

Dear Editor,

The authors appreciate the opportunity to improve the manuscript ID bg-2017-285 entitled "Delineation of marine ecosystem zones in the northern Arabian Sea during winter" by Saleem Shalin, Annette Samuelsen, Anton Korosov, Nandini Menon, Björn C. Backeberg and Lasse H. Pettersson. We also thank reviewer for critical reviewing and the comments they provided.

All the concerns of referee are addressed and we hope that the after revisions the manuscript will meet the requirements to be published in the Biogeosciences.

Reply by the authors to the referee's comments is herewith attached.

Looking forward to hear from you,
With regards,

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Reply to Reviewer1:

On behalf of the authors I thank the reviewer for the critical review of our article. In particular for the suggestion of including chlorophyll images based on climatological data which verifies that our objective classification appropriately categorizes the Arabian Sea ecosystem zones based on Chl-a characteristics for the winter.

Below we respond to each of reviewer's question. Reviewer comments are in green, and our response in black.

Major comments:

1. On what basis, principal component analysis based six ecological zones were divided into two Longhurst provinces? It should be elaborated in the section 4.1.

Authors' comment: 'Our analysis of 'Chl-a winter variability revealed six distinct ecological zones in the Arabian Sea, which has been compared with the Longhurst biogeographical classification of marine provinces for the study area.' This comparison is done as Longhurst's biogeographic classification is widely accepted for the world oceans including the Indian Ocean. The statement above in quotes will be included in the main text.

2. Because of the lack of satellite data during the monsoon seasons, authors have considered only winter data. We know that the Arabian Sea is most productive during summer. Authors should discuss how ignoring monsoon would impact the delineation of ecological zones?

Authors' comment: Yes, this is a limitation of our study, however the amount of comparable high quality (satellite Earth observation) data coverage in time and space make the statistical analysis and zonal classification robust. Combining satellite Earth observation data with seasonal ship measurements would have been advantageous; however we did not have access to such data to be incorporated in our analysis. The most productive period during summer coincides with persistent cloud cover in the study area (Saha, 1974). Since this work utilises satellite ocean colour data, which are limited by cloud cover, ocean colour data cannot be utilised to study the chosen area during the summer (Martin, 2004). Accordingly our analysis focuses on data from the winter period (Nov-March) in order to examine intra- as well as inter-winter Chl-a variability in the study area. With this limitation in our study we clearly state that we have analyzed the intra and inter-winter variability, though the obtained zones would likely be different had it been possible to include the whole year. How it would change is hard to say, but a more prominent signal from the northwest Arabian Sea upwelling region is likely.

3. It appears that only surface chlorophyll values were used. But we know that ocean has a deep chlorophyll maximum (DCM). The justification provided on pages 2-3 (line 34, line 1-2; “the fact that during: : : : : : : : : : : :content”) is not correct. There are numerous studies showing DCM in the Arabian Sea. Authors have covered almost entire Arabian Sea, and it is not possible to have a weak DCM everywhere. Authors should explain how this analysis would be affected by excluding the most productive parts of the ocean?

Authors' comment: Yes, the present work utilized depth integrated surface chlorophyll values, which is remotely sensed by ocean colour satellite sensors. Reflected radiance is measured by the ocean colour sensor which contains scattered light containing information from ocean recorded up to the depth where it is no longer reflected back to the surface (i.e., 0.1 photosynthetically available radiation (PAR) depth) (Martin, 2004). Hence remotely sensed Chl-a represents the average of Chl-a concentration from surface up to the depth where 0.1 PAR with that of surface is available.

As pointed out in the manuscript, we admit to the fact that the Arabian Sea does not show weak DCM everywhere during winter (Breves et al. 2003; Revichandran et al. 2012; Prasanakumar 2000). Also, some productivity may be excluded as we are not considering DCM-variability; however, with the absence of in-situ observations, there is no good way to include the deep layers. Furthermore, the increased chlorophyll at depth is sometimes a result of the phytoplankton having higher Chl/C ratio, to compensate for low light, not necessarily higher biomass. Again we will argue that our homogenous data set with extensive coverage in time and space found a basis for robust statistical analysis as long as the limitations of using satellite EO data are taken into consideration.

4. Provide a climatological data based Chlorophyll image as Fig. 4 (c). It would help to see whether chlorophyll content are drastically different in these six zones (particularly for sentence on Page 10, lines 17-18)

Authors' comment: Valid comment – Thanks! A Chl-a image (revealing the seasonal average Chl-a values over the winter period (Nov-March) from 2002 to 2013) is provided as a new figure 1, and it can be placed as 4 (c) as per the suggestion. Also, the following sentence provided in quotes is included in the manuscript. ‘The annual winter climatology (seasonal average Chl-a values over the winter period (Nov-March) from 2002 to 2013) of Chl-a distribution revealed distinct features for each of the identified ecological zones (Figure R1). Based on the variability of Chl-a concentrations, zone 1 experiences maximum bloom intensity between 1.5 to 9.6 mg m⁻³ with a mean of ~2.6 mg m⁻³ and standard deviation of 0.7 mg.m⁻³. Next to Zone 1, high Chl-a prevails in Zone 2, with a range of 1.4 to 7.0 mg m⁻³ and a mean ~ 2.8 mg m⁻³. Standard deviation observed in Chl-a are same for both zones. Moderate values of Chl-a (1.3 to 1.9 mg m⁻³) are observed in Zone 3, Zone 5 and Zone 6. Though similar range are observed for these three zones, the temporal evolution are different. In zone 3, Chl-a varies between 0.5 to 4.2 mg.m⁻³, with 0.3 mg.m⁻³ standard deviation. Among coastal zones, zone 6 Chl-a standard deviation is high (0.8 mg.m⁻³) with a range of 0.9 to 6.8 mg.m⁻³ than for zone 5 (0.5 mg.m⁻³) between 1.0 to 4.3 mg.m⁻³. Minimum value of Chl-a for the winter is observed in zone 4 (0.2 to 1.2 mg.m⁻³), also in this zone least mean (0.6 mg.m⁻³) and standard deviation (0.2 mg.m⁻³) is observed. The Chl-a geo-spatial statistical variation in the study area clearly demarcates different ecological zones’

