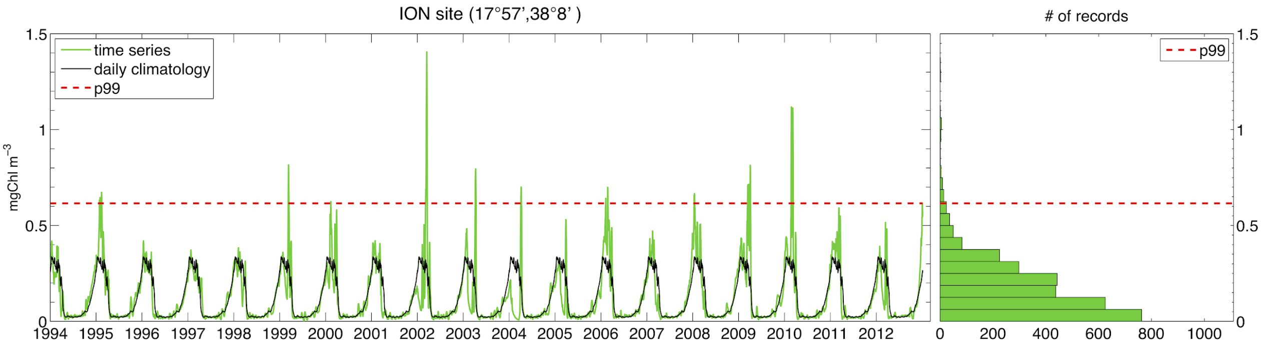

Fig. R1.1 Time series of surface chlorophyll in a site belonging to northern Ionian Sea, with daily climatology computed in the site (left) and histogram of frequency of the chlorophyll values recorded in the site (right). In both panels, the horizontal dashed line indicates the 99th percentile threshold computed in the site.

Thus, considering Reviewer#1's objection, we propose a method to analyse the extreme events; based on our analysis, blooms can be extreme events, but not all extreme events can be classified (generally speaking) as blooms.
We recognise that our use of the terms "bloom" and "maxima" (of chlorophyll/of blooms) in the previous version of the manuscript was quite confusing, and we have avoided these terms in the revised manuscript.

Apart from this main and i think important concern, the study is nice and relevant. the way the authors manage to track and characterize these events is shown to be useful, with lots of relevant information, and could be exported for all kind of extreme event study.
I really appreciate this study, but it has to make clear what we are looking at: extreme? or surface chlorophyll maximum ? depending on the answer, the amount of work needed to correct the paper will be different, corresponding to a major review if you want to make it an extreme event analysis; or a minor review if it rather is a surface chl maximum analysis using an extreme event tool (what i think the authors are doing here).

As previous clarified, we actually conducted an analysis on the top 1% values of the surface chlorophyll distribution (i.e., "extreme events", with respect to p99(x,y) of the local chlorophyll distribution) and the subsequent steps of the method (i.e., the identification of the extreme event waves (EEWs), their characterisation and classification) can be defined an "extreme events tool", as Reviewer#1 suggests.
Nevertheless, we hold that the validity of the whole method is general, i.e., the same definitions can be applied also to deseasonalized time series (see also the second next point). In that case, the "extreme events" under study would be identified by the values differing the most from the daily climatological mean (where "the most" would be set by the 99th percentile threshold of the distribution of the anomalies). The "extreme events" identified in this latter way do not necessarily correspond to the highest values of the variable recorded in the point and identify local perturbations

with respect to the seasonal cycle. The choice to deseasonalize or not the time series depends on the scientific question.
In our analysis, we focused on top 1% values of surface chlorophyll distribution as the highest values recorded in the time series and limited their characterisation and classification to the winter-spring period.
We recognise that the difference between absolute and time-dependent thresholds, as well as the possibility of following the latter approach in the first part of our method, deserves an explicit mention in the manuscript. Thus, we added the following sentences in the Discussion section, at lines 415-419 (old line 393):
Finally, our method of EEW identification, characterisation and classification can also be applied to extreme events that are defined starting from seasonally varying threshold (as e.g. in Hobday et al. 2016). In this case, "extreme events" would correspond to the highest anomalies recorded with respect to the climatological seasonal cycle of the variable and generally not to the highest values of the variable recorded throughout the time series (as in our case of temporally fixed threshold). Such an application would allow us to investigate different kinds of scientific questions, such as chlorophyll anomalies in summer.

== Extreme, Bloom, or Surface Chlorophyll Maximum ?

Although the method is shown to be powerful and useful, I have some questions/concern with the application done with the Mediterranean surface chlorophyll, as I am not sure what we are looking for extremes ? blooms ? strong blooms ? blooms maxima ? maxima of surface chl maximum ? it seems you see all of those including extremes, like the one you have selected for the example. But then... Are blooms considered as extreme events ?

Please refer to our reply to Overall Comments about the concepts of "extreme", "blooms" and "maxima" (of chlorophyll/of blooms).

From the definition you give (Page 2, line 35) "a large deviation from a reference state", but i think the reference state should include the annual cycle... if you are looking for extreme. If your targets are extremes of surface Chl, you still could use the 99th percentile threshold, and only keep those going above the local annual cycle + STD (or 1.5 * STD) for example, or instead of a 2D threshold make it 3D, including an annual cycle, that could also show extreme in summertime (maybe due to dust events for example),... The choice of a 2D 99th percentile on the whole period is somehow too broad if you look for extremes, and of course you will get completely different results in the different area of the Mediterranean sea. In the North-Western part with strong and spiky blooms,you will overshoot the threshold at least once a year, because of this spiky bloom configuration (but that's not extreme... it is the every year bloom), whereas in the oligotrophic region, where the chl phenology is smooth, a relatively stronger event can cover the whole 99th percentile. So, if you were looking for extreme, you should change that, adapt the threshold which seems to be the key of the method. But i am not even sure you are looking for extreme.

As we replied also to the Overall Comments, we think that deseasonalizing or not the time series is a choice that depends on the scientific question. In our case, we investigated the highest values of surface chlorophyll defined by the tail of the distribution of chlorophyll in each point. The investigation of "extreme events" of anomalies with respect to the daily climatological mean is a different (and, for sure, interesting) study. It would give us results of a different kind, which would deserve a separate paper. However, our method can be applied also to the deseasonalized time series, since it analyses the spatio-temporal contiguity of "extreme events" and provides a "tool" for their characterisation and classification.

In our analysis, we propose a description of the phenomenology of extreme events of chlorophyll through the "extreme event waves", defining a tool which is able to detect events with a wide range of values of the variable, as guaranteed by the site-specific threshold. The heterogeneity of the top 1% values of the local distribution of surface chlorophyll in the Mediterranean Sea is captured by our severity index, which shows the highest values in northwestern Mediterranean Sea and the lowest ones in southern Levantine Sea. The fact that a single relatively strong event in the oligotrophic region can cover the whole p99 is a result of the analysis, which highlights the heterogeneity of Mediterranean dynamics.

Moreover, we would like to point out that the time series of surface chlorophyll in northwestern Mediterranean Sea (NWM) do not necessarily overshoot the p99 threshold in each year. We report in left panel of Fig. R1.2 an example of local time series of surface chlorophyll in NWM, which shows that the local threshold is not overcome in 5 of the 19 years (i.e., 1995, 1996, 2007, 2009, 2012):

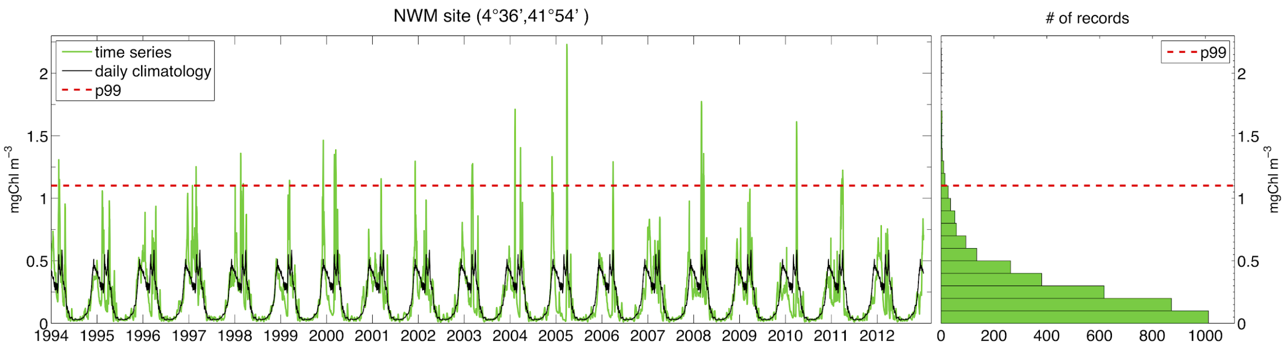

Fig. R1.2 Time series of surface chlorophyll in a site belonging to northwestern Mediterranean Sea, with daily climatology computed in the site (left) and histogram of frequency of the chlorophyll values recorded in the site (right). In both panels, the horizontal dashed line indicates the 99th percentile threshold computed in the site.

Thus, we suggest that our method identifies extreme events that not necessarily are blooms (i.e., in the oligotrophic areas) and that not all blooms are necessarily extreme events (as shown in Fig. R1.2).

The text and the title are confusing. If you are characterizing blooms (or maxima in chl maximum) using an extreme event method, it is great, but present it like this. Please, don't try to oversell it. A title like "Tracking the Mediterranean blooms using Extreme event waves method" or something like that. Of course the current title is more punchy, but personally, when i read it i've imagined dozens of possible things.

Thank you for this comment. Since we have excluded the reference to "blooms" in the revised manuscript and we think that the validity of the model is more general than our specific application to the surface chlorophyll (i.e., it can be applied to integrated chlorophyll, to other ecosystem variables, and to both time series as derived by the model output and deseasonalized time series), we modified the title as:

Extreme event waves in marine ecosystems: an application to Mediterranean Sea surface chlorophyll

Also, make it clear in the text :
-p1 l14: identify the maxima of chlorophyll as exceptionally high and prolonged "blooms"
We modified it as:
identify and characterise surface chlorophyll EEWs

-p2 l54: This allowed to identify maxima of phytoplankton blooms (Desmit et al., 2018), but also positive anomalies with values too low to be actually considered "bloom""
We modified it as:
This application allowed us to identify the extreme events of surface chlorophyll, which can correspond to both phytoplankton blooms (Desmit et al., 2018) and positive anomalies with values too low to be actually considered "blooms" (e.g., in the Levantine Sea)"

-p6 l172 : (i.e., exceptionally high and prolonged "blooms", as clarified in Introduction)
We modified it at line 177 as:
(i.e., continuous and prolonged "waves" of extreme events)

-p9 l272 : probably the clearer explanation : "we propose a new method to tackle extreme events in the marine ecosystems on the basin scale. The method is then applied to the surface chlorophyll in Mediterranean open-sea areas to investigate maxima in the winter-spring blooms".
We modified it (at lines 286-288) as:
We propose a new method to identify and characterise extreme event waves in marine ecosystems. The method is then exemplified by a first application to surface chlorophyll in Mediterranean open sea areas, with specific reference to the winter-spring period.

So sometimes it is "exceptionally high and prolonged", some other time it is "maxima in the winter-spring" blooms. The second (which includes the first) sounds more accurate, but read both is confusing. please make it clearer.
Thank you for the comment. We have just replied point by point in a consistent way.

What struggles me is the lack of definition for bloom and for bloom maxima, Or at least what you consider "blooms" and "bloom maxima" in this study. what gives me the impression of not being sure of what we are looking for, and results with places where a bloom maxima appears every year, and other places where it happens once or twice in 18 years and last 90 days. In the oligotrophic region, where there is no blooms, an EEW is found by construction (as said p6,l181 : "Considering the temporal extension of the simulation (approximately equal to 7000 days), the number of POTs in each grid point is by construction equal to 70.") the long EEW might well be an eddy with higher surface chl concentration inside. It cannot be considered a bloom.

We agree that the use of terms "bloom" and "maxima" (of chlorophyll/of blooms) was misleading in the previous version of the manuscript. As already replied to previous comments, we avoided the use of these terms in the new version of the manuscript.
On the other hand, we maintained the use of term "POTs" (i.e., peaks over threshold) to indicate the "extreme events" in the section dedicated to the indexes of the EEWs (Sect. 2.1.2) and we also added

the expression “the top 1% values” of the local distribution with specific reference to the 99th percentile threshold in the Sect. 2.1.1 (see also the second next point).
However, we would like to specify that in each point we find by construction 70 Peaks Over Threshold (POTs), since our threshold is equal to 99th percentile and we use a simulation of daily chlorophyll for 19 years. The occurrence of an EEW is instead restricted to the chance of occurrence of POTs in consecutive times and neighbouring points (i.e., spatio-temporal contiguity of extreme events). Additionally, we imposed further criteria on duration (at least 2 days, to avoid possible transient spikes) and area (greater than 4 $\Delta x \times 4 \Delta y$, with Δx, Δy grid spacing in the zonal and meridional direction, respectively, Grasso 2000). Not all POTs obtained are thus included in a EEW (the percentage of POTs not included in EEWs is equal to 0.5%). Conversely, an EEW can include different POTs recorded in the same point at different times.
Moreover, for sure there are EEWs also in oligotrophic regions, since the thresholds are site-specific, and we observed also long EEWs in these regions. We have avoided the term “bloom” in those cases, but the obtained results are valid anyway.

A solution could be to:
– Stop talking about blooms for the whole Mediterranean sea. It would make more sense if you were talking of "(...) investigate maxima in the winter-spring surface chlorophyll maximum". That would be more correct, the maxima being not necessarily extreme, and not saying the word "bloom" don’t mislead the attention on something specific that does not occur everywhere in the Mediterranean sea.

We thank Reviewer#1 for this suggestion. We have avoided the terms “bloom” and “maxima” (of chlorophyll/of blooms) in the reviewed version of the manuscript. Nevertheless, the top 1% values of the variable distribution (i.e., the values over the 99th percentile threshold at each point) strictly identify our “extreme events”, as the highest values at each point. Please see our general reply to the Overall Comments.

– And stop talking about extremes everywhere. The method you use is a method that is first made to find extreme events, but the way you use it, you don’t only find extremes. an extreme event that comes back at least once a year is not an extreme, it is part of the normal annual cycle.

As we have already replied to the Overall Comments, we consider the occurrence of values above the 99th percentile threshold computed on the local distribution (i.e., our “extreme events”) independently from their spread over the years. The inter-annual variability is evaluated in retrospect, on the EEWs, by means of the anomaly index and, as pointed out previously, it highlights the great heterogeneity of the Mediterranean Sea.
We added new lines in the section 2.1.1 of the manuscript, at lines 82-84 (old line 84):
Extreme events are thus represented by the highest values (i.e., top 1%) of the variable distribution observed in the (x,y) point. These events are “rare” events and are selected from the total records independently from their distribution over the years.
and we replaced old line 284 in the Discussion section with (new lines 298-304):
In our specific application, it is noteworthy to specify that the top 1% values of surface chlorophyll (i.e., extreme events, as defined in Sect. 2.1.1) do not necessarily correspond to “blooms” (Siokou-Frangou, 2010) since extreme events are identified in all points of the domain, including oligotrophic

areas. Moreover, the top 1% values of chlorophyll are not necessarily distributed in a regular way over the years due to the inter-annual variability of the chlorophyll time series.
Our method is able to characterise the intensity and regularity of extreme events in retrospect by means of the mean severity and anomaly indexes computed on the EEWs.
In particular, the mean severity index associated with a chlorophyll EEW can be ...

– Something else that could help to better visualise how extreme the EEW are. You could try to plot the surface Chl annual cycle (with STD in dashed line) for each Mediterranean regions (Fig 3), with the averaged 99th percentile threshold represented on top. that way we can appreciate how "extreme" an EEW is for each area (Maybe you want to adapt the area so it looks more like the fig 6 ? might be more relevant).

Thanks for raising this point.
In the present reply we show examples of local time series of surface chlorophyll in Ionian Sea and northwestern Mediterranean Sea, in Figs. R1.1 and R1.2, respectively. These plots show how "extreme" are the POTs in the selected sites, through the chlorophyll values with respect to the thresholds and the inter-annual variability (i.e., the regular/irregular occurrence of POTs over the years). The plots show also how the daily climatological series computed in the selected sites are well below the p99 thresholds in the sites.

Moreover, a figure reporting the p99 spatially averaged over regions, superimposed to the spatially averaged annual cycle, would mislead the p99 meaning, since p99 is defined locally. A comparison among different areas which is based on spatial means would not have a direct link with the EEWs indexes and would give information only about the heterogeneity of (mean) surface chlorophyll in the considered areas.
Understanding and thus quantifying how "extreme" are the EEWs in the different Mediterranean areas (e.g., their mean severity, anomaly, duration, uniformity) can be instead done from Fig. 5 and Table 2 of the manuscript.

We decided not to add figures like R1.1 and R1.2, since they do not add information needed for the method illustration. Nevertheless, if Reviewer#1 think that figures like R1.1 and R1.2 are important, we propose to add one figure for each area of Figure 3, in a new Appendix of the revised manuscript.

Unless you want to talk about extremes and only extremes. Then you have to adapt the threshold by taking into account the surface chlorophyll annual cycle as suggested above.

We do not agree with this point, since we think that our study tackle "extreme events" consistently from a statistical point of view, as rare events corresponding to the upper tail of the distribution of the chosen variable, as the highest values recorded in a certain time period. Moreover, conducting the same analysis on the deseasonalized time series (which is anyway possible within our scheme) would give different results, which answer to a different scientific question. Please see also our reply to the Overall Comments.

To complete the list of our corrections related to the semantic question raised so far by Reviewer#1, we report here our revised expressions about "extreme events", "bloom" and "maxima" (of

chlorophyll/of blooms) not explicitly indicated in our previous reply to Reviewer#1's comments posted in the Biogeoscience open discussion.
In particular, we replaced "extremes" with:
extreme events
at lines 20, 46, 50, 64, 65, 85, 89, 203, 292, 295, 393, 409, 412-413, 425, 443, we deleted the expression "for brevity: "extremes" at old line 82 and we replaced "the extreme" with:
extreme event
at lines 293, 405.
We replaced the title of Sect. 2.1 (i.e., "The method for spatio-temporal extremes investigation") with:
The method for the spatio-temporal investigation of extreme events
and the sentences at old lines 156-158 (lines 161-162 in the new version of the manuscript) with:
In particular, we used the daily chlorophyll concentration computed at the surface (i.e., averaged on the first 10 m), restricting our investigation to the January-May period.
We added lines 174-175:
The local "extreme events" for this application thus correspond to the top 1% values of the surface chlorophyll distribution in each grid point (Sect. 2.1.1).
We modified the expression "inter-annual variability of the blooms" at old line 292 by:
inter-annual variability of the extreme events of surface chlorophyll
at line 311.
We replaced "blooms belonging to cluster #7" with:
EEWs occurring in cluster #7
at line 344 and "blooms whose chlorophyll values" with:
extreme events of surface chlorophyll whose values
at line 357-358.
We replaced at line 372 "a persistence of the blooms" with:
a persistence of extreme events of chlorophyll
We modified "In the specific application to the open-sea Mediterranean chlorophyll, we characterised the maxima of "blooms" (in a local and statistical sense)" by:
In the specific application to surface chlorophyll in the open sea areas of the Mediterranean, we characterised the top 1% values of chlorophyll distribution
at lines 432-433.
We replaced "blooms" with:
chlorophyll EEWs
at lines 434-435, 437, 438.

Apart from this (important) semantic question, the method is nice and prove to be able to identify, characterize and track the EEW beautifully.
– Also, talking about extremes, i wanted to rise a question, just for discussion. I understand the choice of surface Chl maxima is mainly to test the method and show how it works. But thinking about Mediterranean sea, climate change and extreme events, i wonder if tracking maxima of surface chlorophyll maximum is what i would do. I don't think we can get hypoxia or eutrophication with 12th degree model, this is rather a coastal and river mouth problem. We know that a climate impact could be to lower the deep water formation and hence the bloom. We could use your method (adapting the threshold, considering the Annual cycle) to track years with little or no bloom, and understand

why, and see the trends. Or in summertime if your model include dust deposition on high frequency, see if the model shows EEWs linked to dust deposition events,... There is lots of other application of your methods that could make lots of sense (Lots of nice study in perspective).

Thank you for this meaningful observations.
As a first application of the method, we chose the surface chlorophyll since: it is representative of the marine ecosystem functioning; it has been widely investigated in previous studies; model simulation is comparable also with remote sensing measurements (as done in Sect. 3.1, Fig. 4), which increases the confidence level on our model-derived results. These reasons make the chlorophyll a good choice to show how the method works, as you wrote.
However, we agree that there are a lot of possible and interesting applications, thanks for your suggestions. We deepened the discussion about the possible applications in Sect. 4, lines 393-402.
As written in the last part of our reply to the Overall Comments, we explicitly added in Discussion section (lines 414-418) the possibility to apply our method starting from seasonally varying threshold, with a mention of the anomalies of chlorophyll in summer as example of investigated process.

== Text remarks

– I think there are few places where the English could be corrected, but not being a native English myself, i am not the right person to do that. Maybe you could ask a native English around you to double check your manuscript.
We followed your suggestion and sent the new version of the manuscript to an English Editing Service (whose certificate is added at the end of this document).

– from p5.l134 and all units following : double check the units the -2 and -1 should be up, if you write with latex, you should write kg km^{-2} day^{-1}
Done

– p6 l73 : " chlorophyll as a proxy for the phytoplankton biomass" Surface chlorophyll is representative of the surface biomass (probably why one of your idea in the discussion is to check the event in 3D)
We corrected the expression by:
surface chlorophyll as a proxy for surface phytoplankton biomass
at line 178.

– p6 l82 to 85: "Mapping the 99th percentile threshold values computed at each grid point on the whole basin (Fig. 3), it can be noticed that grid points that are near in space exhibit small differences in their threshold values and also that different patterns are recognisable in the basin. Hereafter, we use the abbreviations indicated in Fig. 3 to refer to different Mediterranean regions" – So the 99th percentile is fixed in time. This means that you compare toward an ~annual 99th percentile threshold of Chl. basically you will only have EEW during the bloom period. A summer with exceptional summertime Chl will not appear with this method as it will never exceed bloom period values. can't you do a time varying 99th percentile threshold to be able to see non- bloom period EEW ? otherwise you will probably miss the most interesting events... probably needs a longer run to get enough data to keep it statistically feasible.

We are aware that a percentile threshold which is fixed in time allows to recognise only the highest values of chlorophyll in the considered time period, and in this paper we focus on those events.
We do not exclude to investigate also fall blooms, or high anomalies of chlorophyll in summer, but these are different processes, and would deserve separate papers. Please see also our reply to the Overall Comments.

– p7 l191 : " The model-derived chlorophyll patterns (Fig. 4, second column) are in good agreement with the remote sensing data (first column) in the same temporal interval of the EEW" – Hard to tell, seems the sat Chl has a more extended bloom than the model, and starts slightly later (and probably ends later as well). But both model and sat presents an EEW on the same period, what is already a nice model performance ! And you have a nice bloom in the Ligurian sub-basin, that's impressive! Talking about e Ligurian bloom, it does not appear in the EEW area. it is considered as a separated EEW ?

Thank you for this comment. We replaced lines 191-193 "The model-derived chlorophyll patterns (Fig. 4, second column) are in good agreement with the remote sensing data (first column) in the same temporal interval of the EEW. In fact, a strong increase…" with:
Both the model and satellite data show patterns of high values of chlorophyll in the period of EEW occurrence (second and first columns of Fig. 4, respectively). Strong increases…
at lines 196-198.
However, the high values recorded in the Ligurian Sea are included in another EEW. We added this information at lines 209-210 as:
The high values of chlorophyll recorded in the Ligurian Sea on 20th March are associated with a separate EEW (not shown).

– p8 l235 : " are around half of the ones of ALB or NWM." needs to be rephrase.
We rephrased it (at lines 242-243) as:
being approximately 50% lower than the values displayed in ALB or NWM

– p8 l239 : "with a similar chlorophyll EEWs phenomenology."
Thank you for the suggestion. We modified the first part of the sentence that includes this expression (line 247) as:
Seven Mediterranean Sea regions with similar chlorophyll EEWs phenomenology were identified...

– p10 l288 : "pointed out the heterogeneity of the blooms intensity in the Mediterranean Sea" - back to my main comment, you don't see blooms everywhere...
As we replied to the Overall Comments, we have avoided the use of the term "bloom" in the new version of the manuscript. We replaced that expression with:
revealed the heterogeneity of the chlorophyll EEWs in the Mediterranean Sea
at lines 307-308.

– p10 l310 : Furthermore ?
Thank you for the correction. However, we preferred to delete the whole sentence at old lines 310-311, as reported in the next reply.

– p10 l310 : you could have shown the "spatio-temporal persistence", it looks like a nice index. Why not show it ?

We did not include the map of the spatio-temporal persistence in the first version of the manuscript because this additional index is directly obtained as the product of two indexes, more meaningful in our opinion, which have been already shown in Fig. 5: uniformity, i.e., (spatial) persistency of the EEW, and duration, i.e., total time of occurrence of the EEW.

We recognised that this index should have been defined in Sect. 2.1.2 before its mention in Discussion, but we preferred to avoid it, to not weigh down the manuscript. Therefore, we decided to delete the sentence at old lines 310-311.

– p12 l360 to 374 : Good idea!

Thank you for the comment.

– p12 l375 : "A critical parameter of our method is the choice of the local percentile threshold" - I agree looks like one of the key of the method. but why this choice of a simple percentile threshold, and not include the local annual cycle (maybe + a*STD) in the threshold (As i mentioned above depending what you want to analyse, it can be justified, it can be the right choice) ?

We agree that the choice of the threshold depends on the scientific question. Please see our reply to the Overall Comments.

– p13 l 197 : "Of the clusters with the highest content of all the indexes has been generally maintained both in case of higher and lower thresholds" - rephrasing : of the clusters with the highest index values,...,

Done

– p13 l396 : "A key issue" - not issue, it is one of the strength of this method, not issue i think, and from all what you could do in your study because of that.

We agree with your comment. We rephrased "key issue", by using:

key point

at line 423.

– p13 l400 : "The time series in the grid point" - rephrase : Each grid point's time serie

Thank you for the suggestion.

The sentence including this expression was corrected by the English Editing Service, but the indicated expression was not modified.

– p13 l400 : " allowed to maintain a definition of "extreme" relative to the local ecosystem properties." This i do not agree. in some places like the most oligotrophic regions, you probably find extremes, but in the bloom regions, it is not.

We do not agree with this observation. Also the time series recorded in points belonging to bloom regions (e.g. Gulf of Lion) can show an inter-annual variability such that the 99th percentile threshold is overcome only in some years, as shown in Fig. R1.2 in the first part of this reply.

–P23-Fig4–You talk about the MLD in the text,but you don't show it on the plot. Of course, we can guess the Mixed layer is very deep where the NO3 is high and Chl low, but, it might be good to add iso-contour with depth values on the Chl plot for example. That would help both the writer and the reader. – very nice bloom in the Legurian sub- basin! You must have a very high res atm model with high freq coupling. you should add these details in the model description. It help understand the results.

In the reviewed version of the manuscript we added further details related to the atmospheric forcing in the model description, at lines 158-160:

The atmospheric fields used to force the simulation come from a 12 km horizontal resolution regional downscaling of ERA-Interim reanalysis (Llasses et al., 2016; Reale et al., 2017) and drive the simulation every 3 hours.,

thanks for the suggestion.

With regard to MLD, we have already plotted its time series in three points, internal, peripheral and external to the EEW in Appendix (Figs. A.2-A.4) to help the interpretation of the results.

We recognise that including MLD also in Fig. 4 can help the reader, but we are worried about the readability of the new resulting figure, since Fig. 4 is already full of detailed information. Thus, we decided to keep Fig.4 as it is now and to refer to Figs. A.2-A.4 for MLD evolution.

– P24 - Fig 5a – Difficult to interpret.... and the color-scale does not help. how many EEW occur per year ? how many on the hole period ? I don't understand what you mean here.

We recognise that Fig. 5 in the previous version of the manuscript needed graphic improvement. However, Fig. 5a represented in each grid point the probability of occurrence of more than one EEW per year. However, considering Reviewer#1's comment, we decided to modify it, by representing more simply the total number of EEWs in the period 1994-2012. Therefore, we replaced Fig. 5a with the following (Fig. R1.3):

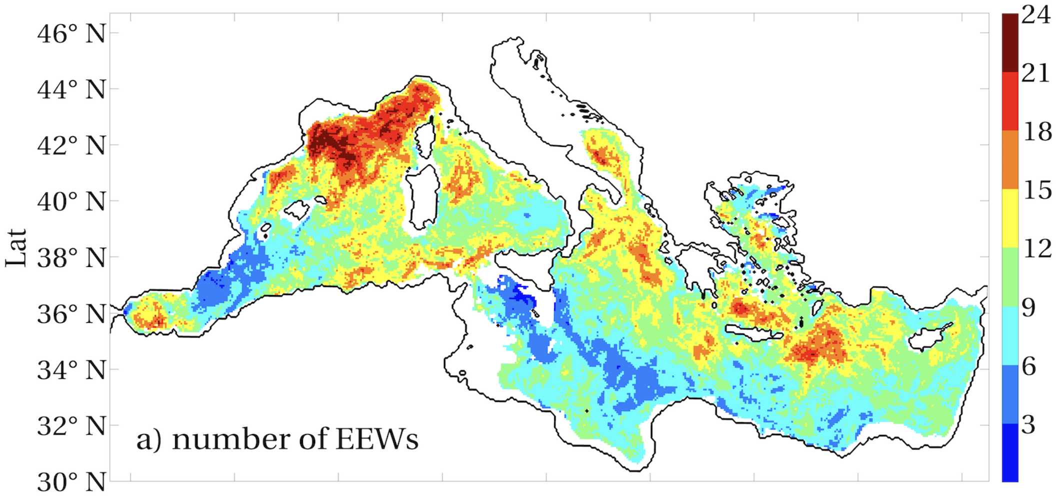

Fig. R1.3 - Proposed reviewed Fig. 5a.

and the first part of the Fig.5 caption accordingly:

Fig.5: Number of surface chlorophyll EEWs that occurred in Mediterranean Sea in 1994-2012 (a) and means of the indexes referring to the EEWs:...

Moreover, we modified the text referred to Fig. 5a, in Sect. 3.2.1 at lines 230-234, as:
Figure 5 displays the total number of EEWs that occurred in each point of the Mediterranean domain (Fig.5a) and the mean values of the EEW indexes, which were computed as the mean of the indexes of all the EEWs that involved that point (Figs. 5b-f).
Since some Mediterranean areas show more than one EEW per year (as can be inferred from Fig. 5a), the initiation time in each grid point and year was associated with the most severe EEW of that year.
and in Discussion, at lines 329-330:
The initiation index was excluded from the computation since there are areas of the basin showing more than one EEW per year per grid point (Fig. 5a).

– P27 - Fig A.2, A.3, A.4 – I cannot do the difference between the climatological line end the 2005 one. Please, try with different dashed or doted line to find one that we really can see.
Thank you for your comment. We have improved the graphic quality of the Figs. A.2, A.3, A.4 in the new version of the manuscript, as reported here for the new Fig. A.2 (Fig. R1.4). The other figures have been modified accordingly.

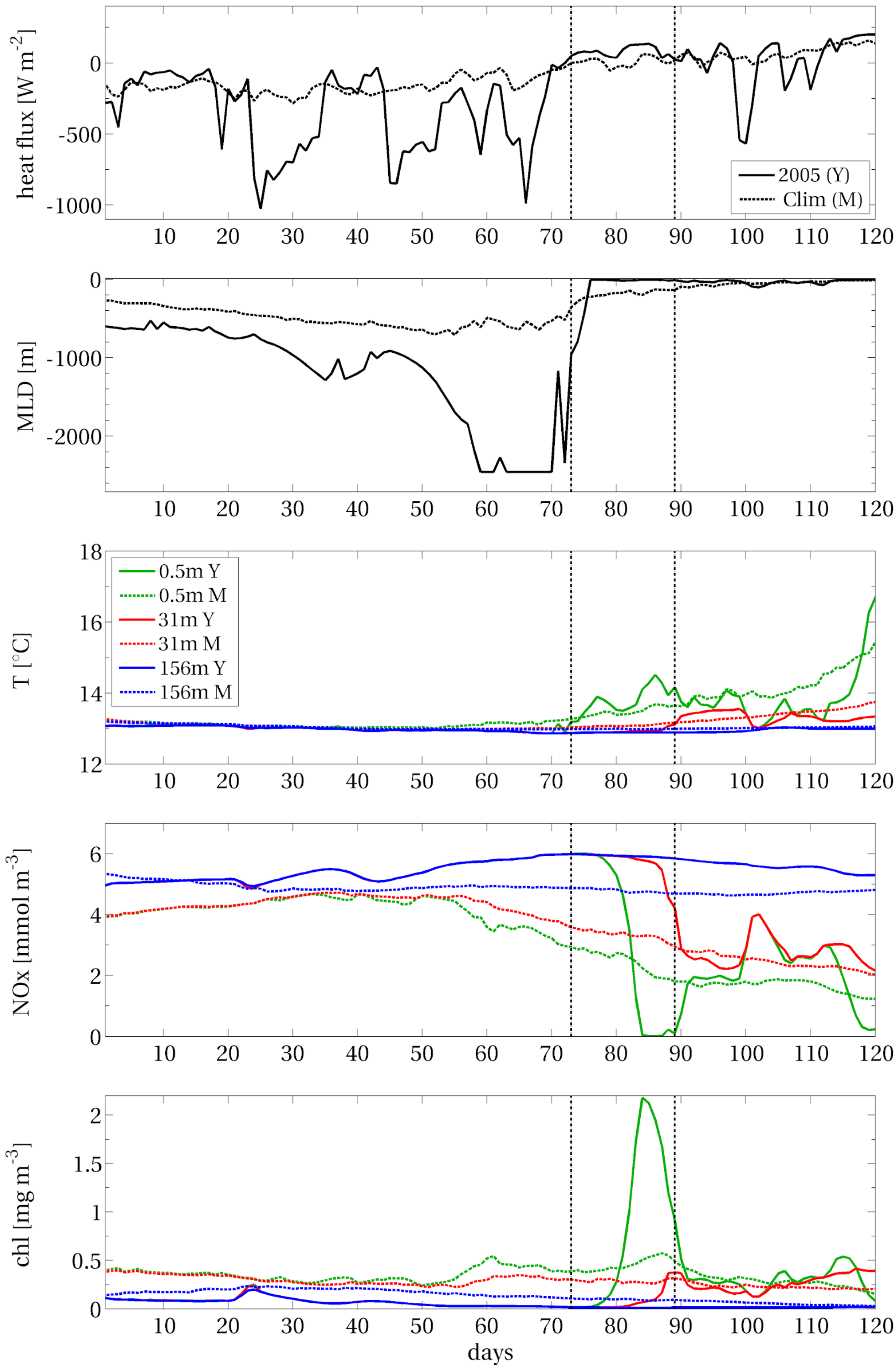

Fig. R1.4 - Proposed reviewed Fig. A.2.

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Reply to Reviewer#2's comments

We sincerely thank Reviewer#2 for his/her comments, which gave us the opportunity to deepen some points of our paper.
We indicate our reply in blue colour and the corrections of the manuscript text in italic red.
The English language has been revised by an Editing Service, as proved by the certificate at the end of the document.

The manuscript "Characterisation of extreme events waves in marine ecosystems: the case of Mediterranean Sea" describes a new method to characterize extreme events bases upon simulated chlorophyll concentrations for the period 1994-2012. Using a cluster analysis applied to a set of indices that define the occurrence of extreme events waves, different ecosystem regimes were defined. In my opinion, the manuscript is very interesting and deserves publication in Biogeosciences after minor to moderate revisions. In detail:

1) The language should be checked by a native English speaking person. There are several typos that should be removed. For instance in line 270 there is a reference to Fig. 9 that does not exist.

We have carefully revised the text references to Figures and Tables and we sent the new version of the manuscript to an English Editing Service (whose certificate is added at the end of this document).

2) The method uses surfaces chlorophyll concentrations averaged over the uppermost 10 m and does not consider vertical profiles. Please discuss why subsurface blooms do not play a role.

We considered surface chlorophyll particularly suitable to show the functioning of the method, since surface chlorophyll has been widely investigated in literature and it is comparable also with remote sensing measurements (as done in Sect. 3.1, Fig. 4). However, also subsurface processes (e.g., associated to the deep chlorophyll maximum feature) can be analysed by our method, using the same model implementation (which provides 3D chlorophyll concentration fields). For sure, it can be a further interesting application of our method and we have specified it in the new version of the manuscript, in Sect. 4, within a deepen discussion about the general validity of the model and its possible applications.
In particular, we replaced the two sentences at old lines 360-364 at lines 394-403 by:
In fact, we have applied this method to surface chlorophyll, as one of the most representative and investigated variables of the marine ecosystem, which potentially influences ecosystem function (e.g., food web and carbon fluxes). However, our method can be applied to any ecosystem variable, including other phytoplankton variables (e.g., HAB-like phytoplankton groups, Vila and Masó, 2005), temperature, oxygen and fluxes (e.g., carbon fluxes at the ocean-atmosphere interface, von Schuckmann et al., 2018). The C(x,y,t) variable can be defined at the surface, the sea bottom (e.g., oxygen minimum or oxygen deficiency, OSPAR, 2013; Ciavatta et al., 2016), and specific surfaces in the ocean interior (e.g., deep chlorophyll maximum, Lavigne et al., 2015; Salon et al., 2019), or it can be vertically integrated (e.g., integrated chlorophyll, which accounts for subsurface growth of phytoplankton). In some cases, the selected variable may require multiplication by the cell volume (e.g., if the variable is a concentration) or by the cell area (e.g., for surface fluxes and vertically

integrated variables) in eq. (2.3) and eq. (2.4) to provide a consistent and meaningful definition of the severity and the excess indexes, respectively.