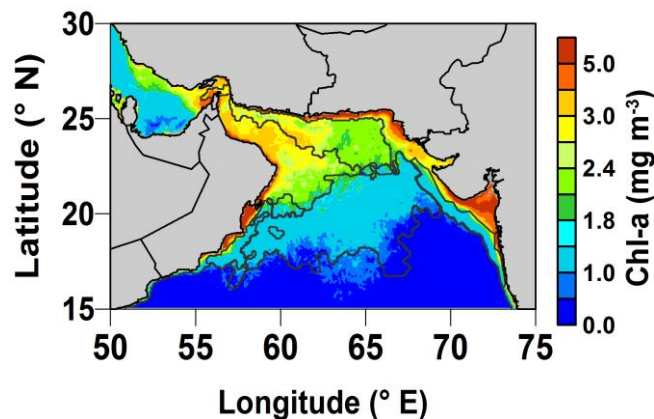


Figure R1: Annual winter climatology (seasonal average Chl-a values over the winter period (Nov-March) from 2002 to 2013) of Chl-a revealed from satellite data. The black line indicated the delineated zonal boundaries.

Minor comments:

1. Title should be revised as “Delineation of marine ecosystem zones in the northern Arabian Sea during winter”

Authors’ comment: The suggested title is appropriate for this work and hence it will be changed according to suggestion.

2. Page 3, lines 9-12 can be deleted as they do not provide any info

Authors’ comment: The sentence is retained, as this sentence connects various supplementary data used in this work.

3. Page 4, lines 12-13, same font should be used for variables

Authors’ comment: Suggestion will be incorporated in manuscript.

4. Page 4, line 19: (Levitus, 1982) has proposed density criteria to estimate MLD which is used widely (Gardner et al., 1995) and a better criterion than temperature.

Authors’ comment: We thank the reviewer for this suggestion. The reason we use a MLD based on temperature criteria is because numerous other studies, including Rao et al. 1989; Rao and Sivakumar, 2000 and Kumar and Narvekar, 2005 used MLD based on temperature criteria in the Indian Ocean basin to study the MLD dynamics in the area. By using the same definition of MLD as these authors allows us to compare our results qualitatively to these previous studies. Moreover, a comparison of MLD obtained from the HYCOM modeled data using both temperature as well as density criteria’s with the Argo datasets available for winter are carried out. A total of 6256 points are collocated for winter for the entire study area for the comparison. MLD calculated from density criteria have higher RMSD and error percentage (RMSD: 36 m and an error of 68 %) compared with that derived from temperature criteria using 1° C, 0.5 ° C and 0.2 ° C (RMSD: 20 m and an error of 28 %). This analysis showed better MLD derivation is with temperature criteria. Hence, a second analysis based on different temperature based MLD criteria (1°, 0.5° and 0.2° drop from that at surface) with the Chl-a in the six zones were carried out. From this analysis, it was found that MLD calculated using temperature criteria (1°C degree) could explain the Chl-a pattern in each of the six selected zones more accurately than those computed using other temperature values. This is the reason for include temperature based MLD in the present work.

5. Page 5, line 18: I should be in italic, in fact all the variables should be made italic throughout

Authors’ comment: Suggestion will be incorporated in manuscript

6. Page 7, line 4: Oman is an upwelling so how could it be oligotrophic (Wyrтки, 1973)

Authors’ comment: Thank you for pointing out this error, we replaced the term with “mesotrophic”. The explanation of the Principal Component Analysis (the corresponding paragraph) is rewritten based on periodicity of Principal Components and hence this sentence will be removed from manuscript.

7. Page 8, line 2: (Naqvi et al., 2010) have not done sampling off Gujarat and Pakistan

Authors' comment: Author apologies for the mistake. The reference Naqvi et al. 2010 should be replaced by Sarma et al. 2012. However, this sentence too coincides with Principal Component Analysis which is rewritten and this sentence will be removed.

8. Page 8, line 13: How was coastal Chl a found erroneous?

Authors' comment: We used the NASA OBPG chlorophyll-a product derived with the OC4 band ratio algorithms performing well only in Case-I waters (see also reply to question 5) (O'Reilly et al., 1998). Since the coastal zone is loaded with turbid waters (due to river inflow or resuspension) and may be optically shallow, the OC4 algorithm is not applicable and these zones were excluded from the analysis.

9. Page 9, line 2: blows should be replaced by blow

Authors' comment: Suggestion will be incorporated in manuscript

10. Page 9, line 17: "These coastal areas: : : : .winter." Reference is needed.

Authors' comment: Reference viz. Kumar and Prasad, 1996; Kumar et al. 2001 will be included in the manuscript.

11. Page 10, line 2: zone 6 is also an upwelling region (Sudheesh et al., 2016)

Authors' comment: Two reference will be added including Sudheesh et al. 2016 and Shalin and Sanilkumar 2014 in the manuscript

12. Page 10, lines 3-4: "Nutrient supply: : : : .zones". Provide reference, perhaps (Singh et al., 2012; Singh and Ramesh, 2011)

Authors' comment: The corresponding sentence referee asked is 'Nutrient supply from Narmada and Tapi rivers as well as atmospheric deposition of nitrogen enhances marine production in zone 6.' Authors found nutrient supply from rivers Narmada and Tapi during winter (November to March) is less (Figure R2). The relevant reference on atmospheric deposition on nitrogen in the study area is Singh et al. 2012, which has reported the contribution of atmospheric nitrogen during winter is 0.06 mmol N m⁻² day⁻¹ based on 43 in-situ measurements. Assuming that all the six zones are exposed to this level of atmospheric deposition of nitrogen and comparing this with concentration available for the study area (Figure 9 of manuscript), it is clear that the contribution is low. As nitrate contribution is less during winter, this sentence with respect to river discharge and atmospheric nitrate deposition are removed in the revised version.