This part of the Discussion section refers to the modified definitions of severity and excess indexes (eqs. (2.3) and (2.4)):

$$S = \sum_{(x,y)\in A} M(x,y) = \sum_{(x,y)\in A} \sum_{j\in J_{(x,y)}} C_j(x,y) \quad (2.3)$$

$$S = \sum_{(x,y)\in A} M(x,y) = \sum_{(x,y)\in A} \sum_{j\in J_{(x,y)}} C_j(x,y) \quad (2.4)$$

at lines 127 and 131, respectively, and to the lines 133-135:

Depending on the ecosystem variable under investigation, eqs. (2.3) and (2.4) may require multiplication by the cell volume or by the cell area in the inner summation to provide a consistent unit of measurement (e.g., if $C_j(x,y)$ is a concentration, it should be multiplied by the cell volume V(x,y) to obtain an actual mass).,

which were added as a consequence of the extension of the method to any ecosystem variable, declared at line 74:

with reference to any ecosystem variable C(x,y,z,t)

Anyway, as we replied also to Reviewer#1, we decided to avoid the reference to "bloom" processes in the new version of the manuscript, and to restrict our argumentation to extreme events (i.e., top 1% values of surface chlorophyll distribution).

3) It is discussed but I am still worried about the stability of the identified regimes using different thresholds. You showed that the clustering of the mean values of the indices do not change much. However, are there changes in the spatial distribution of the regimes shown by Figure 6?

Thank you for this comment, which gives us the opportunity to deepen some aspects.

We applied the fuzzy k-means analysis also in case of 98th and 99.5th percentile thresholds and we report the results in Figs. R2.1 and R2.2, respectively.

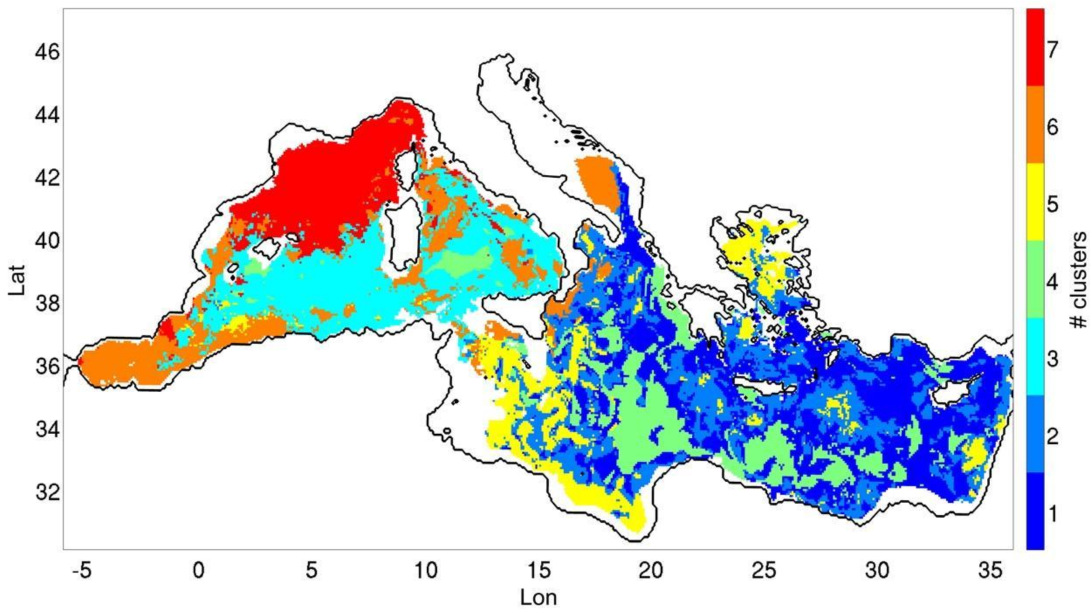

Figure R2.1 Fuzzy clusters with maximum membership, in case of 98th percentile threshold.

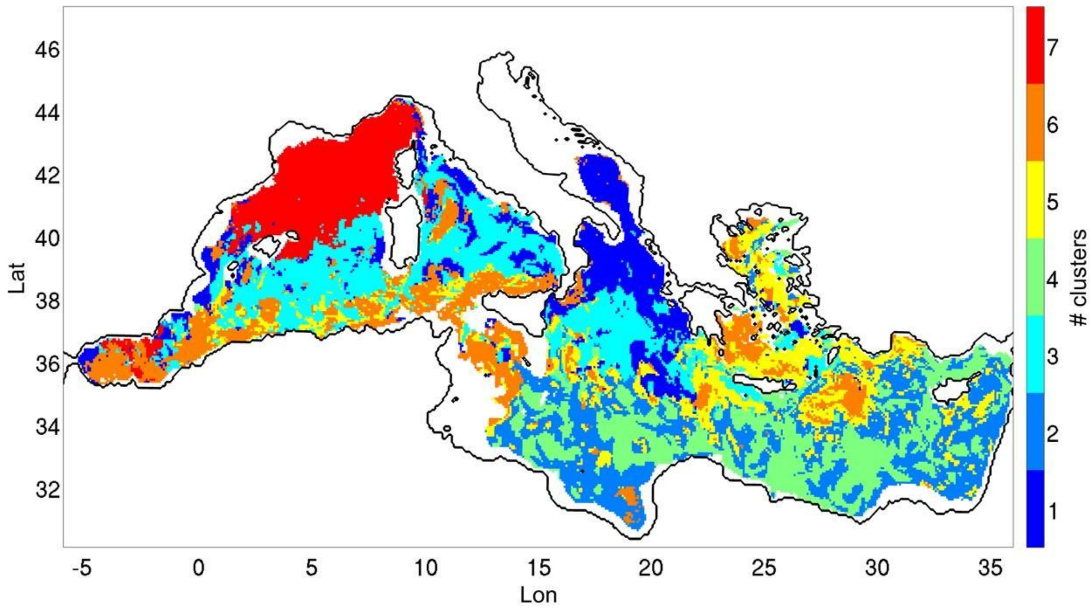

Figure R2.2 Fuzzy clusters with maximum membership, in case of 99.5th percentile threshold.

From a general point of view, the cluster distribution for 99.5th percentile threshold (Fig. R2.2) is very similar to the cluster distribution for 99th percentile (Fig. 6 of the manuscript), while the cluster distribution for 98th percentile (Fig. R2.1) differs mainly in Ionian and Levantine Sea.

More in details, the spatial distribution of clusters #3, #6, #7 in the western basin does not considerably change with respect to Fig. 6 of the manuscript, as well as the spatial distribution of cluster #4 in the eastern basin.
Clusters #1, #2, #3 #5 and #6 display instead differences, mainly in the cluster distribution for 98th percentile, in the eastern basin, i.e., southern Adriatic Sea, central Ionian Sea, Aegean Sea, Libyan coast and eastern Levantine Sea.

Since the identification of clusters depends on four indexes (i.e., mean severity, uniformity, duration, anomaly) which do not necessarily scale in the same way with the local threshold, the fact that the spatial distribution resulting from the fuzzy k-means analysis (as "combination" of the four indexes) for different thresholds can differ from Fig. 6 is a reasonable result.
Moreover, it should be highlighted that Figs. 6, R2.1, R2.2 show the clusters referred to the maximum membership.
In addition to maximum membership, we also considered the "confusion index" (Burrough et al., 1997), which, applied to our case, quantifies how well each point of the Mediterranean domain has been classified. High values of the confusion index (CI) index are related to higher sensitivity of some areas in the cluster classification with respect to variations in the local threshold (i.e., to differences of Figs. R2.1, R2.2 with respect to Fig. 6).
We estimated the confusion index (CI) as:
$CI=1-(MF_{max}-MF_{max2})$,
where MF_{max} denotes the dominant membership value and MF_{max2} is the subdominant membership value for each point, and we computed it in case of 99th percentile threshold. Figure R2.3 shows values of CI greater than 0.7 (i.e., "high values" of CI) as black dotted points.

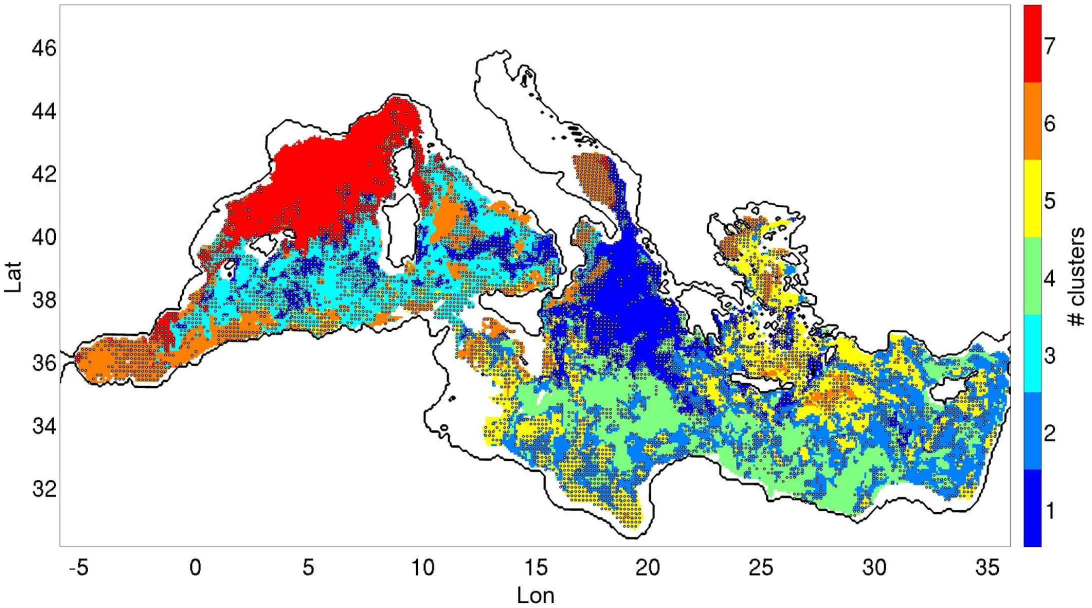

Figure R2.3 Fuzzy clusters with maximum membership, in case of 99th percentile threshold, with black points indicating a confusion index higher than 0.7.

We can observe that most of the areas displaying differences in the spatial distribution of the clusters with respect to variations in the threshold (Figs. R2.1, R2.2) correspond to high CI in the reference case (Fig. R2.3) and that the identification of the clusters generally appears to be consistent with the other two clusterizations.

We recognised that this point deserved a revision in the manuscript.
Therefore, we replaced Fig. 6 by Fig. R2.3 (updated to the format requested by the journal) in the revised manuscript, adding the expression:
with black points indicating a confusion index higher than 0.7
at the end of the figure caption and the definition of the confusion index in the text. Accordingly, our statement about the robustness of the classification (old lines 387-390) have been reformulated and referred to this new version of Fig. 6.
In particular, we replaced old line 239 by:
Seven Mediterranean Sea regions with similar chlorophyll EEWs phenomenology were identified by the maximum membership values and are indicated by different colours in Fig. 6. To evaluate the robustness of the clusterisation, we also computed the "confusion index", i.e., one minus the difference between the dominant and subdominant memberships for each point (Burrough et al., 1997). We obtained a value less than 0.7 (i.e., limit for "high confusion" condition) for the largest part of the domain. Values higher than 0.7 are shown in only patchy and limited areas (e.g., part of the southern Adriatic Sea, Fig. 6). Moreover, we computed the mean…
at lines 247-252.

Moreover, we replaced old lines 318-320 by:
We obtained robust clusterisation, with only some areas of the domain showing a high confusion index (Fig. 6). This subdivision of the Mediterranean Sea displays several similarities to previous Mediterranean bio-regionalisations (D'Ortenzio and Ribera D'Alcalà, 2009; Lazzari et al., 2012;

Ayata et al., 2018; Salon et al., 2019), indicating that the four indexes are meaningful in characterising the heterogeneity of the basin.
at lines 334-337.
We replaced old lines 387-390 by:
Overall, Fig. 7 shows that the identification of the clusters with the highest index values was generally maintained in the case of both higher and lower thresholds, confirming that the main regimes of chlorophyll EEW were identified in a robust way.
at lines 390-391.
Finally, we further clarified the text at old lines 263-265, that we reformulated at lines 275-278 as:
We repeated the steps of the method (Sects. 2.1.1-2.1.3) up to obtaining the mean maps of the indexes on the Mediterranean domain for the 98th and 99.5th percentile thresholds. Then, we spatially averaged the values of the indexes within the seven clusters of Fig. 6 and finally we computed the total means by averaging the means of the seven clusters.

4) In Section 4 and the Appendix, ecosystem dynamics characterizing some of the regimes are discussed. However, some clusters lack any dynamical explanation and might be rather artificial. It would increase the scientific value of the manuscript if you could discuss these clusters more in detail as you have done it for NWM in the Appendix.

Section 3 and Appendix of the first version of the manuscript present in detail one of the extreme event waves (EEWs) identified in the 1994-2012 dataset, to show how the method works. In particular, Appendix highlighted that the method catches all and only the relevant information of the event. We selected the EEW associated to the highest value of mean severity of the whole dataset (and occurred within the area covered by cluster #7) as a particularly meaningful case.
Since the main focus of the paper is to propose a method to identify and classify EEWs, rather than to analyse in detail surface chlorophyll dynamics, we did not include other examples of EEWs (e.g., associated to areas covered by other clusters, as suggested) in the first version of the manuscript, avoiding to enlarge too much the length of the manuscript and to shift the attention more on the specific application than on the method. For the same reasons, we decided not to add new figures and comments in Appendix of the revised manuscript.
However, if the Reviewer#2 still suggests to do it, we are open to include other examples of EEWs occurring in areas covered by other clusters.

5) In the abstract you mentioned that "There is a growing interest about events that can affect ecosystem functions and services in a changing climate". However, is the method suitable for following the temporal shifts in the regimes without any discontinuities? I suggest that you split the period in half and that you use the cluster analysis for both periods. By this, the impact of trends in some of the indices on the spatial distribution of the regimes might be investigated and compared with observed changes.

Thank you for the comment.
Yes, our method is suitable for following the temporal changes in the characteristics of the EEWs, provided that the time series is long enough for a robust trend or regime shift evaluation on a multi-decadal scale. Unfortunately, our time series is not very long (i.e., 19 years). Thus, we think that the

approach to split the chlorophyll dataset in two parts, i.e. 9-10 years for each part, would not guarantee statistical robustness to the analysis.

Indeed, we conducted a non parametric analysis of the trend slope (Theil-Sen method) and showed the results in Tab. 2 of the manuscript, by reporting the cases in which the ratio between slope and mean is higher than 1% (red cells) and lower than -1% (blue cells). For sake of clarity, we report here the annual time series (and trend slope) of each cluster for the duration, uniformity, mean severity and anomaly indexes (Figs. R2.4-R2.7). As it can be intuitively grasped, the length of the time series does not allow further speculations on temporal changes of the EEWs characterisation and classification.

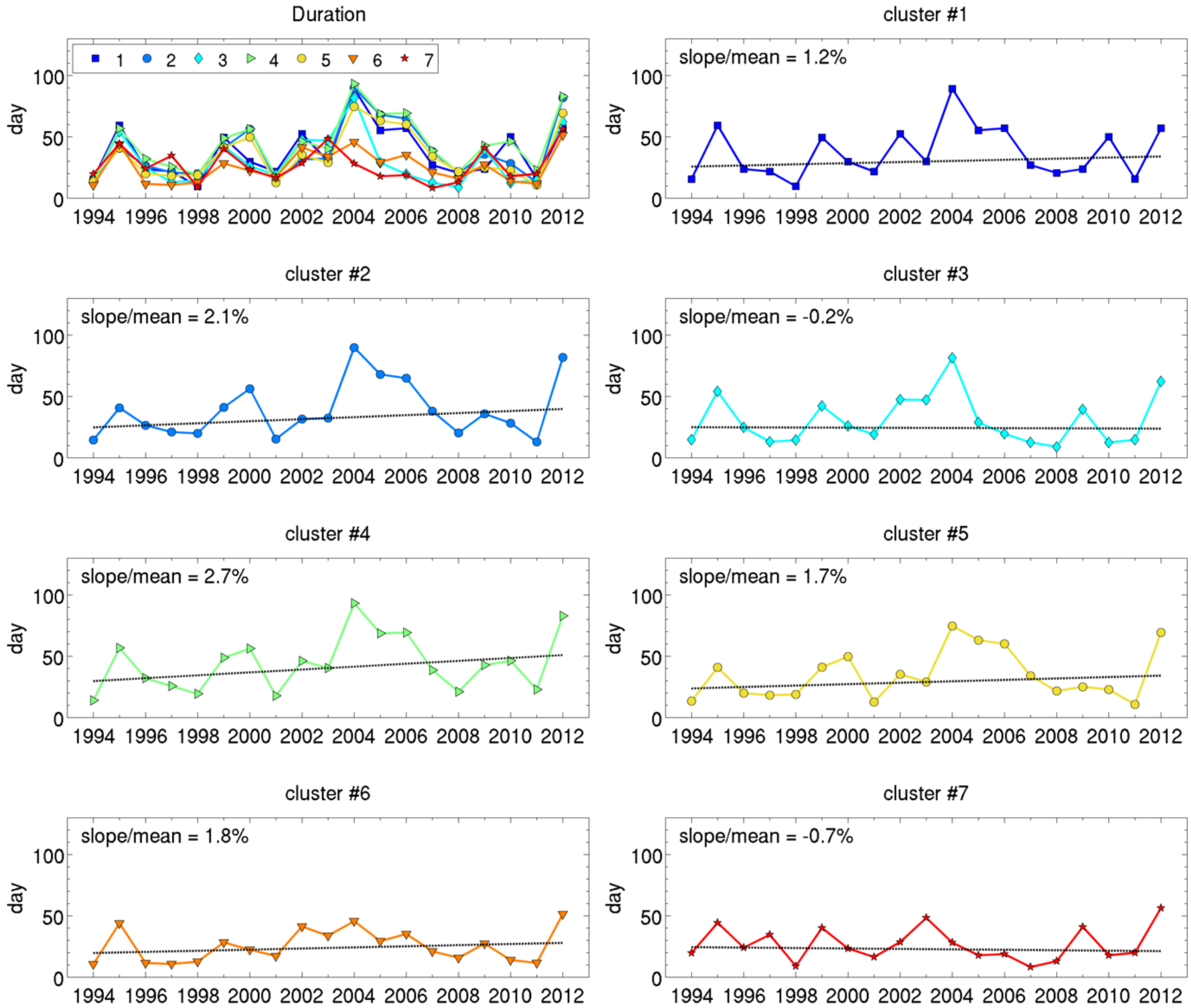

Figure R2.4 Trend evaluation (as slope over mean) on the clusters in Fig.6, referred to duration index.

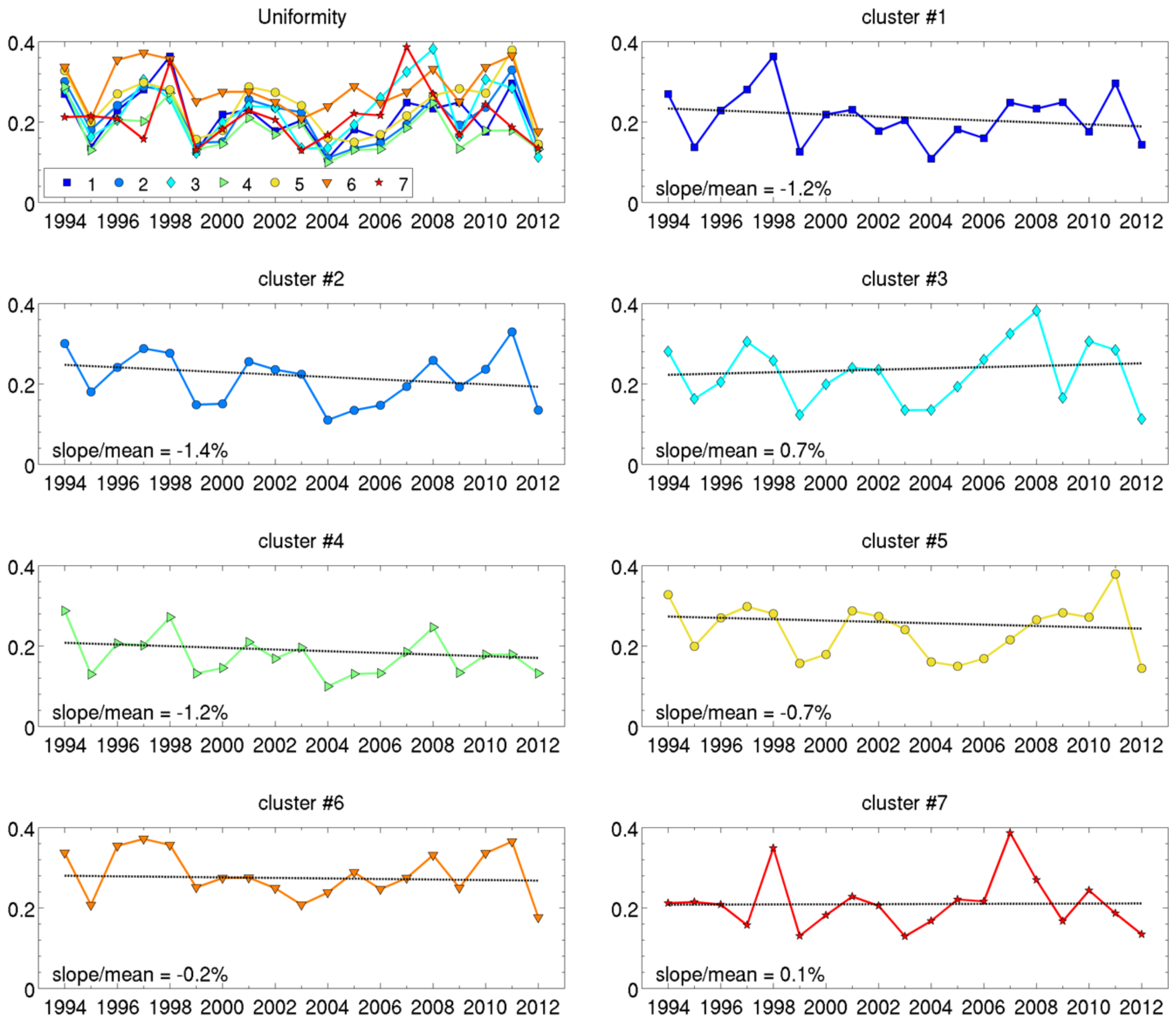

Figure R2.5 As Fig. R2.4, but referred to uniformity index.

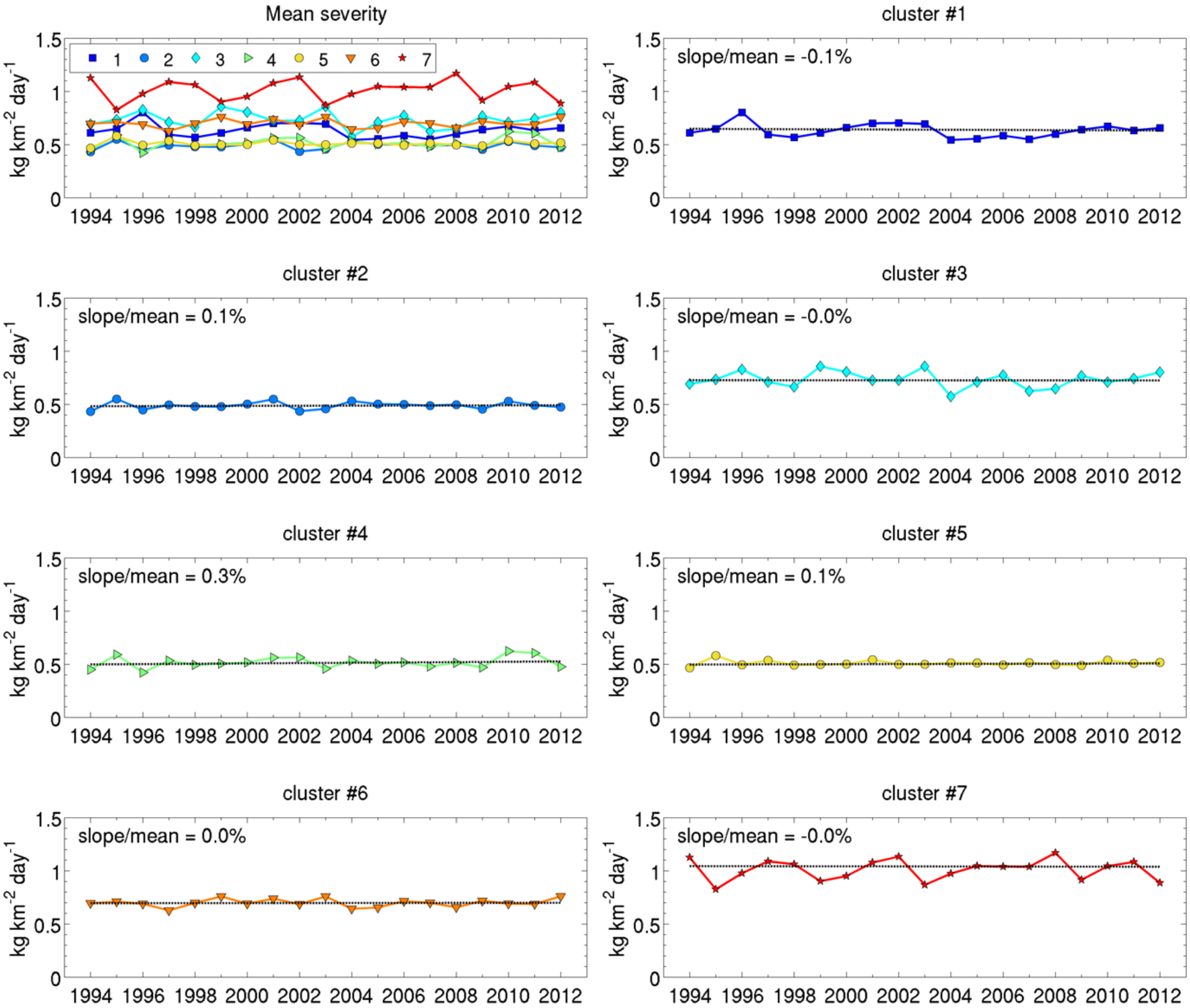

Figure R2.6 As Fig. R2.4, but referred to mean severity index.

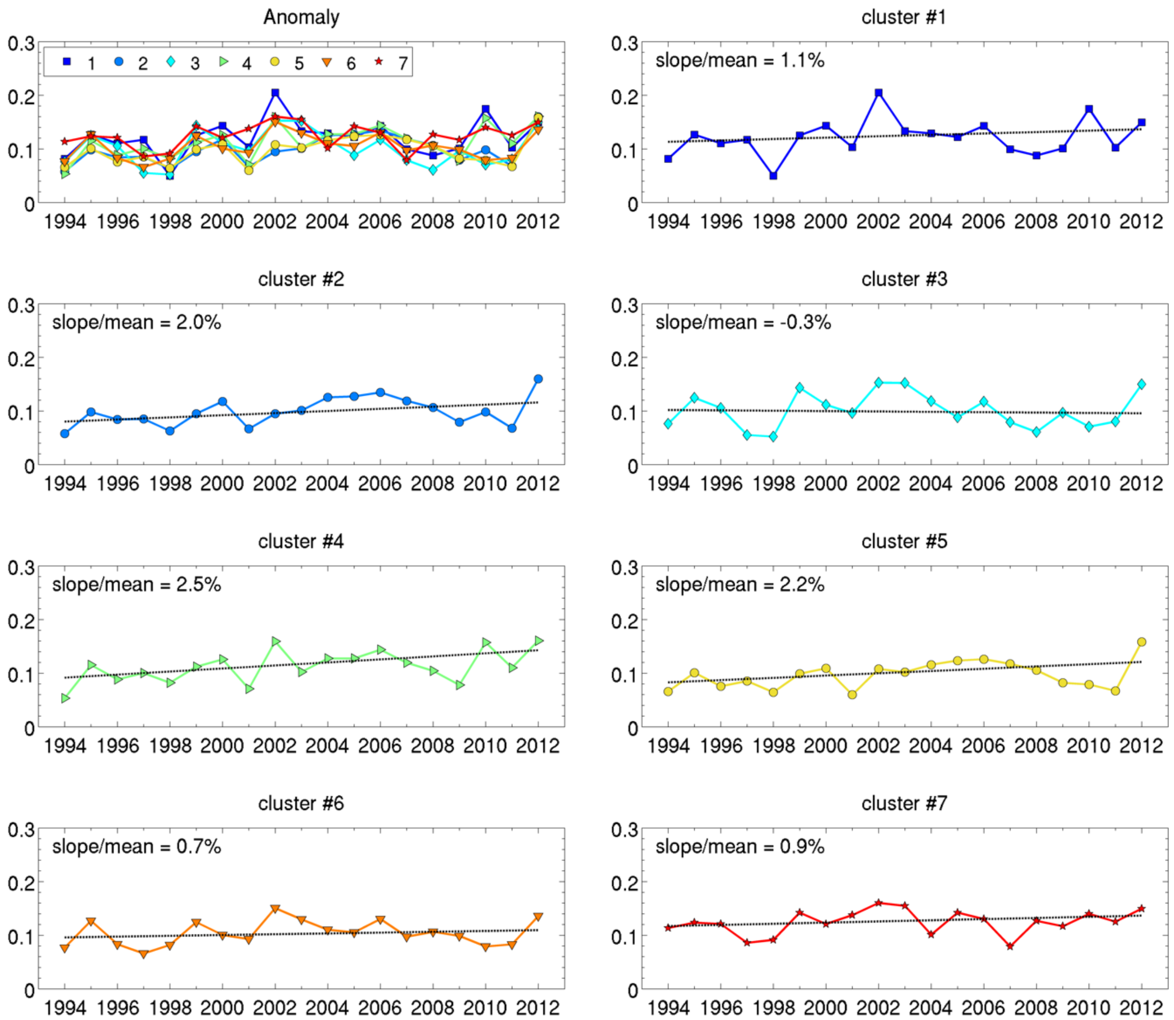

Figure R2.7 As Fig. R2.4, but referred to anomaly index.

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Extreme event waves in marine ecosystems: an application to Mediterranean Sea surface chlorophyll

Valeria Di Biagio, Gianpiero Cossarini, Stefano Salon, Cosimo Solidoro
National Institute of Oceanography and Applied Geophysics - OGS
Correspondence to: Valeria Di Biagio (vdibiagio@inogs.it)

Abstract. We propose a new method to identify and characterise the occurrence of prolonged extreme events in marine ecosystems at the basin scale. There is growing interest in events that can affect ecosystem functions and services in a changing climate. Our method identifies extreme events as the peak occurrences over a predefined threshold (i.e., the 99th percentile) computed from a local time series and defines a series of extreme events that are connected over space and time as an extreme event wave (EEW). The main features of EEWs are then characterised by a set of novel indexes, which are referred to as initiation, extent, duration and strength. The indexes associated with the areas covered by each EEW were then statistically analysed to highlight the main features of the EEWs in the considered domain. We applied the method to a multidecadal series of winter-spring daily chlorophyll fields that was produced by a validated coupled hydrodynamic-biogeochemical model of the Mediterranean open sea ecosystem. This application allowed us to identify and characterise surface chlorophyll EEWs in the period from 1994-2012. Finally, a fuzzy classification of EEW indexes provided bio-regionalisation of the Mediterranean Sea based on the occurrence of chlorophyll EEWs with different regimes.

1 Introduction

Extreme events affecting the Earth system have been widely investigated in hydrology and atmospheric sciences (e.g., Delaunay, 1988; Katz, 1999; Luterbacher et al., 2004; Allan and Soden, 2008; Perkins and Alexander, 2013; Tramblay et al., 2014), also in connection with social sciences (Raymond et al., 2020). The study of extreme events in the ocean has mainly focused on sea levels (e.g., Zhang and Sheng, 2015), especially in relation to hydrology (e.g., Walsh et al., 2012), with recent works on extreme wave height (e.g., Hansom et al., 2014), current velocity (e.g., Green and Stigebrandt, 2003) and marine heat waves (e.g., Hobday et al., 2016, Galli et al., 2017). However, extreme events in marine biosphere properties (e.g., biogeochemical species concentrations) have received relatively little attention in recent years, despite the related heavy impacts on marine ecosystem functions and services (e.g., Zhang et al., 2010), with cascading effects at large scales on biogeochemical cycles (e.g., Doney, 2010).

Ocean warming, increase of atmospheric CO_2 and anthropogenic eutrophication are among the major stressors of marine ecosystems (Hoegh-Guldberg et al., 2018) and potential drivers of extreme events. Therefore, estimates of sea surface temperature (SST), seawater pH, dissolved oxygen and the saturation state of $CaCO_3$ minerals are often used as probes to monitor marine ecosystem health (e.g., Belkin, 2009; Andersson et al., 2011; Paulmier et al., 2011).

In particular, some studies on marine heat waves (Hobday et al., 2016), hypoxia events (e.g., Conley et al., 2009) and low aragonite saturation states (Hauri et al., 2013) have identified extreme events at a given site by starting from the values of a specific ecosystem variable that are above/below a certain threshold for a finite time duration. Although a common definition of "extreme event" in this context is lacking, its main emerging features include (i) the intensity (i.e., the absolute difference of the variable value with respect to the threshold), which is considered a large deviation from a reference ecological state; (ii) the duration, which is considered a further stress factor on the ecosystem and is eventually combined with the intensity in an overall "severity" index (as in Hauri et al., 2013); and (iii) the local characteristic, which is linked to the heterogeneity of the ecosystem within the area of interest and/or due to sparse data sampling (e.g., from fixed stations). In fact, the spatial extension of an extreme event is possibly evaluated in retrospect (e.g., Rabalais et al., 2002; Galli et al., 2017).

Our purpose is to design a general method that is able to not only capture the previously listed features of an "extreme event" but also account for the persistence of the event within a certain impacted area and over a specific time duration (as Andreadis et al., 2005 and Sheffield et al., 2009 proceeded in case of droughts) up to the basin scale.

The use of numerical models has been shown to be necessary to conduct such a study, which requires seamless and long sampling times at high frequency at the basin scale. In fact, remote sensing observations are limited by cloud coverage and L4 data are based on filtered reconstructions (using climatology or the EOF method, as in Volpe et al., 2018), which can partly mask the occurrence of extreme events. On the other hand, in situ measurements do not offer suitable spatial and temporal sampling at the basin scale and can lack standardisation. In contrast, numerical models provide data with continuity at high frequency in both time and space. Moreover, models also account for physical and biological processes that occur in marine ecosystems in subsurface layers (e.g., vertical mixing, nutrient transport), allowing for a more complete reconstruction of the dynamics of extreme events.

For our investigation, we used the dataset provided by the MITgcm-BFM hydrodynamic-biogeochemical model of the Mediterranean Sea ecosystem at 1/12° horizontal resolution (Di Biagio et al., 2019).

In particular, we applied the proposed method to the surface chlorophyll concentration, an essential ocean variable (EOV, e.g., Muller-Karger et al. 2018) that is representative of the marine ecosystem state and evolution. This application allowed us to identify the extreme events of surface chlorophyll, which can correspond to both phytoplankton blooms (Desmit et al., 2018) and positive anomalies with values too low to be actually considered "blooms" (e.g., in the Levantine Sea). In fact, due to the general oligotrophy of the basin, marked increases in phytoplankton chlorophyll are strictly considered "blooms" in only some regions (north-western Mediterranean Sea, Alboran Sea, Catalan-northern Balearic area, isolated coastal areas near some river mouths, see Siokou-Frangou et al., 2010). Our method is instead formulated to identify extreme values of chlorophyll as peaks over a threshold defined in the time series of all basin points, i.e., from local and statistical perspectives. We focused our investigation on the open sea domain, thus avoiding the areas that are directly affected by bottom and riverine dynamics (e.g., Oubelkheir et al., 2014).

The article is structured as follows. The Material and methods section (Sect. 2) is divided into two parts, presenting the method to identify the extreme events and the model-derived dataset that was used (Sect. 2.1 and Sect. 2.2, respectively). Section 2.1 consists of three parts: the identification of local extreme events and extreme event waves (EEWs, Sect. 2.1.1), characterisation (Sect. 2.1.2) and classification (Sect. 2.1.3). The results are presented in Sect. 3. A chlorophyll EEW, identified and characterised following the proposed method, is described in Sect. 3.1, with further analyses in terms of its internal physical and biogeochemical dynamics given in the Appendix. Section 3.2 presents the classification of all the modelled chlorophyll EEWs in the Mediterranean Sea from 1994-2012, including a sensitivity test for the local thresholds. Section 4 includes a discussion about the proposed method and the main results, and it is followed by the conclusions in Sect. 5.

2 Material and methods

2.1 The method for the spatio-temporal investigation of extreme events

The method illustrated here allows us to identify, characterise and classify the "extreme event wave" in marine ecosystems, accounting for their time duration, intensity and spatial extension, and with reference to any ecosystem variable $C(x,y,z,t)$. Hereafter, we refer to a daily sampling of the variable time series and a two-dimensional variable $C(x,y,t)$ for simplicity. However, the method can be easily extended to any regular time discretization and to the 3D spatial case with few modifications in the definition of the indexes, as discussed in Sect. 4.