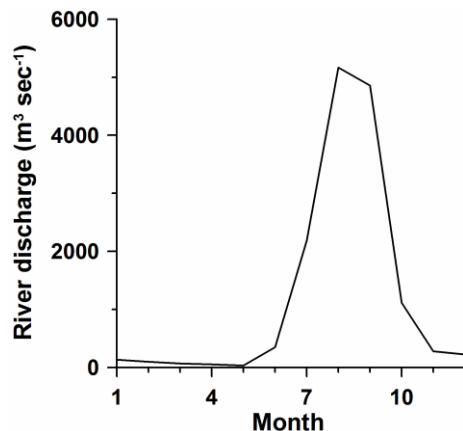


Figure R2: Annual river discharge from Narmada and Tapi. (Data source: <http://nelson.wisc.edu/sage>)

13. Page 10, line 9: parts has should be parts have; and this whole sentence should be revised for grammar

Authors' comment: Suggestion is included by incorporating the following sentence given in quotes in the manuscript. 'However, we have identified high Chl-a concentration ($>0.5 \text{ mg m}^{-3}$) in the entire study area, with significant differences between various parts, particularly higher values to the waters closer to the coast.'

14. Page 20, lines 5-25: These points should (also) be discussed in the main text (preferably in the discussion).

Authors' comment: Suggestion of included lines 5 to 25 from summary to discussion section will be incorporated in the manuscript.

15. Page 20, line 13: (Kumar et al., 2017) is another new reference for higher N₂ fixation.

Authors' comment: Suggestion will be incorporated in the manuscript in page number 18.

16. It is not clear what Fig. 8 conveys

Authors' comment: The sentence provided in quotes will be included in the Figure caption. "Zones 1 to 6 are represented by violet, blue, green, light green, yellow and red lines respectively."

17. Units have periods (.) at most places (e.g., Fig. 5, mg.m-3, m.s-1). These periods should be removed throughout the manuscript.

Authors' comment: Suggestion will be incorporated in the manuscript.

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Reply to Reviewer2:

We thank the reviewer for taking the time to provide such detailed comments to our manuscript. Special thanks for the suggestions on AOT_{ma} calculation and the comment on including a figure with wind rose along with DOT. However, we disagree with the reviewer's comment on the lack of merit of the work, particularly the comment that the marine zones can be readily discerned by the spatial distribution of Chl-a. While this is indeed possible, such an approach remains qualitative and subjective, here we provide a more objective and quantitative approach which provides a delineation of the marine ecological zones in the Arabian Sea during winter. Moreover, our method is in agreement with previous literature and we have expanded our analysis to ensure that is robust.

Below we respond to each of reviewer's question. Reviewer comments are in green, and our response in black.

General comments: "Can't say I like this paper. The innovative information established by the authors is meager: all prime features of the phytoplankton field across the north Arabian Sea and their driving processes are known and the present research has not contributed to this knowledge. The authors regard as a major merit of their work a more fine delineation of marine zones in the north Arabian Sea as compared to the ones determined previously by other workers. First of all, the zones established by the authors are readily discernible in the spatial distributions of Chl, and secondly, the established contours of the zones are not proven."

Authors' comments: In order to ensure the robustness of our delineation of the identified zones a new figure representing the seasonal average of Chl-a over the winter period (Nov-March) is included as Figure R1, which reveals distinct Chl-a characteristics for each of the identified ecological zones. Our objective classification based on winter average of Chl-a values from eleven winter seasons takes into account both spatial and temporal information. To say that the same result could be obtained by the authors by looking at the spatial distribution is highly uncertain and the result would probably depend both on the person doing the subjective analysis and how the data was presented in terms of colormap etc. In the initial manuscript itself, the authors have compared Chl-a variability in six obtained zones with the well-accepted biogeographic classification of Longhurst falling in the selected area. As our study has utilised Chl-a concentration obtained from satellite sensors which has about 100 times finer spatial resolution used by Longhurst for regional mapping for classifying ecological zones in the northern Arabian Sea, this regional classification could delineate the spatial Chl-a variability better with more detailed regional information than obtained from Longhurst's classification. The objectivity of the methods used and the increased amount of information in modern ocean color products are the basis for author's argument about 'finer delineation of marine zones in the north Arabian Sea' is true.

We have analysed physical and chemical characteristics within each of the identified marine ecological zones, and the respective relation between cooling, deepening and production between the six zones. In the analysis section, we have made use of the established, published, knowledge on the driving processes of Chl-a in the study area. Our information is based on surface-data and limited number of variables – hence we must utilize previous studies to better understand our results. However, the in-situ observation coverage in the Arabian Sea is lacking both spatially and temporally and the utilized literature base their result on observations from shorter periods compared to our study. Such long period of information is very essential for resolving inter-annual variability in the ecosystem characteristics. Our study contributes understanding of the temporal/spatial variability of phytoplankton and hence, we disagree with the reviewer’s comment on ‘*The innovative information established by the authors is meager: all prime features of the phytoplankton field across the north Arabian Sea and their driving processes are known and the present research has not contributed to this knowledge*’.

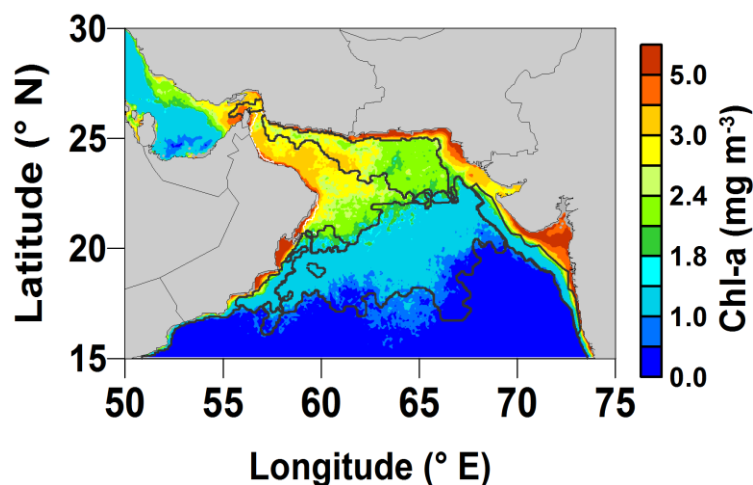


Figure R1: Annual winter climatology (seasonal average Chl-a concentration over the winter period (Nov-March) from 2002 to 2013) of Chl-a revealed from satellite data. The black line indicated the delineated zonal boundaries.