2.1.1 Identification

We define "extreme events" as the occurrences of values $C(x,y,t)$ that are higher than a reference percentile threshold (e.g., Asch et al., 2019), computed over the whole time series of the variable. In particular, we search for the peaks over threshold (POTs), with the threshold referring to the 99th percentile of the time series. Extreme events are thus represented by the highest values (i.e., top 1%) of the variable distribution observed in the (x,y) point. These events are "rare" events and are selected from the total records independently from their distribution over the years.
Then, we identify a "wave" of extreme events, or "extreme event wave" (EEW), as a set of extreme events that are connected in space and time. Thus, an EEW tracks anomalous events that are not merely local but that co-occur in more than one grid point and possibly are transported in space and evolve over time.
Operationally, the spatial and temporal occurrence of all the POTs can be mapped on a binary 3D matrix, representing the (2D map x day) flags of the extreme events, equal to 1 for the (x,y,t) points of POT occurrence and 0 for the points without POT occurrence. EEWs are then defined as sets of POT occurrences that are "the closest neighbours" in space and in time.
The EEW definition is thus a filter for the spatio-temporal dataset: it allows us to identify single events that affect a portion of the domain for a certain time period, in which all the involved points display extreme values of the selected variable. In the EEW, the spatial contiguity of the points with variable values above their own threshold at the same time is a further request

(e.g., Andreadis et al., 2005), which adds to the temporal contiguity typical of the definition of local extreme events (e.g., Hobday et al., 2016).

2.1.2 Characterisation

We introduce the characterisation of EEWs based on two kinds of metrics: spatio-temporal indexes (sketched in Fig. 1) and strength indexes (sketched in Fig. 2).

The spatio-temporal indexes, which are used to localise and describe an EEW in space and time (green shape in Fig. 1), are the following:

- the *initiation*, as the first day when at least one POT belonging to the EEW occurs;
- the *duration* T (yellow arrow in Fig. 1), as the time interval in which there are POTs included in the EEW. This metric is labelled by the maximum temporal difference between two POTs of the EEW, in *day* units;
- the *area* A (grey area in Fig. 1), as the union of all the surface grid cells housing the POTs included in the EEW. This metric is labelled by the sum of these cell areas, measured in km^2;
- the *width* W, as the measure of the spatio-temporal region occupied by the EEW. This metric is computed as the sum, over the grid points covered by A, of the spatio-temporal regions identified by the grid point area as the base and the total time interval of POTs of the EEW referred to that grid point as the height. This metric is measured in units of $km^2 \times day$;
- the *uniformity* U, as the ratio between the width W and the spatio-temporal region defined by the prism with A as the base and T as the height:

  $$U = \frac{W}{AT} \quad (2.1)$$

  This metric represents the percentage of the prism that is occupied by the EEW and quantifies how persistent (on average) the EEW is in the single grid point belonging to A.

We excluded both EEWs with duration T<2 days (e.g., Asch et al., 2019) to neglect possible transient spikes and EEWs with area $A < 4\Delta x \times 4\Delta y$ (with Δx and Δy grid spacing in the zonal and meridional directions, respectively) since the estimated factor between the effective resolution and grid spacing of the numerical models is 4 or more (Grasso, 2000).

The strength indexes of an EEW can be defined starting from some quantities that are introduced locally (sketched in the top right box of Fig. 1). That is, considering the time series at each grid point (x,y), the $j-th$ POT included in the EEW is characterised by the value $C_j(x,y)$ of the ecosystem variable and by the intensity $I_j(x,y)$ above the threshold $p99(x,y)$ computed on the time series:

$$I_j(x,y) = C_j(x,y) - p99(x,y). \quad (2.2)$$

Given the set $J_{(x,y)}$ of all the occurrence indexes j of the POTs that refer to the specific grid point (x,y) and are included in the EEW, we can define the following strength indexes:

- the *severity S*, as the total "mass" of the variable characterising the EEW, which is computed as the sum over the grid points covered by *A* of the local sum *M(x,y)* of the "masses" supplied by the POTs included in the EEW:

$$S = \sum_{(x,y)\in A} M(x,y) = \sum_{(x,y)\in A} \sum_{j\in J_{(x,y)}} C_j(x,y) \quad (2.3)$$

  The severity is represented in a simplified way in Fig. 2a.

- the *excess E*, as the total intensity above the "threshold" (i.e., the locus of points of the local thresholds, *P99*), associated with the EEW. Its formulation is analogous to eq. (2.3) but referred to $I_j(x,y)$ rather than $C_j(x,y)$:

$$E = \sum_{(x,y)\in A} I(x,y) = \sum_{(x,y)\in A} \sum_{j\in J_{(x,y)}} I_j(x,y) \quad (2.4)$$

  Additionally, the excess is represented in a simplified way in Fig. 2a.

  Depending on the ecosystem variable under investigation, eqs. (2.3) and (2.4) may require multiplication by the cell volume or by the cell area in the inner summation to provide a consistent unit of measurement (e.g., if $C_j(x,y)$ is a concentration, it should be multiplied by the cell volume $V(x,y)$ to obtain an actual mass).

- the *mean severity* $< S >$, as the ratio between the severity and the width *W* of the EEW:

$$\langle S \rangle = \frac{S}{W} \quad (2.5)$$

- the *anomaly,* as the ratio between the excess and the severity:

$$AN = \frac{E}{S} \quad (2.6)$$

  This index represents the percentage of the excess in the severity of the EEW. The index, which is adimensional, is sketched in Fig. 2b for two different EEWs, which have the same severity but different excess and, thus, anomaly. Since the locus of points of the thresholds of the second EEW is lower, this EEW has a higher anomaly value than the first one and has a larger impact on the ecosystem.

2.1.3 Classification

The EEWs introduced in our formulation are identified starting from the local 99th percentile thresholds of the variable time series. The concept of "extreme" adopted in this work is related to the local characteristics of the marine ecosystem, which can be largely heterogeneous across the domain. Here, we propose a classification of EEWs suitable to highlight the main features of EEWs in the considered spatial domain.

For each index defined in Sect. 2.1.2, the values obtained for each EEW can be associated with all the points belonging to the *A* areas (Fig. 1), and then, a mean map over of the considered spatial domain can be obtained by averaging all the values of the related index point by point. Finally, fuzzy clustering analysis (Bezdek et al., 1984) can be conducted on the mean maps of all the indexes. In this way, different bio-regions of EEWs can be identified, depending on the relative weight of the indexes under consideration, and specific regimes of EEW can therefore be highlighted.

2.2 Data: Mediterranean Sea surface chlorophyll by MITgcm-BFM

We used the results of the 1994-2012 hindcast simulation discussed in Di Biagio et al. (2019) and produced by the MIT general circulation model (MITgcm, Marshall et al., 1997), coupled with the biogeochemical flux model (BFM, Vichi et al., 2015) following the online scheme described in Cossarini et al. (2017). The configuration in use has a horizontal resolution of 1/12°, with 75 unevenly spaced vertical levels. The atmospheric fields used to force the simulation come from a 12 km horizontal resolution regional downscaling of ERA-Interim reanalysis (Llasses et al., 2016; Reale et al., 2017) and drive the simulation every 3 hours.

In particular, we used the daily chlorophyll concentration computed at the surface (i.e., averaged on the first 10 *m*), restricting our investigation to the January-May period. We considered only grid points with depths greater than 200 *m*, which are identified as the "open sea". With this spatial constraint, we neglected both the coastal points, which are directly affected by river nutrient discharge, and the points where interactions with the sea bottom occur within the euphotic layer, since modelled variables in these regions are possibly affected by high uncertainties (Di Biagio et al., 2019).

The chosen MITgcm-BFM simulation has the characteristics required by the extreme events analysis: it is seamless, it provides high frequency patterns (as shown by wavelet analysis in Di Biagio et al., 2019), it lacks spurious leaps in the ecosystem state (that might occur in case of filter data assimilation process, Teruzzi et al., 2014), and it reproduces the heterogeneity of the marine ecosystem across the basin and its main biogeochemical properties.

3 Results

3.1 Chlorophyll EEWs: identification and characterisation

We applied the method illustrated in Sect. 2 to the surface chlorophyll concentration, so that $C(x,y,t) \equiv chl(x,y,t)$, measured in $mg\ m^{-3}$, with daily samplings provided by the simulated Mediterranean Sea biogeochemistry in the 1994-2012 period (Sect. 2.2). The local "extreme events" for this application thus correspond to the top 1% values of the surface chlorophyll distribution in each grid point (Sect. 2.1.1).

From the ecosystem point of view, the most suitable indexes to describe the phenomenology of the surface chlorophyll EEWs (i.e., continuous and prolonged "waves" of extreme events) are the mean severity $<S>$, the anomaly AN, the duration T and the uniformity U (Sect. 2.1.2). In fact, when considering the surface chlorophyll as a proxy for surface phytoplankton biomass (e.g., Boyce et al., 2010), the mean severity provides the mean amount of biomass supplied by the EEW to the surface layer in 1 day over a unit area of 1 km^2 and is expressed in $kg\ km^{-2}\ day^{-1}$. The anomaly index instead represents the anomalously high amount of chlorophyll with respect to the history of the local ecosystem. The duration T measures the overall ongoing impacts on the marine ecosystem, which are considered in this study as responses of ecosystem processes and status to an excess of phytoplankton biomass. On the other hand, the uniformity index quantifies the local persistence of the chlorophyll

EEW on the points included in area *A*. In fact, with constant values of *A* and *T*, an EEW with higher *U* will affect the single unit of *A* for longer times, with higher potential ecological consequences on the ecosystem unit.

Considering the temporal extension of the simulation (approximately equal to 7000 days), the computation of the 99th percentile over the time series gives a value equal to 70 for the number of POTs in each grid point. The mapping of the 99th percentile threshold values computed at each grid point throughout the basin (Fig. 3) indicates that grid points that are spatially close exhibit small differences in their threshold values and that different patterns are recognisable in the basin. Hereafter, we use the abbreviations indicated in Fig. 3 to refer to different Mediterranean Sea regions.

The total number of surface chlorophyll EEWs, which were identified by applying the definition (Sect. 2.1.1) and the further requests on the *A* and *T* indexes (Sect 2.1.2) in the investigated period, was 947. We show in Fig. 4 an example of a detected EEW, which is represented in the spatio-temporal domain and compared with remote sensing data (http://marine.copernicus.eu/, product OCEANCOLOUR_MED_CHL_L3_REP_OBSERVATIONS_009_073, Volpe et al., 2019). The values of the spatio-temporal and strength indexes computed for this EEW are summarised in Tab. 1. The EEW occurred in the Gulf of Lion (region NWM) during early spring (15th-31st March 2005). Both the model and satellite data show patterns of high values of chlorophyll in the period of EEW occurrence (second and first columns of Fig. 4, respectively). Strong increases in chlorophyll in the Gulf of Lion and the Ligurian Sea are recognisable on the satellite maps starting from 20th March, after a period of very low chlorophyll concentration (even lower than 0.05 $mg\ m^{-3}$, not shown). Although the model uses a spatial resolution (approximately equal to 7 *km*) that is coarser than the satellite resolution (1 *km*), it is able to capture a surface signature typical of deep convection dynamics (second column, compared with the first column, on 20th March). However, the comparison between the model and satellite data points out that the impact of cloud coverage on remote sensing measurements is a limiting factor for the reconstruction of the spatio-temporal dynamics of chlorophyll extreme events. The comparison of the modelled chlorophyll maps (second column) with the patterns of the daily area *A* of the EEW (third column) shows that the EEW patch actually includes points with noticeably high chlorophyll values in the region. Nevertheless, *A* also contains points with chlorophyll values that are low on the same absolute scale, yet higher than the local 99th percentile thresholds (as ensured by our procedure). Moreover, the EEW patches appear to be advected by the current velocity field (third column) and to follow both convection weakening (see plots in consecutive panels) and the patches of high nutrient concentrations in the previous days (by comparison with the right panel referred to the day before). The high values of chlorophyll recorded in the Ligurian Sea on 20th March are associated with a separate EEW (not shown).

From Tab. 1, we quantify a mean severity equal to 1.389 $kg\ km^{-2}\ day^{-1}$ and an anomaly index equal to 0.205% for this EEW. In fact, this EEW was the most severe and the sixth most anomalous in all of the EEWs identified in the Mediterranean domain, as reproduced by our simulation. This result indicates that the large amount of chlorophyll supplied by this EEW was also considerably high throughout the history of the impacted local ecosystem. Moreover, even if the overall duration of the EEW was 17 days, each unit area was actually affected for only approximately 3 days ($U\ T \approx 3\ days$). This result means that the EEW spread out in space and time with an articulated shape, as shown in Fig. 4.

In the Appendix, further analysis conducted on three points that are located internally, externally and on the border of the EEW area showed that the EEW identification actually takes into account all and only the relevant information associated with it; thus, that the proposed method acts like a filter to properly circumscribe the extreme events in space and time. In fact, this specific EEW captured the dynamics of the exceptionally intense bloom observed in the NWM in 2005 (Estrada et al., 2014; Mayot et al., 2016), which was triggered by very strong vertical mixing (and deep convection, in the internal point), followed by the restoration of stratification.

3.2 Classification in the Mediterranean Sea

This section shows the results of the basin-scale classification of all the surface chlorophyll EEWs identified from 1994-2012 (Sects. 3.2.1 and 3.2.2) by means of the spatial spreading of the values of the indexes on the areas covered by the EEWs and the subsequent clusterisation of the mean maps of the indexes (as explained in Sect. 2.1.3). This section also displays the results of a sensitivity test of the EEW indexes, which were averaged over the outcome clusters, to different thresholds computed on the local time series (Sect. 3.2.3).

3.2.1 Mean maps of the indexes

Figure 5 displays the total number of EEWs that occurred in each point of the Mediterranean domain (Fig. 5a) and the mean values of the EEW indexes, which were computed as the mean of the indexes of all the EEWs that involved that point (Figs. 5b-f).

Since some Mediterranean areas show more than one EEW per year (as can be inferred from Fig. 5a), the initiation time in each grid point and year was associated with the most severe EEW of that year. We found that the most severe chlorophyll EEWs occurred mainly in the winter months in the central and southern open sea parts of the basin and later in the early spring period in NWM, central ALB, northern ION, ADS, AEG and the Rhodes Gyre (Fig. 5b). The duration of the chlorophyll EEWs reached 90 days in the southern part of the eastern basin, whereas it decreased to 30 days in NWM and the Rhodes Gyre and to approximately 15 days in ALB and ADS (Fig. 5c). Long duration was typically associated with low uniformity (e.g., southern ION and LEV areas), while EEWs with high uniformity were found in ADS and ALB (Fig. 5d). The western Mediterranean displayed the EEWs with the highest mean severity, which were associated with the highest produced biomass in ALB and NWM (Fig. 5e). Nevertheless, the regions with the highest values of anomaly occurred in the eastern ADS and the northern Ionian Sea (Fig. 5f), despite their values of severity being approximately 50% lower than the values displayed in ALB and NWM.

3.2.2 Clusterisation of the indexes

Figure 6 displays the clusterisation provided by fuzzy k-means analysis (Bezdek et al., 1984) conducted on the maps of the main indexes (i.e., duration, mean severity, uniformity and anomaly, Fig. 5) by adopting a fuzziness parameter equal to 2. Seven Mediterranean Sea regions with similar chlorophyll EEWs phenomenology were identified by the maximum membership values and are indicated by different colours in Fig. 6. To evaluate the robustness of the clusterisation, we also computed the "confusion index", i.e., one minus the difference between the dominant and subdominant memberships for each point (Burrough et al., 1997). We obtained a value less than 0.7 (i.e., limit for "high confusion" condition) for the largest part of the domain. Values higher than 0.7 are shown in only patchy and limited areas (e.g., part of the southern Adriatic Sea, Fig. 6). Moreover, we computed the mean and standard deviation of the indexes within the seven clusters to quantify the mean impact of the EEWs on the related ecosystem (Tab. 2). Finally, we estimated the trends of duration, mean severity, uniformity and anomaly in the simulated period (1994-2012), applying the Theil-Sen method (Theil, 1950 and Sen, 1968) to the annual means of the indexes computed on the points included within the clusters. The red (blue) colour in Tab. 2 indicates an annual increase (decrease) higher than 1%.

In Fig. 6, cluster #7, which covers NWM and eastern ALB, displays EEWs with durations of 29 days, with the highest values of mean severity (approximately equal to 1 $kg\ km^{-2} day^{-1}$), along with high anomaly and intermediate uniformity with respect to the other clusters (Tab. 2). The EEWs with the highest uniformity ($U \simeq 0.28$) and the shortest duration (T=26 *days*) were identified in the areas of cluster #6, i.e., ADS, ALB, the coastal areas of the southwest Mediterranean and some spotted areas in the north Ionian Sea, TYR, Sicily Strait, the Rhodes Gyre and AEG. These areas display intermediate severity and low anomaly. Relatively high uniformity ($U \simeq 0.22$) also characterises cluster #5, in northern and eastern LEV, AEG and the southern coastal areas of ION, with intermediate duration and low severity and anomaly values. Cluster #4 represents the EEWs with the longest duration (T=63 *days*) and lowest uniformity ($U \simeq 0.14$), with low severity but relatively high anomaly. Cluster #1, corresponding to most of the North Ionian Sea, eastern ADS and spotted areas in the western central Mediterranean, displays the EEWs with the highest anomaly (i.e., $AN \simeq 0.135$), along with intermediate values of the other indexes. Clusters #3 and #2 display very similar intermediate values of uniformity and anomaly, but the EEWs in cluster #2 exhibit lower severity and longer duration than cluster #3.

Throughout the simulated period, the western Mediterranean (except ALB), which was identified by clusters #3 and #7, did not display any significant trend (Tab. 2). On the other hand, the duration of EEWs in the eastern sub-basin and in ALB increased, whereas the uniformity of EEWs in ION and south-eastern LEV (i.e., clusters #1, #2 and #4) decreased. A significant increase in the anomaly was recorded in the eastern basin, except for ADS and spotted areas in AEG and the Rhodes Gyre (i.e., clusters #1, #2, #4, #5).

3.2.3 Sensitivity to the threshold

We conducted a sensitivity test of the method to two different thresholds computed over the time series in each grid point. We repeated the steps of the method (Sects. 2.1.1-2.1.3) up to obtaining the mean maps of the indexes on the Mediterranean domain for the 98th and 99.5th percentile thresholds. Then, we spatially averaged the values of the indexes within the seven clusters of Fig. 6 and finally we computed the total means by averaging the means of the seven clusters. Figure 7 shows the results compared with the 99th percentile (i.e., p99) reference threshold.

The duration and anomaly indexes show decreasing values for increasing thresholds. In contrast, the mean severity and uniformity display increasing values. The relative cluster ranks are generally preserved. Moreover, clusters #4, #6, #7 and #1 maintain the highest values of duration, uniformity, mean severity and anomaly, respectively, for all the selected thresholds, except in the case of the overall mean anomaly for the 98th percentile, in which anomaly values of cluster #7 overcome those of cluster #1 (Fig. 7).