This thesis is underpinned by my comments to the text. The paper composition is also unsatisfactory: instead of partitioning the respective part of the paper into Results and Discussion sections, the authors mixed up the reporting on the results obtained and underpinning of the results’ validity. This caused numerous repetitions and unnecessary lengthening of the text. The authors’ English needs to be brushed up In light of the above and the comments below, I reckon that the paper should be subsumed under the category “major revision”.

We have kept the present format with presenting results and discussion together by topic rather than in separate section, however we have made an effort to clean up the manuscript and avoid repetition. The English has been revised and improved.

We do appreciate the reviewer's suggestion regarding AOT_{ma} calculation and plotting of a wind rose. These two additions in addition to several other comments on poorly written statements have significantly improved our manuscript. However, we disagree with the reviewer's opinion about the PCA and objective analysis. The Chl-a geo-spatial statistical variation in the study area clearly demarcates different ecological zones (see Figure R1 of 4b and additional description related to this figure in the manuscript), which proves the significance of PCA and objective analysis, compared to any subjective method.

Specific comments

1. Specify the desert(s); [5 (page 2)]

Authors' comment: Arabian desert in the west and Thar desert to the east are the major dust contributing deserts. This sentence is added in Appendix A3.

2. It is insufficient to anticipate: this needs to be proven. [15 (page 2)]

Authors' comment: Agreed. The statement has been rephrased and the following references were included in the text that justifies our argument: Longhurst 1995, Longhurst 1998 and Longhurst 2006; Spalding et al. 2012.

3. Why the Chl concentration at 0.5 mg/m³ is used as a criterion? [25 (page 2)]

Authors' comment: The concerned statement is a general argument for Chl-a concentration for the study area in an annual cycle (Sarma et al. 2012; Ravichandran et al. 2012). Based on Chl-a monthly climatology for the study area, annual concentration considering all seasons is approximately 0.5 mg m⁻³.

4. Firstly, Mignot et al. reported solely on Pacific and Mediterranean oligotrophic waters (typically, Chl is significantly under 1 mg/m³). The actual location and degree of "weakness" of deep Chl maxima (DCM) are site-specific. For the locations within the study waters the assertion that DCM did not affect the satellite-borne Chl concentrations needs independent confirmation. The authors write that DCM in the study area is presumingly shallow because of the strong attenuation by surface Chl. A rather strange argument: if the DCM is shallow then it can be "sensed" by the satellite sensor. Besides, the Chl concentrations reported in your study are not likely to affect the downwelling light to a degree of eliminating the DCM optical influence. At least, a Hydrolight experiment can bring certainty in this issue. [30 (page 2)]

Authors' comment: We agree that deep Chl maxima are site-specific. However, some regions in the selected area show shallow DCM (24 m) during winter (Al-Niami et al. 2017), and concurrently regions with deeper DCM exist in the study area (Breves et al. 2003; Ravichandran

et al. 2012; Kumar 2000). Since, it is clear that DCM is not shallow in the entire study area during winter, the statement ‘DCM is shallow during winter’ is deleted. However, it is to be mentioned here that in-situ coverage on Arabian Sea is not sufficient to give complete spatial and temporal variability on DCM and hence we have to accept the uncertainty on this issue (Barlow et al. 1996).

5. There are no assessments of Chl retrieval errors. This issue is essential, because of the above comment, and also because of the optical heterogeneity within the study waters. It is unnecessary to mention that the NASA algorithm used by the authors is valid (and produces really accurate values of Chl concentrations) only for case I waters (i.e. strictly oligotrophic). However, the authors haven’t elucidated this issue with regard to the studied waters in view of the impacts produced by the river discharge, and dust fallouts. The observed variations in Chl could arise, inter alia, from the inability of the NASA algorithm to retrieve Chl correctly in those parts of the study sea where waters are not strictly case I waters. In this case the zoning [in essence, based on Chl variations] might be compromised (at least the declared contours of six zones, which are supposed to be the main advantage of the study). That is why the realistic error bars relevant to the study sea are indispensable for all illustrations of Chl concentrations in the selected zones. The issue of retrieval error arises also with respect to other satellite-borne variables used in the study. [15 (page 3)]

Authors’ comment: The NASA OBPg chlorophyll product that we used does not have values of uncertainties associated with each value of chlorophyll and, therefore, region-wide assessment of errors in the chlorophyll product is not feasible to perform. The validation shows that in oligotrophic waters the algorithm accuracy is quite high: $r^2 = 0.86$, $RMS = 0.25 \text{ mg m}^{-3}$ (Feldman, 2017; Hu et al., 2012). Large errors are presumably observed in the turbid waters of the Persian Gulf as well as the coastal areas. Our region of interest excluded coastal areas and included only phytoplankton dominated open ocean areas, where the standard algorithm of NASA is known to work well.

6. As a matter of fact: the coefficients taken from the literature are not necessarily relevant to the study area, e.g. f_{du} , and AOT_{m_a} (the later was determined by Smirnov et al., for Midway Island in the Pacific, located in waters located far away from the study area; meanwhile, it is known that AOT_{m_a} depends not only upon the above water surface wind but also on a number of other parameters, that is why there are many parameterizations suggested for specific marine locations). [5 (page 4)]

Authors’ comment: We thank the reviewer for this comment. This question is a valid one, we were not aware of the stated scenario. It is clear now that in the Indian Ocean an exponential relationship between wind speed and sea salt formation exists, where as in Pacific this relation is

linear. As a result of which we have now replaced Smirnov et al. 2003 with Moorthy 1997 to estimate AOT_m . DOT obtained using the new formula is super-imposed in the manuscript figure below (pink line) while red represents DOT as computed with the old formula, as can be seen the values differ, but the temporal evolution is similar in zone 1, 2 and 5 (Figure R2). In the revised manuscript, Figure 9 (figure with DOT) is updated with latest data.