4 Discussion

In this work, we propose a new method to identify and characterise extreme event waves in marine ecosystems. The method is then exemplified by a first application to surface chlorophyll in Mediterranean open sea areas, with specific reference to the winter-spring period.

One of the key points of this method is the definition of an "extreme event". In fact, the spatial extension of extreme events is scarcely addressed in the literature, although it can be an important ecosystem indicator, e.g., to predict a possible recovery of an ecosystem (O'Neill, 1998; Thrush et al., 2005), and it is sometimes estimated a posteriori (Rabalais et al., 2002). In contrast, the spatial contiguity of local extreme events has been evaluated here in addition to the temporal contiguity, following Andreadis et al. (2005). In this way, the definition of the extreme event from a time series in a grid point was extended to define the EEW, which covers an extended area for a certain time duration. Consequently, the metrics necessary to characterise and classify biogeochemical extreme events that can be introduced for a time series at specific sites (e.g., in Hauri et al., 2013; Hobday et al., 2016; Asch et al., 2019; Salgado-Hernanz et al., 2019) have been further developed to describe the shape and strength of EEWs and provide meaningful insights into related biogeochemical phenomenology.

In our specific application, it is noteworthy to specify that the top 1% values of surface chlorophyll (i.e., extreme events, as defined in Sect. 2.1.1) do not necessarily correspond to "blooms" (Siokou-Frangou, 2010) since extreme events are identified in all points of the domain, including oligotrophic areas. Moreover, the top 1% values of chlorophyll are not necessarily distributed in a regular way over the years due to the inter-annual variability of the chlorophyll time series. Our method is able to characterise the intensity and regularity of extreme events in retrospect by means of the mean severity and anomaly indexes computed on the EEWs.

In particular, the mean severity index associated with a chlorophyll EEW can be interpreted as the mean amount of biomass supplied daily to the sea surface over a unit area and could be used as an indicator of eutrophication (Gohin et al., 2008; Ferreira et al., 2011) and food availability for secondary production (Calbet and Agustí, 1999; Ware and Thomson, 2005). The map of the mean severity index obtained for the 1994-2012 period (Fig. 5e) revealed the heterogeneity of the chlorophyll EEWs in the Mediterranean Sea and is in good agreement with the spatial patterns of the chlorophyll amplitude index shown in Salgado-Hernanz et al. (2019), with the highest values recorded in ALB and NWM.

The anomaly feature, which corresponds to the case when the supplied biomass is much higher than usual for a certain area, can instead be ascribed to the inter-annual variability of the extreme events of surface chlorophyll (as in Mayot et al., 2016).

As an example, the reconstruction of the most severe and highly anomalous EEW that occurred in NWM in 2005 showed that the main variables exhibited significant deviations from the climatological values (Figs. A.2-A.3). Nevertheless, high anomaly values do not necessarily correspond to high values of mean severity. In fact, the highest anomaly values are in the northern ION and eastern ADS, which display relatively low values of mean severity (see Fig. 5f, compared with Fig. 5e). The anomaly highlights the episodic occurrence of the chlorophyll EEWs in some areas, such as the northern ION, where the surface chlorophyll values exceed the local p99 thresholds, approximately equal to 0.6 $mg\ m^{-3}$ (Fig. 3), in only some years (e.g., 1999, 2002, 2010), reaching values up to 1.5 $mg\ m^{-3}$ (not shown).

On the other hand, the uniformity feature, i.e., the persistence of a chlorophyll EEW in a certain area, can be linked to specific spatial constraints that circumscribe the EEW. In particular, the circulation structure can play an important role in providing the high values of uniformity in Fig. 5d. In fact, permanent cyclonic gyres in ADS (which also impose a topological constraint) and northern LEV (i.e., the Rhodes Gyre; Pinardi et al., 2015) potentially support a major vertical transport of nutrients and, consequently, increased biomass values (Siokou-Frangou et al., 2010). Moreover, regular upwelling near the southern coast of Sicily can explain the high uniformity values in the Sicily Strait (e.g., Patti et al., 2010). Finally, other spotted areas with high uniformity in the ALB, SWW and TYR areas are characterised by semi-permanent mesoscale structures that are associated with the inflow of Atlantic water (Navarro et al., 2011), eddies originating from the Algerian Current (Morán et al., 2001) and dynamics of the northern TYR gyre (Artale et al., 1994; Marullo et al., 1994; Marchese et al., 2014), respectively.

The fuzzy k-means analysis in this study used mean severity, anomaly, duration and uniformity to classify the EEWs in the Mediterranean Sea. The initiation index was excluded from the computation since there are areas of the basin showing more than one EEW per year per grid point (Fig. 5a). However, as a general characterisation of EEW occurrence, the initiation index showed a south-north gradient from winter to early spring for the most severe EEWs in the open sea areas of the Mediterranean (Fig. 5b), which is in agreement with the phenology of surface chlorophyll in the Mediterranean Sea reported by D'Ortenzio and Ribera d'Alcalà (2009).

We obtained robust clusterisation, with only some areas of the domain showing a high confusion index (Fig. 6). This subdivision of the Mediterranean Sea displays several similarities to previous Mediterranean bio-regionalisations (D'Ortenzio and Ribera D'Alcalà, 2009; Lazzari et al., 2012; Ayata et al., 2018; Salon et al., 2019), indicating that the four indexes are meaningful in characterising the heterogeneity of the basin.

In particular, cluster #7, corresponding roughly to the north-western area (as the "Bloom" region in D'Ortenzio and Ribera d'Alcalà, 2009; NWM in Lazzari et al., 2012), has been associated with the highest mean severity (Tab. 2). A decreasing gradient of the mean severity is observed toward the eastern Mediterranean areas (clusters #3 and #6 showed higher values of mean severity than clusters #1, #2, #4 and #5), which is in agreement with the west-to-east oligotrophication gradient (e.g., D'Ortenzio and Ribera d'Alcalà, 2009; Colella et al., 2016) and the gradient of surface chlorophyll maxima (i.e., map of amplitude index by Salgado-Hernanz et al., 2019). Moreover, this cluster is also characterised by a very high anomaly content, highlighting that EEWs occurring in cluster #7 can occasionally supply a very substantial amount of chlorophyll, as in the case of the already mentioned EEW that occurred in 2005, which developed after a deep convection event (see Appendix). This interpretation is in agreement with that referring to the “High Bloom” regime, which takes the place of the “Bloom” regime in some years in the NWM area (Mayot et al., 2016).

Cluster #1 identified the regime with the highest anomaly (i.e., high inter-annual variability of the EEWs) and a decoupling between mean severity and anomaly. This regime in the Mediterranean Sea is found in the northern ION and eastern ADS (Fig. 6).

Both clusters #5 and #6 are associated with high uniformity and low anomaly, i.e., EEWs that are well localised in space and that regularly occur over the years. Nevertheless, cluster #6 is characterised by EEWs that have higher biomass content (i.e., more severe) and that expire more quickly (i.e., shorter) than those in cluster #5. In this way, ALB, coastal SWW, ADS and the central part of the Rhodes Gyre (i.e., cluster #6, Fig. 6) are differentiated by the south-western ION, AEG, and outer part of the Rhodes Gyre (i.e., cluster #5).

Cluster #4 displays the longest EEWs with the lowest uniformity, which are rare (not shown) and have relatively high anomaly and low severity. This typology of EEWs identifies a regime of spatially diffuse extreme events of surface chlorophyll whose values do not markedly differ from the chlorophyll means in the concerned area. This cluster covers a large part of the south-eastern Mediterranean Sea (Fig. 6) and is crossed by the Atlantic-Ionian Stream and the Cretan Passage Southern Current (Pinardi et al., 2015). We ascribe the very low uniformity and the high overall duration of these EEWs to the transport and spreading of chlorophyll along the meanders of these currents (not shown).

Finally, clusters #2 and #3 display in-between conditions with respect to others, since the values of all the indexes are intermediate, except the mean severity, which is very low in cluster #2 and relatively high in cluster #3. In the Mediterranean basin, this result corresponds to the decreasing gradient in the severity between the central part of the western part (i.e., cluster #3) and of the eastern (cluster #2) Mediterranean Sea (Fig. 6).

The obtained clusters (Fig. 6) were also used to evaluate the long-term evolution of ecosystem phenomenology. Our results did not show any increase in the intensity (i.e., in the severity index) of surface chlorophyll EEWs in any clusters over the period from 1994-2012 (Tab. 2). This result is in agreement with the estimations of trends in the amplitude index by Salgado-Hernanz et al. (2019), except in NWM. Moreover, no significant trend (defined here as an annual variation in an index that was higher than 1%) was estimated for any of the four indexes in the central and north-western sub-basin. In contrast, the eastern Mediterranean and ALB showed trends in the duration, uniformity and anomaly of chlorophyll EEWs. In particular, positive trends of duration found in areas with very uniform EEWs suggest a persistence of extreme events of chlorophyll that has prolonged over time. On the other hand, positive trends of duration and anomaly, along with low values of uniformity (with also negative trends), denote an increase in EEWs with articulated shapes in the areas with low productivity. The trends recognised in the eastern Mediterranean Sea suggest a possible increased tendency of this sub-basin to changes in the identified regimes, despite the productivity being lower than that in the western Mediterranean. This result is one of the features that could emerge only because we accounted for the local thresholds in the identification of the EEWs (Sect. 2.1.1).

The choice of the local percentile threshold (Sect. 2.1.1) is a critical parameter of our method. In our case, this threshold was computed as the 99th percentile on the surface chlorophyll time series in each grid point. A priori, the choice of a higher (lower) threshold corresponds to a definition of an “extreme” value that is narrower (broader) than the reference value. As shown in Fig. 7, the choice of higher thresholds increases the mean severity index, since it is computed on local values that are higher. In contrast, both the anomaly and the duration indexes decrease at increased thresholds because of the occurrence of local POTs over a smaller number of days (i.e., shorter duration) and the decreased detectability of the inter-annual variability (i.e., lower anomaly). The increase in the uniformity index is due to the promotion of grid points with more similar values of high local thresholds (i.e., closer in space, see Fig. 3). However, uniformity shows lower sensitivity to the threshold than the other indexes because of the occurrence of POTs in a few grid points with thin spatial connectivities extending over great distances (as discussed in Sheffield et al., 2009). In this case, a further sensitivity analysis over the area covered by the EEWs could be envisaged to identify a minimum area threshold (stricter than the $4\Delta x \times 4\Delta y$ constraint introduced in Sect. 2.1.2) to better characterise the uniformity.

Overall, Fig. 7 shows that the identification of the clusters with the highest index values was generally maintained in the case of both higher and lower thresholds, confirming that the main regimes of chlorophyll EEW were identified in a robust way.

Since different variables of interest could highlight a different sensitivity of the indexes, we believe that conducting analyses with different local thresholds could help to identify the specificities of the phenomenology underlying the extreme events.

In fact, we have applied this method to surface chlorophyll, as one of the most representative and investigated variables of the marine ecosystem, which potentially influences ecosystem function (e.g., food web and carbon fluxes). However, our method can be applied to any ecosystem variable, including other phytoplankton variables (e.g., HAB-like phytoplankton groups, Vila and Masó, 2005), temperature, oxygen and fluxes (e.g., carbon fluxes at the ocean-atmosphere interface, von Schuckmann et al., 2018). The $C(x,y,t)$ variable can be defined at the surface, the sea bottom (e.g., oxygen minimum or oxygen deficiency, OSPAR, 2013; Ciavatta et al., 2016), and specific surfaces in the ocean interior (e.g., deep chlorophyll maximum, Lavigne et al., 2015; Salon et al., 2019), or it can be vertically integrated (e.g., integrated chlorophyll, which accounts for subsurface growth of phytoplankton). In some cases, the selected variable may require multiplication by the cell volume (e.g., if the variable is a concentration) or by the cell area (e.g., for surface fluxes and vertically integrated variables) in eq. (2.3) and eq. (2.4) to provide a consistent and meaningful definition of the severity and the excess indexes, respectively. Moreover, the formulation illustrated in Sect. 2.1 could be extended to the full 4D case (i.e., to variables $C(x,y,z,t)$) by adding the vertical dimension to the definition of a local extreme event (i.e., the POTs could be defined in each point in a 3D space) and an EEW (i.e., as 3D spatial volume connected in time). The spatio-temporal indexes would then refer to the spatial volume instead of area A and to the 4D width and prism associated with the definition of uniformity. The 4D formulation could be applied to investigate, for instance, marine hypoxia by identifying volumes in time with extremely low values of oxygen. In this case, a proper threshold for local extreme events might also be defined by a constant value in space in connection with the impacts on benthic fauna and fish species, which have physiological limits (e.g., Rabalais et al., 2002, Vaquer-Sunyer and Duarte, 2008). Strength indexes would be modified and defined as vertical profiles, instead of scalar metrics, to show the intensity and depth of the bottom ecosystem stress. Therefore, the novelty of our method (i.e., the temporal and spatial connection of extreme events) would allow us to compute the extension of the (connected) spatial 3D volumes under hypoxic conditions to estimate the probability of fish survival, which can be enhanced by swimming (avoidance) behaviour (Rose et al., 2017).

Finally, our method of EEW identification, characterisation and classification can also be applied to extreme events that are defined starting from seasonally varying thresholds (e.g., in Hobday et al. 2016). In this case, "extreme events" would correspond to the highest anomalies recorded with respect to the climatological seasonal cycle of the variable and generally not to the highest values of the variable recorded throughout the time series (as in our case of temporally fixed threshold). Such an application would allow us to investigate different kinds of scientific questions, such as chlorophyll anomalies in summer.

5 Conclusions

The present study provides a methodology to describe statistically extreme events in a marine basin-scale ecosystem and is supported by an ecological interpretation.

A key point of the method is the request of contiguity in both time and space of the peaks over the local threshold of the ecosystem variable. This constraint allowed us to define individual events as extreme event waves (EEWs) occurring in localised spatio-temporal regions. In particular, we accounted for the contiguity of the local extreme events, which is an aspect that has been rarely considered in the literature. At the same time, our choice to start from local thresholds, which are computed as a percentile of the time series in the grid point, allowed us to maintain a definition of "extreme" relative to the local ecosystem properties.

For a biogeochemical variable evolving over two-dimensional space, we proposed a set of indexes for EEWs to describe their initiation, duration, total covered area and (spatio-temporal) uniformity, as well as their (mean) severity and anomaly, as measures of overall intensity and inter-annual variability, respectively.

In the specific application to surface chlorophyll in the open sea areas of the Mediterranean, we characterised the top 1% values of chlorophyll distribution as EEWs that potentially influence ecosystem functions. Cluster analysis conducted on the indexes associated with the covered areas allowed us to identify four main regimes. We recognised the occurrence of chlorophyll EEWs with high mean severity and high inter-annual variability in the north-western Mediterranean Sea; chlorophyll EEWs with high inter-annual variability (associated with intermediate intensity) occurred in the northern Ionian Sea; regular and spatially well-localised chlorophyll EEWs occurred in the Alboran and south-western Mediterranean Sea, south Adriatic Sea and the Rhodes Gyre; and weak and diffuse chlorophyll EEWs occurred in the south-eastern Mediterranean Sea.

We did not observe significant trends (i.e., annual variations higher than 1%) of the mean severity of chlorophyll EEWs across the Mediterranean basin, whereas some trends were found for other indexes.

Comparison of the results with available data and previous studies supports the reliability of the method, which could be promisingly applied to other ecosystem variables. However, sensitivity analyses are recommended to select suitable thresholds to highlight the typology of the extreme events under consideration.

Appendix: ecosystem dynamics of the chlorophyll EEW in the NWM in 2005

Fig. A.1 displays area *A* (Sect. 2.1.2) covered by the EEW already shown in Fig. 4, and three points, which are internal, peripheral and external to the area (i.e., points A, B and C, respectively). Figures A.2-A.4 display the time series of physical and biogeochemical modelled variables (i.e., heat flux, mixed layer depth, potential temperature, nitrate and chlorophyll concentrations) at the three points. In each panel of the three composed figures, the data from January-April 2005 are compared with the corresponding climatological means computed from 1994-2012.

At internal point A, 30-40 days preceding the EEW onset were characterised by strong heat losses up to 1000 W/m^2 (top panel of Fig. A.2) due to the wind field (not shown). This condition led to a strong deep convection that mixed the entire water column down to the sea bottom (second panel of the same figure). Surface and subsurface nitrate, whose concentration at the beginning of the year was already above the climatological values, was further enhanced during the mixing (fourth panel). As soon as stratification was quickly established (second panel) and the surface temperature rose (third panel), an abrupt rise in surface chlorophyll occurred (bottom panel). The surface chlorophyll in January, February and the first half of March exhibited values much lower than the climatological values due to the strong convective phase; in the third week of March, chlorophyll increased by a factor of almost 800% in 4 days. Full consumption of surface nitrate can be observed on the same days (fourth panel). A subsequent weaker mixing phase (in half of April) replenished the surface layers with a relatively low amount of nitrate (yet above their climatological values), triggering two weak episodes of increasing chlorophyll. Overall, the features described here are in agreement with the characterisation of the chlorophyll blooms in the NWM area and, in particular, of the 2005 event (Barale et al., 2008; Estrada et al., 2014; Mayot et al., 2016).

The interpretation of the results referring to peripheral point B belonging to the EEW area (Fig. A.3) is similar to the previous considerations about internal point A but in the presence of less intense vertical mixing.

On the other hand, at point C (Fig. A.4), which is external to the EEW area, an evident stratification of the water column below 30 m depth was maintained for throughout the winter months (January-February-March), despite the cooling of the surface layers. The nitrate content in the surface and subsurface layers was much lower than that in the deeper layers, and only a small increase in the surface chlorophyll developed during the duration of the EEW.

Therefore, the strong deep convection (related to the inter-annual variability of the local vertical mixing) appears to be the key factor for the exceptionality of this EEW. It is worth noting that our method identified the spatio-temporal region covered by the EEW (i.e., points A and B) and was shown to effectively include only the relevant information by filtering out other regions characterised by different dynamics (such as point C).

Author contribution

VDB, GC and SS conceived and developed the methodology applied in this work. VDB conducted the formal analysis and prepared the manuscript with contributions from all co-authors. CS supervised the research activity.

Competing interest

The authors declare that they have no conflicts of interest.

Acknowledgements

This work was partially sponsored by OGS and CINECA under the HPC-TRES programme award number 2016-04, and a first formulation of the method was included in Di Biagio (2017). We acknowledge the CINECA award under the ISCRA initiative for providing high-performance computing resources and support (IscraC codes: HP10CPBEJO, HP10C5FMRK, HP10COFIJC). The comparison with ESA-CCI data was conducted using E.U. Copernicus Marine Service Information (http://marine.copernicus.eu/).