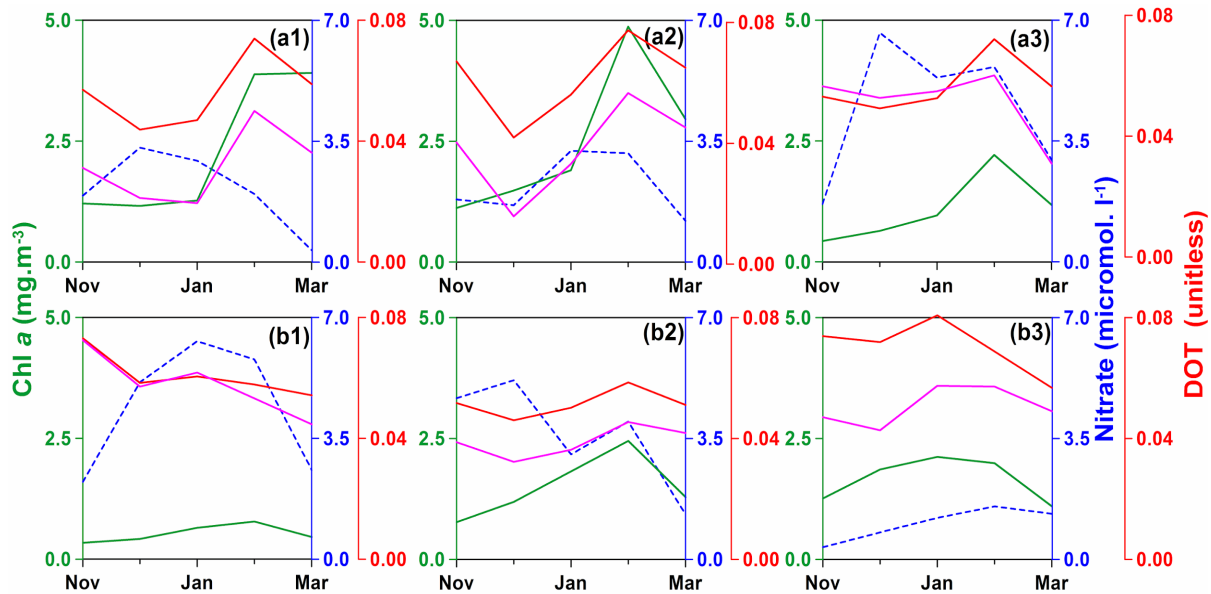


Figure R2: Averaged variability of surface Chl-a, nitrate and DOT in six ecological zones. Viewports (a), (b), (c), (d), (e) and (f) represents variability along first, second, third, fourth, fifth and sixth zones, respectively. Red and pink line indicates DOT computed with the old and new formula.

7. Please, give the major assessments of MLD simulation errors (results of validation by George et al., 2010). Error bars are indispensably required for all illustrations of MLD variations in the selected zones. [20 (page 4)]

Authors' comment: Statistical analysis cannot be carried out using George et al. 2010, hence a comparison of MLD modeled data with the recent Argo derived mixed layer climatology (<http://mixedlayer.ucsd.edu/Argo>) was carried out for winter months. On average a RMSD of 20 m and a 28 % error is observed between model output and Argo dataset. It was found that adding error bars to the plots looked very messy, instead we have added a paragraph in the revised manuscript describing the MLD simulation error in the study region.

8. If only PC 1-3 are meaningful, why you provide illustrations for PC 4 and PC5 (fig. 2). The authors are reporting on the northwestern and southeastern gradients in spatial distributions of PC1 (that is the component that predominantly, accounts for 97% of the spatio-temporal variance in Chl) as one of the important findings. However, this finding could be attained without the PC analysis just by visual examination of the spatial distribution of Chl or/and SST, which is confirmed by the authors themselves. So there is nothing new in this finding. [5(page 7)]

Authors' comment: A simple visual examination remains a subjective approach complicated (or, even, disabled) by the fact that sequences of maps of several variables have to be visualized and analyzed simultaneously. The accuracy of such a subjective method is not described anywhere in the literature, nor proven to be correct. In fact, PC1 accounts for only 80% of the Chlorophyll variance.

We developed an objective method of analysis of time series and provide exhaustive explanations of the methodology and description of several experiments to illustrate its sensitivity to various factors (number of PCs, number of zones, etc.).

PC5 is included for illustration of the speckle noise that contaminates the signal. In case of PC4 some of the signal is still present and, therefore, it is used, but PC5 appears to be useless. We respectfully disagree with the comment that there is nothing new in this finding.

9. First, the authors write that PC4 and PC5 are not informative (mostly noise) and then declare that the final delineation into ecological zones was obtained by combining the first 4 PCs. Please, explain. Also, please, explain what you mean saying “based on general Chl pattern in.”[5 and 10 (page 8)]

Authors' comment: The write-up on five PC's are rewritten considering the periodicity of these components, which was not done initially. Based on periodicity it is clear that PC4 and PC5 represent the intra-winter variability. Since, this work concentrates on intra-winter variability, these two PC's cannot be considered as noise. The amplitude of PC4 is more than 10% of PC1, and PC4 is necessary to include it in the zoning to get the narrow coastal regions that we know exists and is not present when only 3 PCs are included (see argument in appendix A in the manuscript). These arguments show the reason for including PC4 in the final zoning.

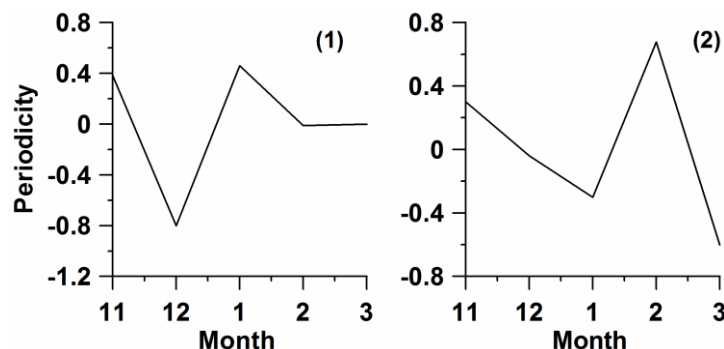


Figure R3: Periodicity for (1) PC4 and (2) PC5.