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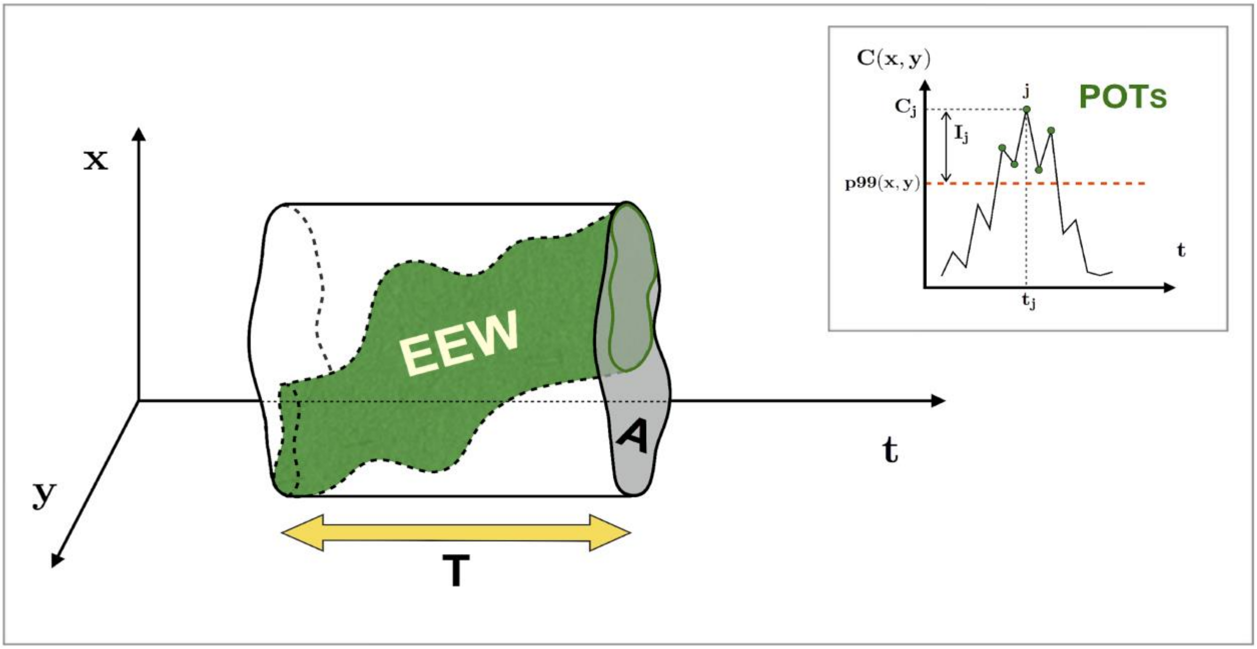

Figure 1: Conceptual diagram of the spatio-temporal indexes of an EEW (green shape) as a region where the POTs are connected in time and space (top right box). The area and duration of the EEW are indicated by *A* and *T*, respectively. The uniformity *U* is the percentage of the spatio-temporal region occupied by the EEW with respect to the total spatio-temporal region of the prism with *A* as the base and *T* as the height. In the top right box, the POTs (green circles) at the grid point *(x,y)* are identified by the daily values of the variable above the 99th percentile threshold (orange dashed line). The value of the ecosystem variable C_j and the intensity I_j related to the POT index *j* are also shown.

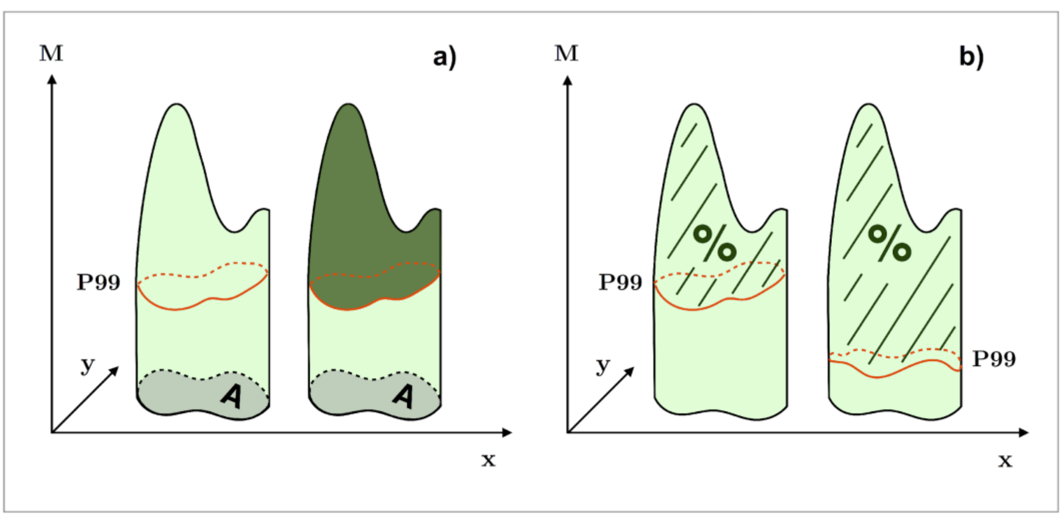

Figure 2: Conceptual diagrams of the strength indexes: severity and excess (a) and anomaly (b). Fig. 2a): The severity (represented by the shaded green volume, on the left) is the sum of all the *M* values over each *(x,y)* grid point belonging to base *A*. The excess (dark green portion, on the right) is the part of this volume that is above the locus of points of the 99th percentile threshold, i.e., *P99*, delimited by the orange contour. Fig. 2b): The anomaly, as the percentage of the excess with respect to the severity, is compared between two cases, which refers to two EEWs with the same severity but with different P99 loci of points.

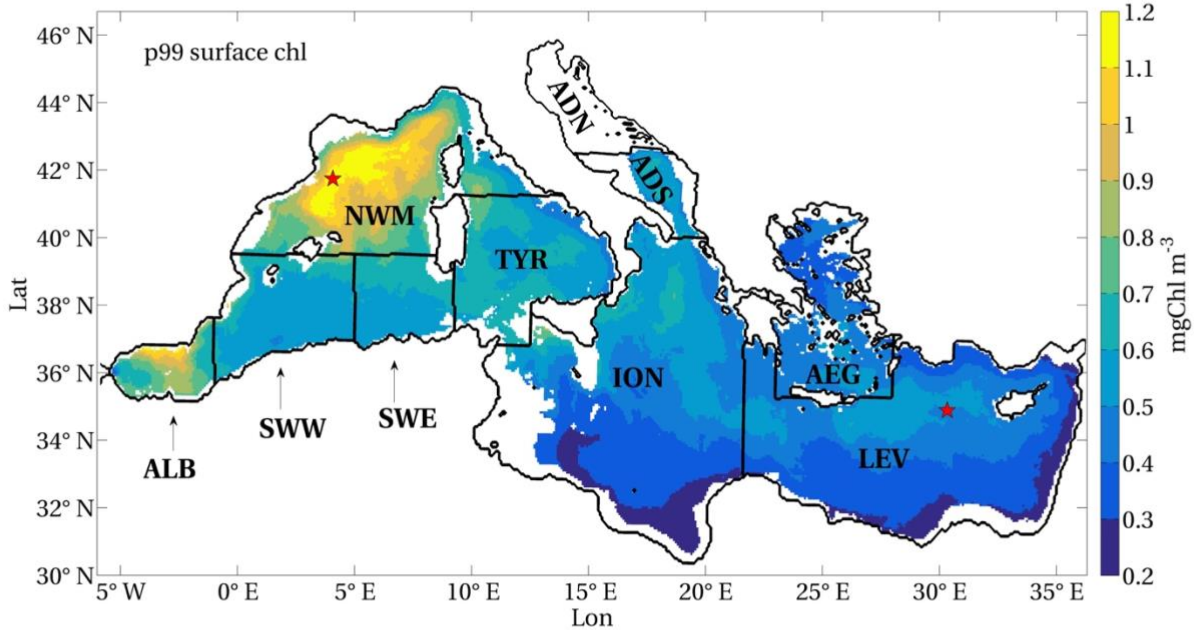

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Figure 3: Model-derived 99th percentile thresholds of the surface chlorophyll in the Mediterranean open sea domain (1994-2012). Isolated grid points with depths higher than 200 m in the Northern Adriatic Sea and the Gulf of Corinth (Greek inlet) are masked. Mediterranean regions delimited by black contours (as in Lazzari et al., 2012) are indicated in the text for simplicity by the corresponding abbreviations (ALB = Alboran Sea, SWW = western side of the south-western Mediterranean Sea, SWE = eastern side of the south-western Mediterranean Sea, NWM = north-western Mediterranean Sea, TYR = Tyrrhenian Sea, ION = Ionian Sea, LEV = Levantine Sea, ADN= northern Adriatic Sea, ADS = southern Adriatic Sea and AEG = Aegean Sea).

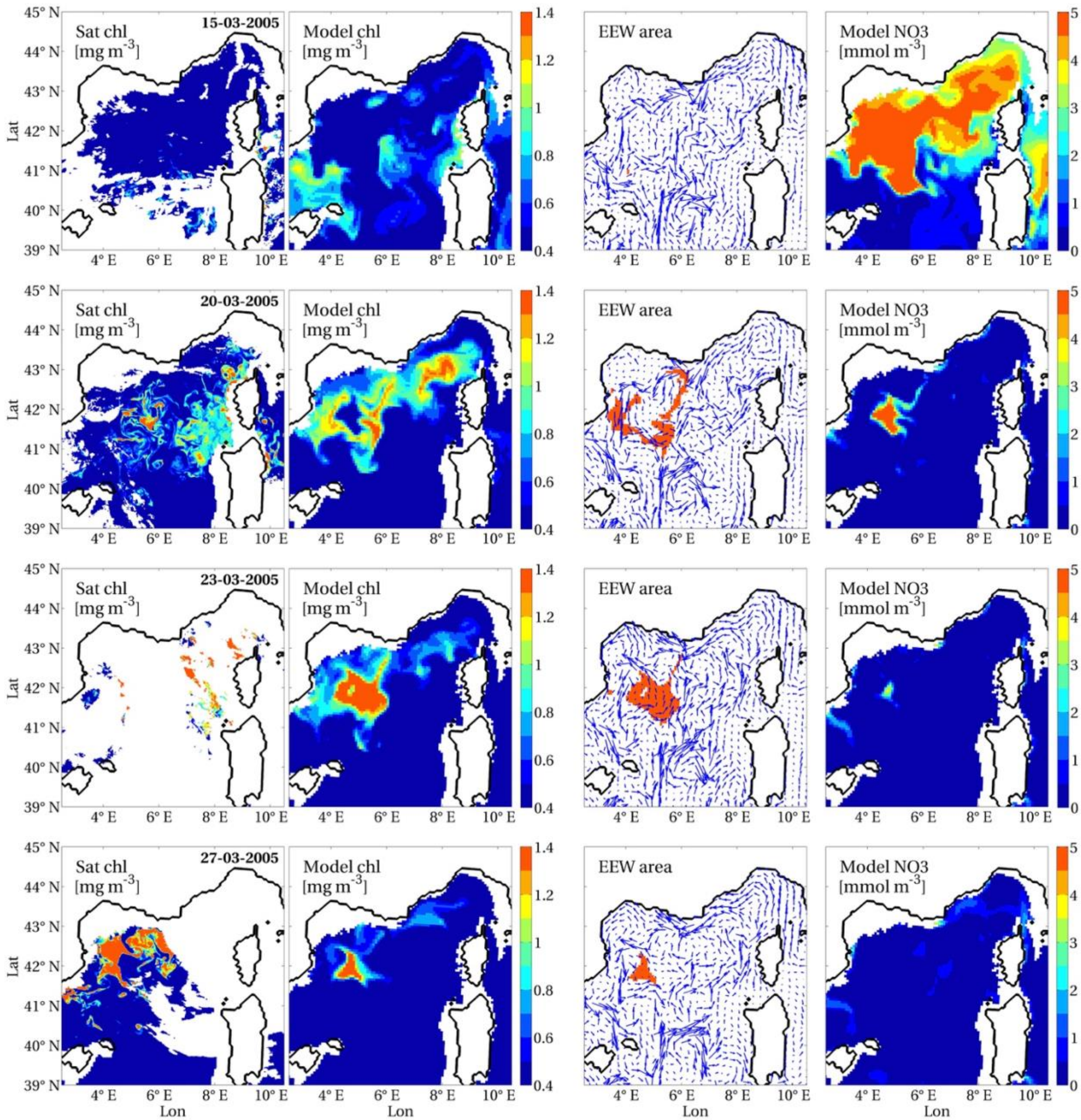

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Figure 4: Surface chlorophyll from satellite (Volpe et al., 2019, first column) and model-derived estimates: surface chlorophyll (second column), daily portion of area *A* of the EEW superimposed on the surface velocity field (third column) and surface nitrate (fourth column), for single days of development of the EEW that occurred in the western Mediterranean Sea from the 15th to 31st March 2005 (indicated in the first column). Surface chlorophyll and nitrate were averaged in the first 10 m of depth and are shown only in the open sea, whereas the horizontal velocity field (scaled by a factor of 1.5) refers to the depth of 5 m.

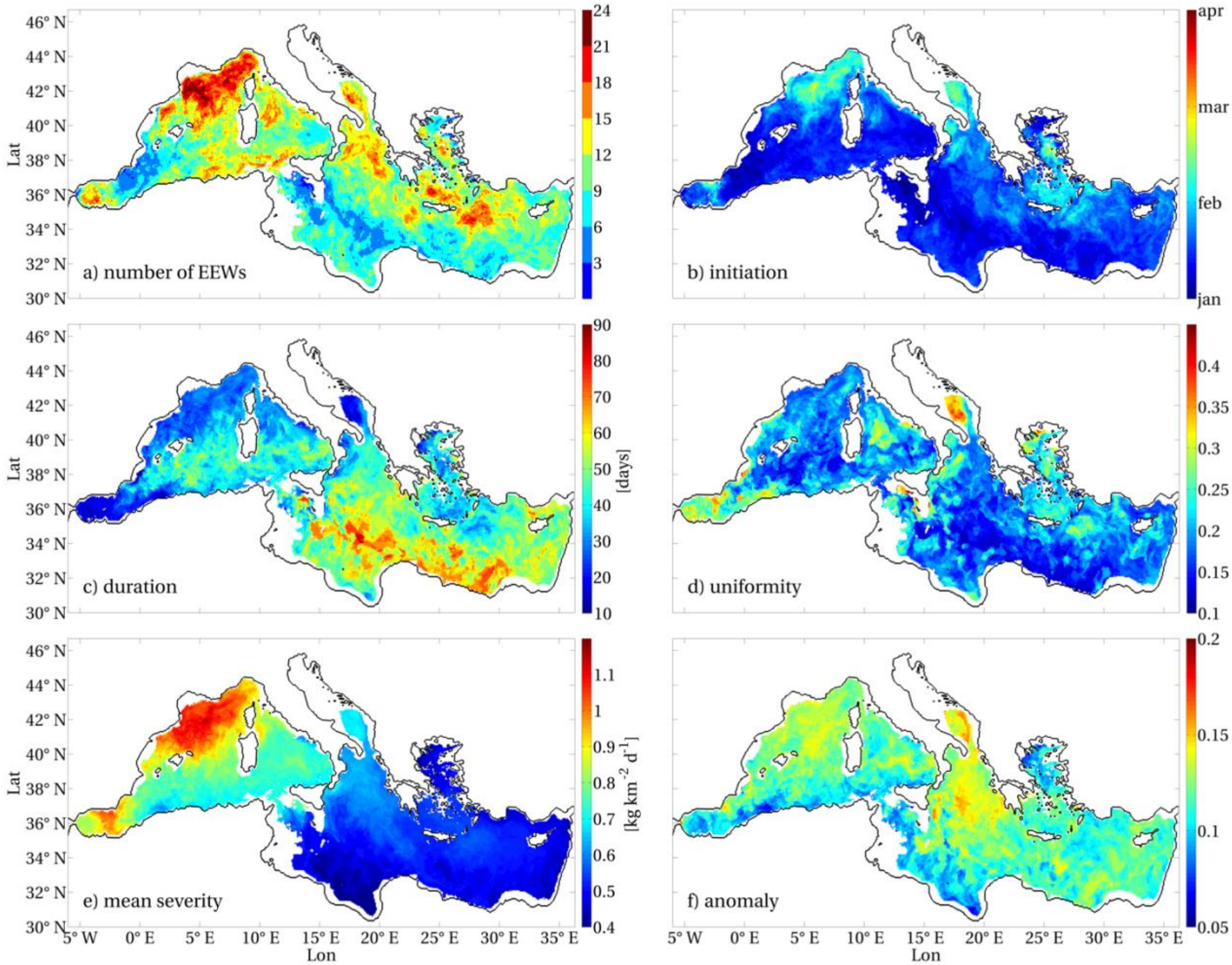

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Figure 5: Number of surface chlorophyll EEWs that occurred in Mediterranean Sea in 1994-2012 (a) and means of the indexes referring to the EEWs: initiation (b), duration (c), uniformity (d), mean severity (e), anomaly (f). The values of the indexes referring to an EEW were associated with all the points belonging to covered area *A* (Sect. 2.1.2).

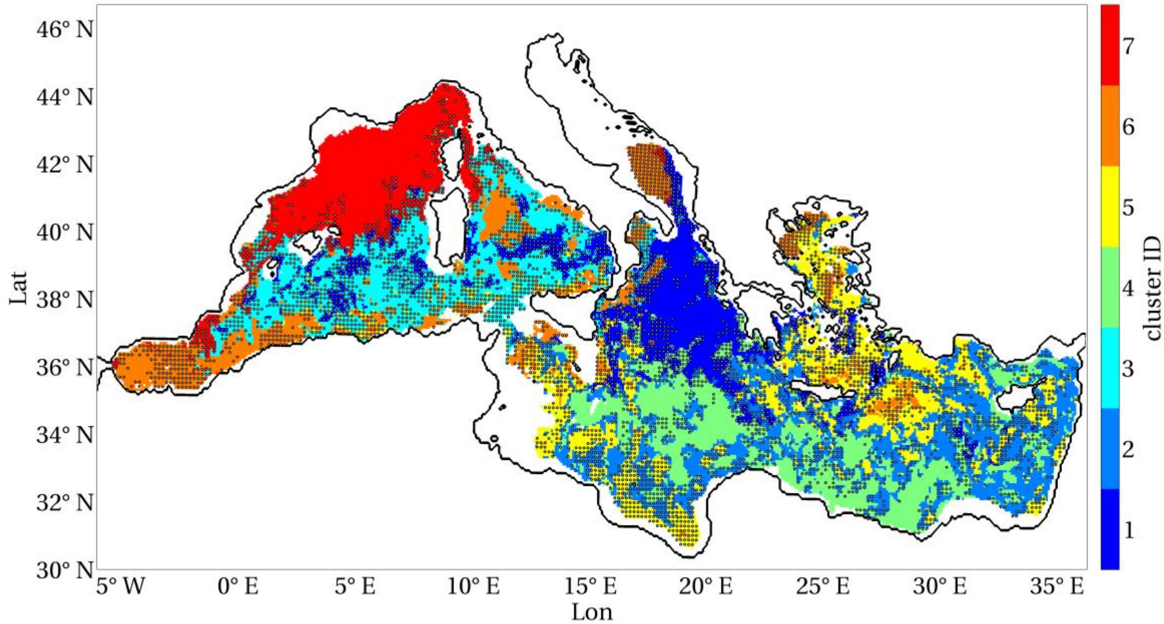

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Figure 6: Fuzzy clusters with maximum membership identified from the duration, mean severity, uniformity and anomaly maps (shown in Fig. 5), with black points indicating a confusion index higher than 0.7.