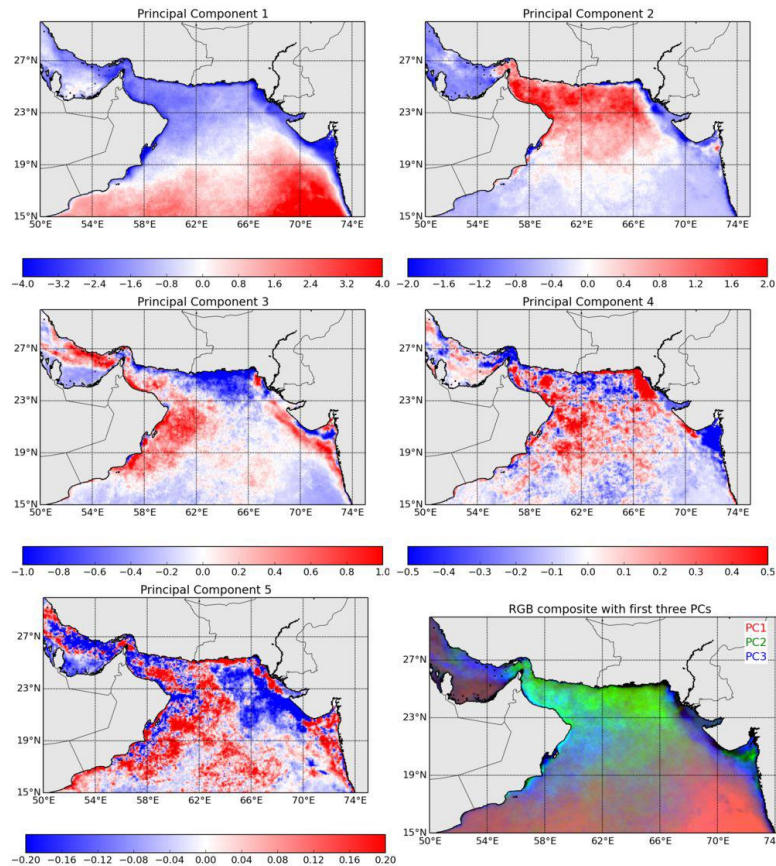


Figure R4 (Figure 2 from manuscript): Individual maps of principal components (PC 1 to 5) and RGB composite of the first three statistically significant components. Corresponding to each PC, the respectively periodicity is shown

PC4 causes high Chl-a production for January, November months and minima during December (Figure 3R(1)). Most of the high variation during January / November occurs during December too, hence in this PC we can observe more regions with zero variation (indicated by white colour) (Figure 3R(2)). Therefore, the regions under this PC are highly scattered within north, central and eastern part of the study area. Next PC demarcates regions with high Chl-a production for February, and follows a decreasing trend for November to January months. Similar, to PC4, region coming under this PC is also scattered highly. However, this PC differentiates Persian Gulf and Pakistan and Gujarat coast from the rest of the north-central region (Figure R4).

Regarding the second part of the question, a map (RGB composite of the first three statistically significant components) illustrating the significance of combined Principal Components (PCs) is

described (line no. 5). This map is generated with the combination of first three PC's (Figure 2). First PC is represented using red, second by green and third by blue. Zones with similar colors have similar combinations of PC values and therefore this figure illustrates similar winter variability on Chl-a. This image is the application of a statistical clustering method to delineate the study region into areas with distinct Chl-a dynamics. This is based on the values of principal components (details is discussed in section 3 of manuscript).

The same method was applied with the PCs 3, 4 and 5. Clustering in the case, is done making use of the technique 'k-mean Cluster Analysis' (CA). Several combinations of PC and CA is carried out (described in Appendix A). Based on the available knowledge of Chl-a variability as well as oceanographic characteristics in the area the combination of 4 PC and 8 CA is selected (Figure 3 and Appendix A in the main manuscript).

10. Please, explain, on the basis of what it was decided that satellite-derived Chl values along coastal and shallow waters were erroneous.

Authors' comment: Retrieval of Chl a concentration from optical satellite data near to the coast is complex. The water masses contain optical properties of riverine fresh water influx, containing terrogenous dissolved organic compounds, and these contribute to an error in Chl-a retrieval. In addition, shallow water depth regions (depth < 30 m) may include signals from bottom reflections (with clear waters conditions), which can introduce additional errors in the retrieval process (Martin, 2003). Considering the fact that our present work uses a global Chl-a retrieval algorithm (OCI) to obtain Chl-a along with the above mentioned two points, we mask out the analysis of satellite derived Chl-a values near the coast. Additionally, in our response to question number 5 we explain that only regions classified as case-1 waters during winter in the selected study area, where the NASA algorithm will work well, are selected.

11. Please, explain in the paper what are the reasons to believe that “ the physical forcing affecting chl concentration along the two regions is likely to be different” ... [10 (page 8) 15 (page 8)]

Authors' comment: Based on knowledge available through published studies (Kumar and Prasad, 1994; Kumar et al. 2000; Shetye et al. 1994) it is concluded that the two regions are likely to be different. Accordingly, these references will be included in the revised manuscript.

12. The authors write that 1-3 zones (encompassed by Longhurst's ARAB zone) are strong upwelling regions with high Chl in winter time, and then they refer to Longhurst who defines the ARAB province as a zone with strong upwelling during summer and strong convective cooling during winter. Obviously, some phrase is required to follow these statements in order to clarify the actual hydrodynamic situation therein. [5 and 10 (page 9)]

Authors' comment: We thank the reviewer for pointing out this mistake, and have corrected the text accordingly. Zones 1-3 are regions where strong convective overturning occurs during winter (page nos 9 (line number 8, 12 and 19), 10 (line number 1) and 11 (line number 20)).

Hence, the comparison of Chl in the convective zones identified with Longhurst province during winter has been carried out.