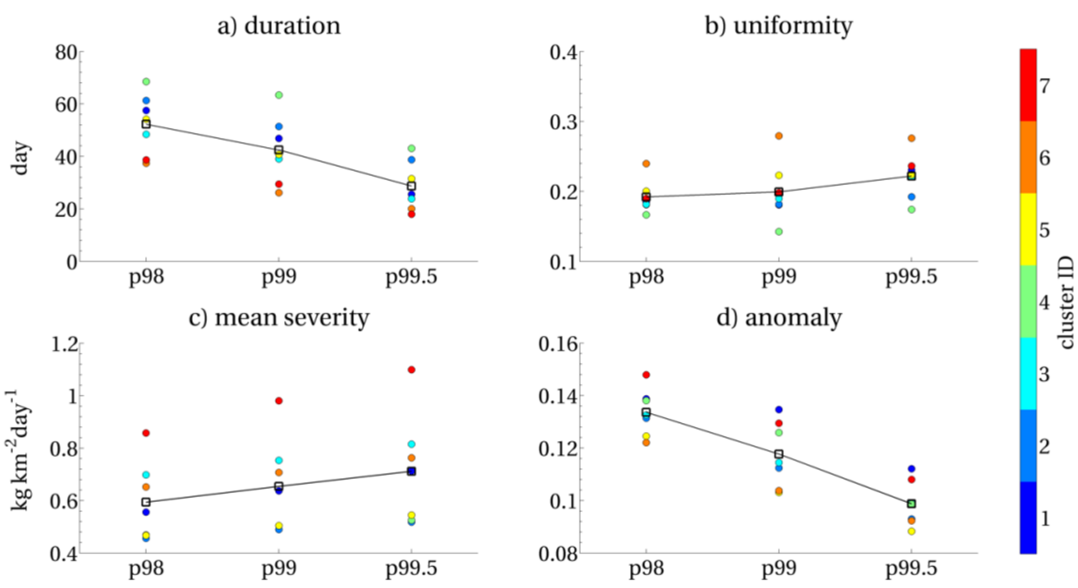

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Figure 7: Means of duration, uniformity, (mean) severity and anomaly computed for the surface chlorophyll EEWs obtained from different local thresholds (Sect. 2.1.1), with the 99th percentile (p99) as reference used in the present study. Coloured dots represent the mean values of the indexes computed in the corresponding clusters (with the same colour legend of Fig. 6). The total means (black squares) are computed by averaging the means of the seven clusters.

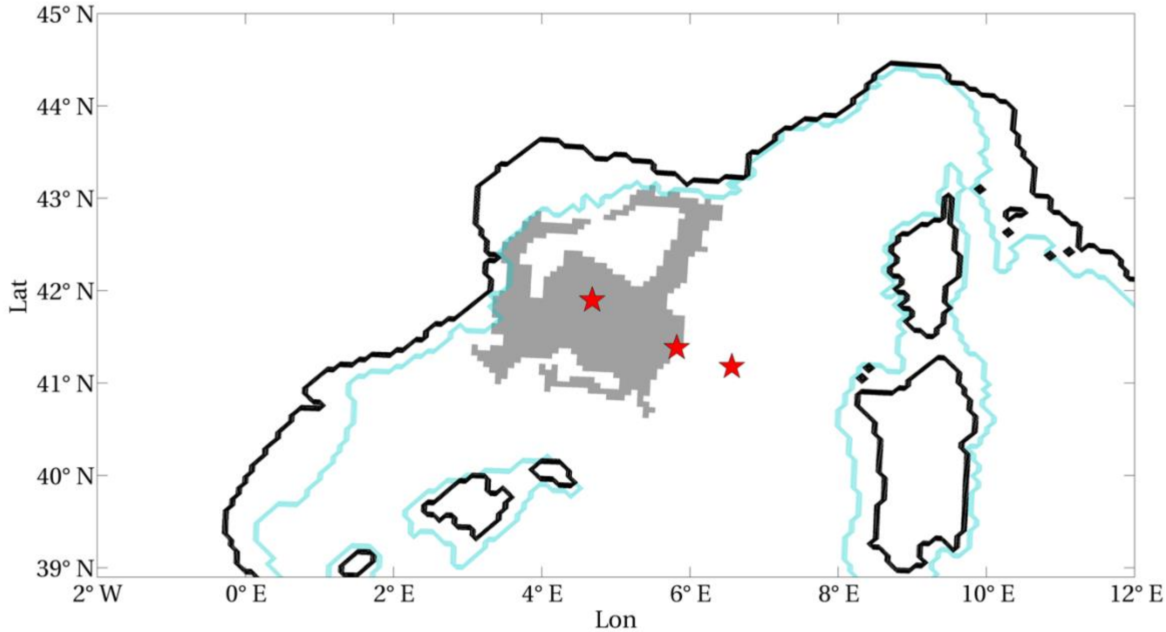

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Figure A.1: Area *A* of the surface chlorophyll EEW shown in Fig. 4 (grey patch). Red stars indicate grid points in internal (A), peripheral (B) and external (C) positions with respect to the EEW. Blue contours delimit the open sea area (i.e., depths greater than 200 m).

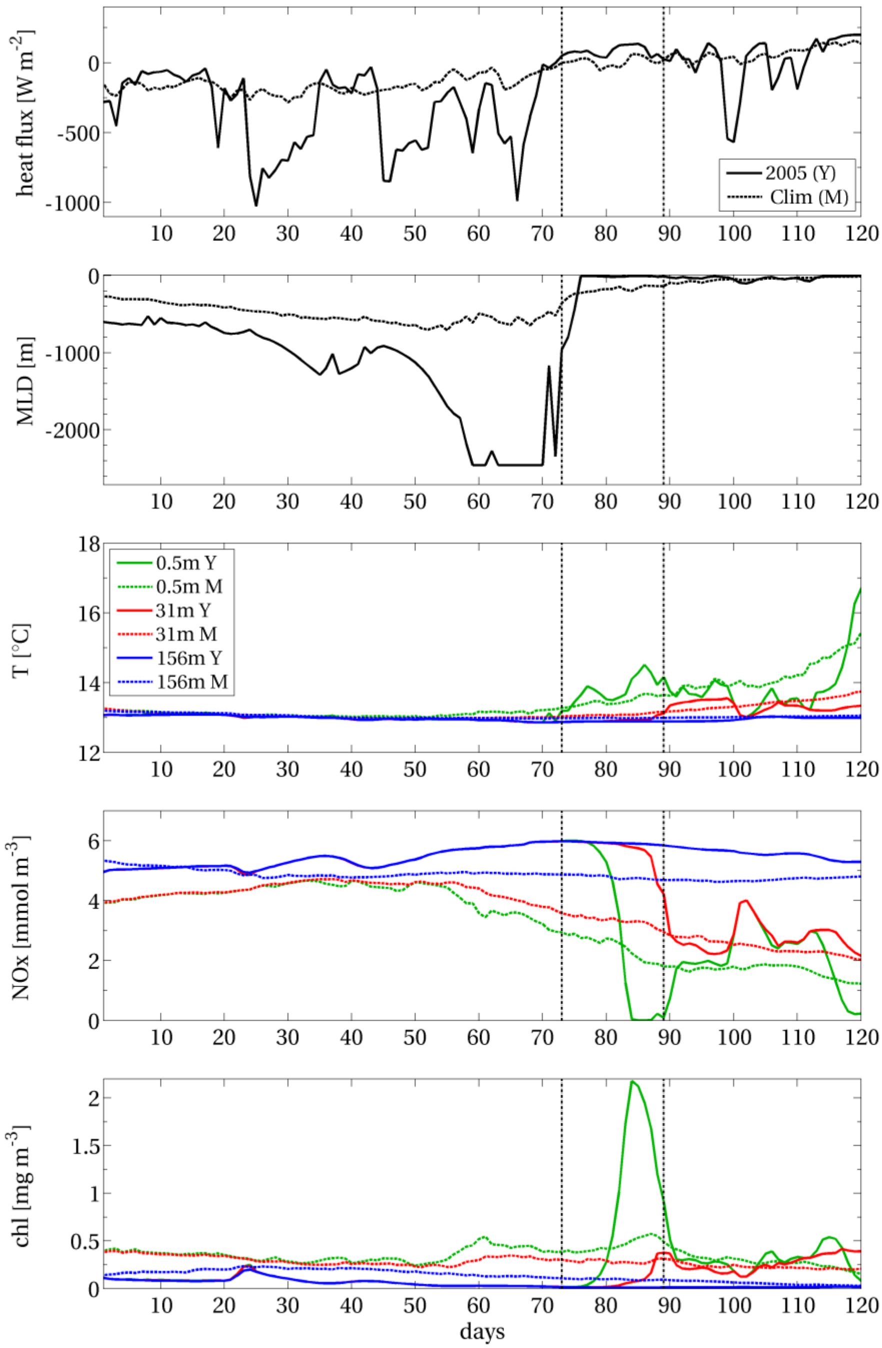

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Figure A.2: Net surface heat flux, with negative sign for ocean cooling, mixed layer depth and potential temperature and concentrations of nitrate and chlorophyll at different depths (see the legend in the central panel), computed at the internal point A of the EEW in NWM (Fig. A.1). Acronyms: Y = year (2005), M = (climatological) mean. Days are computed from the 1st Jan 2005. The vertical dashed lines delimit the duration of the EEW.

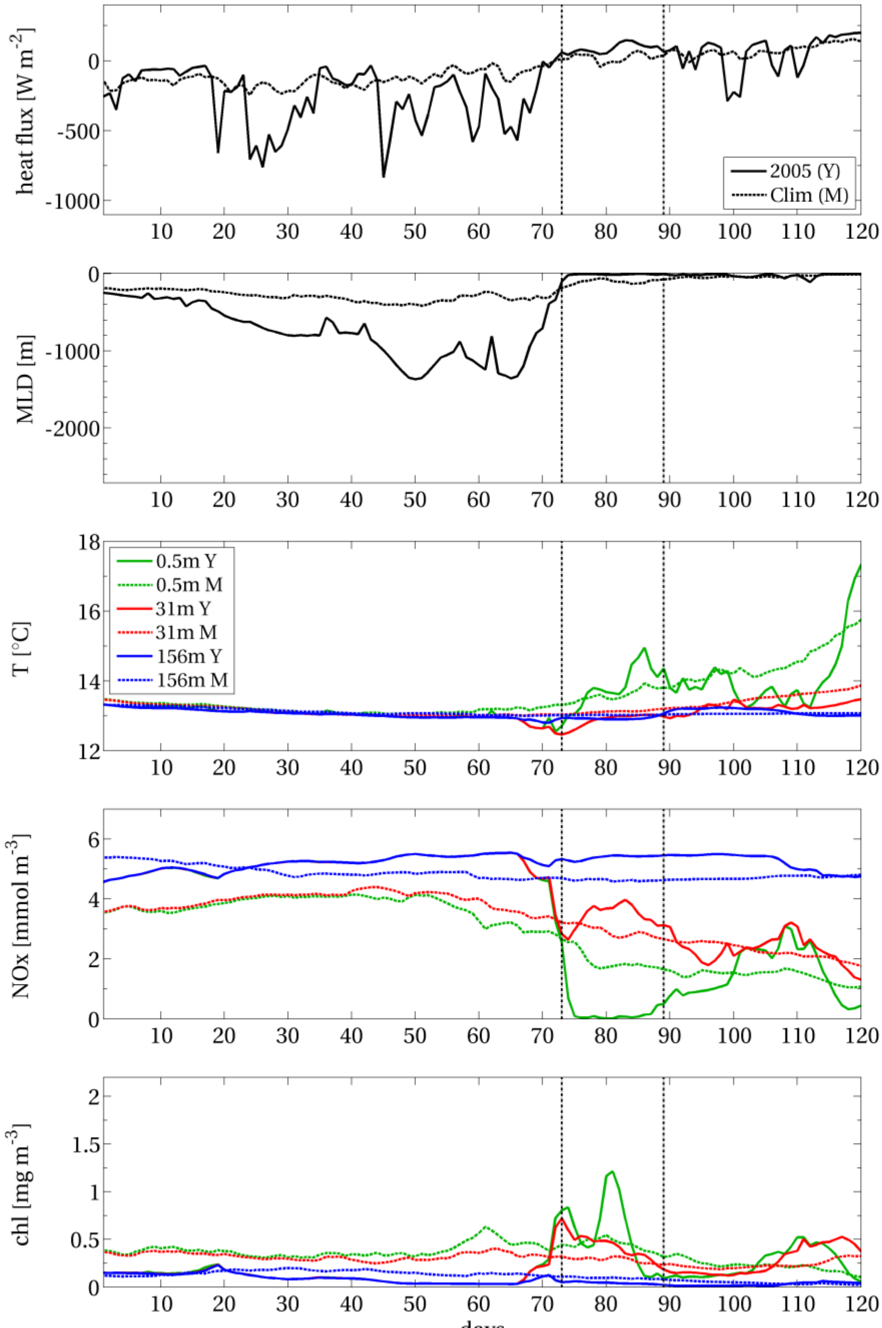

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Figure A.3: As in Fig. A.2, but in the peripheral point B of the EEW area in Fig. A.1.

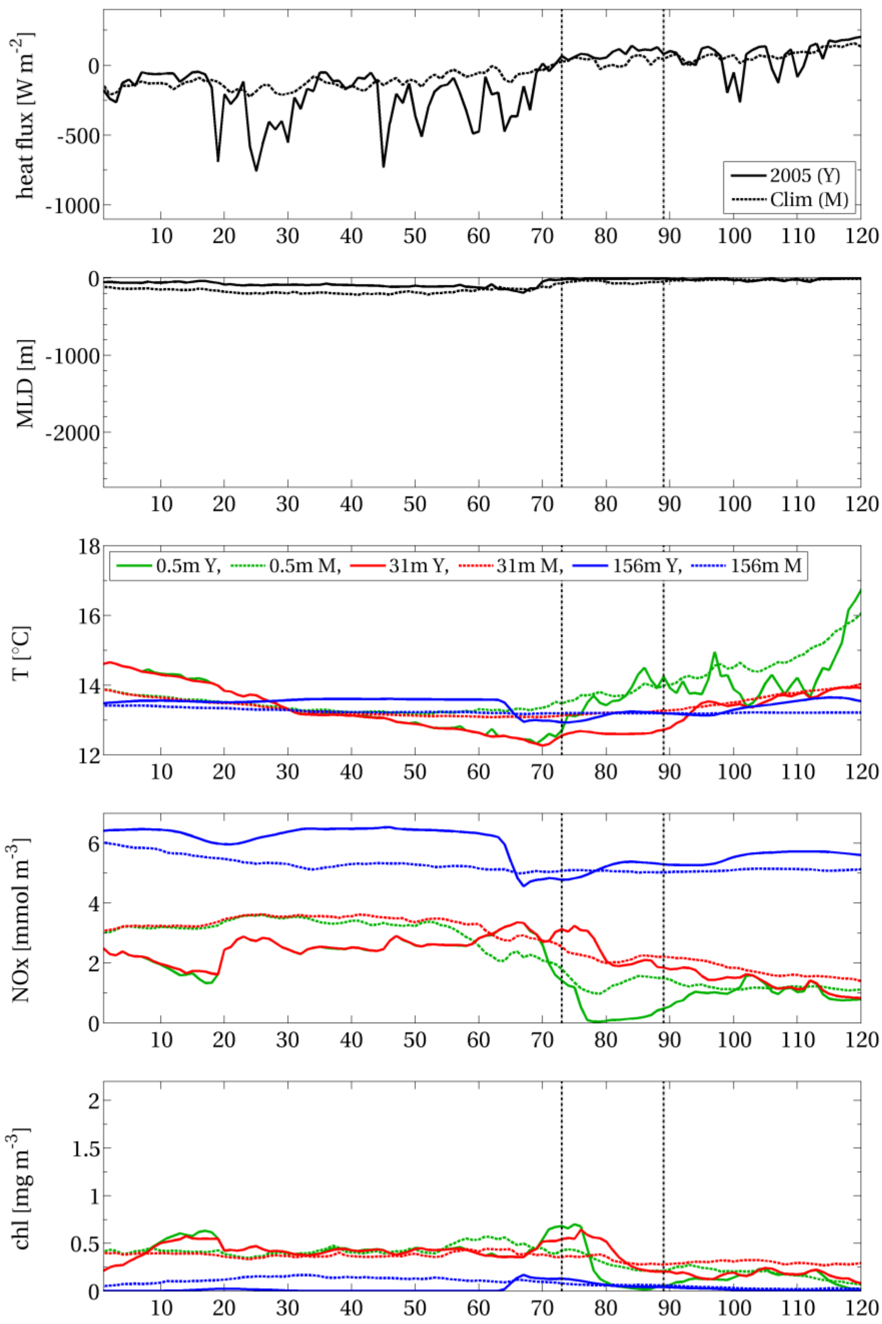

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Figure A.4: As in Fig. A.2, but in the point C external to the EEW area in Fig. A.1.

Spatio-temporal	Initiation	15th March 2005
	Area *A* [km^2]	33.1×10^3
	Duration *T* [*day*]	17
	Width *W* [$km^2 \times day$]	1.06×10^5
	Uniformity *U*	0.189
Strength	Severity *S* [*kg*]	1.479×10^5
	Excess *E* [*kg*]	3.032×10^4
	Mean Severity $< S >$ [$kg\ km^{-2} day^{-1}$]	1.389
	Anomaly *AN*	0.205

Table 1: Metrics, grouped by spatio-temporal and strength indexes (defined in 2.1.2), for the EEW in Fig. 4.

#Cluster	**Duration *T* [*day*]**	**Uniformity *U***	**Mean severity $<S>$ [$kg\ km^{-2}\ day^{-1}$]**	**Anomaly *AN***
1	47±6	0.181±0.027	0.637±0.087	0.135±0.008
2	51±4	0.182±0.017	0.490±0.042	0.112±0.008
3	39±5	0.190±0.026	0.754±0.051	0.115±0.008
4	63±6	0.142±0.015	0.505±0.040	0.126±0.009
5	41±5	0.223±0.020	0.505± 0.067	0.103±0.011
6	26±7	0.280±0.040	0.707±0.135	0.104±0.017
7	29±5	0.198±0.030	0.981±0.084	0.130±0.008

Table 2: Mean and standard deviation of the duration, uniformity, mean severity and anomaly indexes within the seven clusters in Fig. 6. Pale red (blue) refers to an annual increase (decrease) higher than 1% in the 1994-2012 period.

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