13. Please, specify 1. what is known about the atmospheric deposition on nitrogen (there is no respective reference), and 2. why this mechanism of nutrient supply acts only in zone 6 (or, at least, is not mentioned with regard to other zones). Also, specify the annual cycle of stream flow of the Narmada and Tapi rivers to support your thesis that nutrient supply from Narmada and Tapi rivers as well as atmospheric deposition of nitrogen enhances marine production in zone 6. This additional information might clarify the authors' statement that in zone 6 "peak Chl-a is observed during January" as opposed to other zones. [5 (page 10)]

Authors' comment: A relevant reference on atmospheric deposition on nitrogen in the study area is Singh et al. 2012. They have reported the contribution of atmospheric nitrogen during winter is 0.06 mmol N m⁻² day⁻¹ based on 43 in-situ measurements. Assuming that all the six zones are exposed to this level of atmospheric deposition of nitrogen and comparing this with concentration available for the study area (Figure 9 of manuscript), it is clear that the contribution is low. The complexity of zone 6, in particular, can be explained by additional sources of nitrogen supply e.g., likely from rivers discharges (see Figure R5). The sentence will be restructured accordingly.

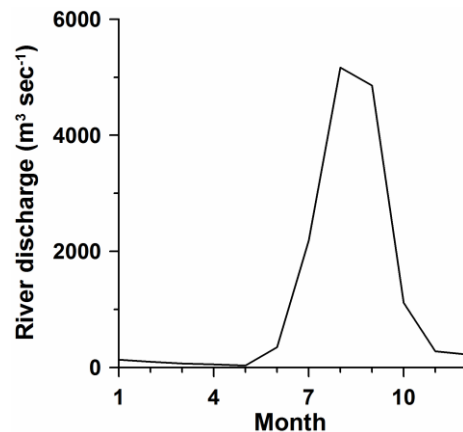


Figure R5: Annual river discharge from Narmada and Tapi. (Data source: <http://nelson.wisc.edu/sage>)

14. First, the authors write that the inverse relationship between SST and Chl-a have weak correlation coefficient 1 in zone 1 ($r = 0.39$, $n=60$) and zone 2 ($r = 0.55$, $n=60$). Then a bit further: "However, MLD and Chl-a in zone 1 and 2 are moderately correlated (correlation coefficient, $r = 0.28$)". What are your criteria in this regard? [15 (page 11)]

Authors' comment: We thank the reviewer for this observation, as you pointed out a criteria based on r value is defined as follows:

- $r > 0.50$ is high,
- $r > 0.35$ is moderate
- $r < 0.35$ is low.

Which will be introduced in the manuscript. Hence, the above mentioned statement will be changed as 'the inverse relationship between SST and Chl-a have moderate correlation coefficient 1 in zone 1 ($r = 0.39$, $n=60$) and zone 2 ($r = 0.55$, $n=60$).' "However, MLD and Chl-a in zone 1 and 2 are poorly correlated (correlation coefficient, $r = 0.28$)".

15. The authors write "Mean wind speed in zone 1 is highest during January (3 m s^{-1}) and in zone 2 during December ($> 3 \text{ m s}^{-1}$) (Figure 5a)". Does fig. 5a corroborate this statement? Further on: "During November to December, low PAR ($33\text{-}36 \text{ E m}^{-2} \text{ day}^{-1}$) prevailed in the study area, corresponding to low temperature and enhanced mixing, deepening the MLD. But according to fig. 5 in November –December MLD is still rather shallow, especially in November. [25 (page 11)]

Authors' comment: Thanks for the critical observation. The sentence is rephrased now as 'Wind speed fluctuates strongly for zones 1 and 2. In zone 1, maximum variability ($0.5\text{-}3.0 \text{ m s}^{-1}$) is seen during November and December and for zone 2, wind varies strongly throughout winter, with maximum wind speed ($0.5\text{-}3.0 \text{ m s}^{-1}$) for December and January months.' This sentence is corroborated by the data presented in Figure 5A.

Regarding the second suggestion, the sentence is changed to 'Decreasing pattern in PAR ($33\text{-}36 \text{ E m}^{-2} \text{ day}^{-1}$) prevailed in the study area during November to December for both zones, which corresponds to a reducing trend in temperature and deepening MLD cycle.'

16. The fig. captions are poorly written: "Time series of the monthly average concentration of wind speed and PAR (a1 and a2) SST and MLD" [5 (page 12) and 5 (page 13)]

Authors' comment: The figure caption has been rephrased:

"Temporal variability of wind speed and PAR (a), SST and MLD (b) and surface Chl-a (c) averaged for zone 1 (left, denoted by suffix 1) and zone 2 (right, denoted by suffix 2) during the winter period for the years 2002–2013. Pink colour is used to represent Chl-a, SST and wind speed and blue to represent MLD and PAR. Thick lines represent mean and the shaded areas the standard deviation for each parameter. The time series for the individual years are shown using thin lines. Vertical dotted lines represent the timing (month) of peak algae blooms in each zone."

17. Please, comment on your finding that PAR and Chl for zone 5 are not correlated at all, and for zone 6 they are inversely correlated. Also, some interpretational comments are required for

the phrase “For zone 5, wind and Chl-a production are weakly correlated ($r = 0.30$, $n=60$), while in zone 6, these parameters are not correlated ($r = -0.09$, $n=60$)” [5 (page 16)]

Authors’ comment: MLD in Zone 5 are ~30 - 40 m shallower than in zone 6 and hence strong winds for the entire month will have triggered mixing, supplying more nutrients than by convective mixing alone to the mixed layer enhancing Chl-a production. In zone 6, wind fluctuates strongly compared to zone 5. Zone 6 is classified as INDW in Longhurst’s classification, where wind induced blooms are observed. However, the time scale of wind induced bloom, will be of the order of days / weeks and not months and hence on monthly scales, the wind’s influence will not be resolved.

18. why the regression equations do not include such variables as MLD, concentration of nitrates nitrates and iron. It would be much better to do so instead of discussing the relations between Chl and the above variables apart from the variables reflected in Table 1. [Table1]

Authors’ comment: Linear regression as well as the multiple regression analysis is done utilizing monthly data. Whereas, the nitrates and iron data is available only as monthly climatology. Therefore, regression analysis on monthly scale cannot include nitrate or iron concentration using the available data.

19. Caption for Fig. 8 lacks the designations of colours. [Page 17]

Authors’ comment: Sentence provided in quotes will be included in the Figure caption. “Zones 1 to 6 are represented by violet, blue, green, light green, yellow and red lines respectively.”

20. Please, give (at least in the Appendix section) the rose of winds in winter in order to let the reader better understand why in some parts of the sea DOT is higher than in the others. It would be good to give alongside it the field of DOT over the study area. [15 (page 13)]

Authors’ comment: As suggested we have plotted the wind roses for the respective zones in order to reveal the possible source locations of DOT (Figure R6). For Zone 1, both the Thar desert and Arabian desert contribute to DOT, as the strong winds have directions between northerly to north-westerly. Similarly for zone 2, both these zones can be significant. While, for zone 3, its the Arabian desert contribution more to DOT enhancement as revealed from wind rose diagram. While for zone 4, it’s the continental wind from Indian sub-continent available in the area. This is consistent with Patel et al. 2017.

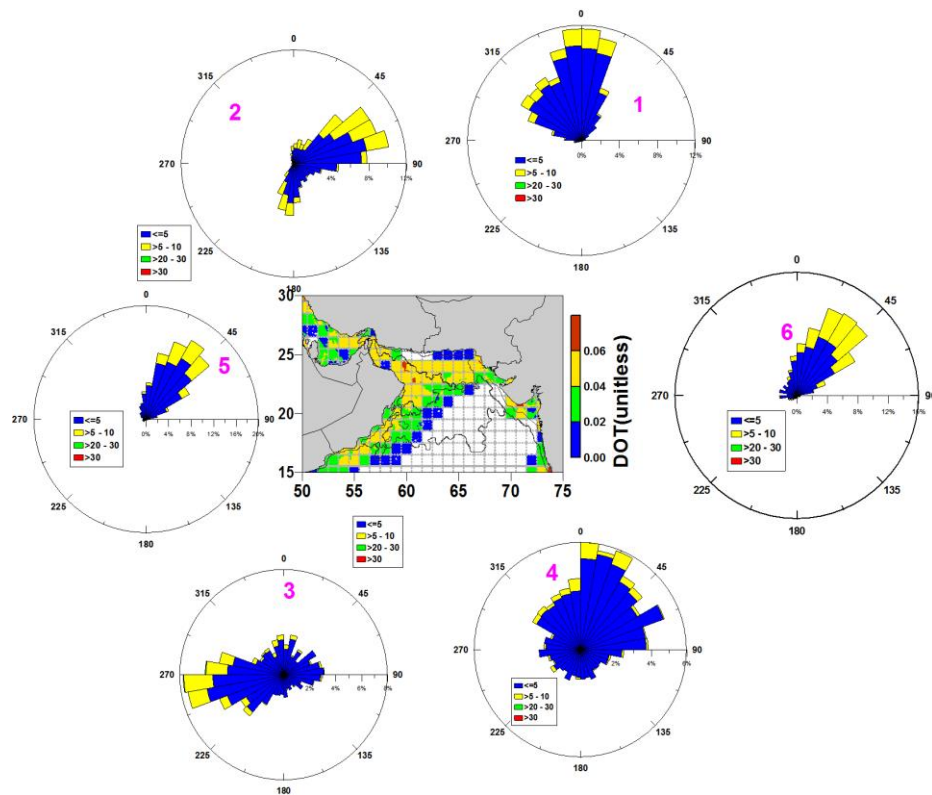


Figure R6. Wind rose diagram for the six zones. Zone number corresponding to wind rose plot is provided.

21. As was commented above, the reported finding on the north-south gradient in Chl is stale and had been established without any complicated processing procedures. The same comment can be made with regard to the identified number of [10 (page 19)]

Authors' comment: The north-south gradient in Chl-a is visible in satellite images (individual and binned data, however identification of other PC's contributing to Chl-a distribution during winter cannot be done with subjective / visual analysis. An objective method is required to handle it and in this paper we have elaborated a method using the combination of principal component analysis and cluster analysis. The number of differentiated zones in the region is consistent with what is found in literature for other marine areas.

22. The reported finding that “The increased amount of Chl-a production in the open ocean zones are found to be directly related to sea surface temperature variability (ie. cooling) and the deepening of the mixed layer “ is neither an unknown phenomenon for the study area. [5 (page 20)]

Authors' comment: The sentence has been modified: “In agreement with other studies, an increase in the concentration of Chl-a in the open ocean zones (zones 1, 2, 3 and 4) are found to

be directly related to the variability of the sea surface temperature (ie. surface cooling) and the deepening of the mixed layer.

23. “The combined analysis of DOT and nitrate suggests that the variability of the algae blooms depend on both sources in these zones. The variability of Chl-a in the northern and northwestern parts of the Arabian Sea is correlated strongly with the atmospheric deposition of iron from January to March” The two statements appear kind contradictory. [15(page 20)]

Authors’ comment: The initial sentence is in general for all zones, a dependence of both parameters is observed in six zones. However, in the north and northwestern Chl-a production and DOT follows similar trend of variation and hence in these zones [zone 1, 2, 3 and 5] strongly is observed with the atmospheric deposition of iron from January to March.

Clarification of the sentence, according to comment; “The combined analysis of DOT and nitrate suggests that the variability of the algae concentration depend on both sources of nutrient supply in all six identified ecological zones. However, the variability of Chl-a in the northern and northwestern parts of the Arabian Sea (zones 1, 2, 3 and 5) is predominantly correlated with the atmospheric deposition of iron during the period from January to March.”

24. It is difficult to agree with the authors’ statements that “This study provides a more comprehensive understanding of the environmental factors controlling the spatio-temporal variability of the marine chlorophyll a concentration in the northern Arabian Sea during winter conditions”, and further on “Additionally, this study reveals the need for better understanding of factors controlling the marine primary productivity in other coastal upwelling zones”. Indeed, to justify/prove the validity of each zone the authors refer to the relevant publications of other workers who investigated in depth the factors and mechanisms controlling the spatiotemporal variability of the marine chlorophyll a concentration. Also, in many studies of the north Arabian Sea the need of further investigations, and more thorough sampling/in situ determinations of physico- and biogeochemical variables. [30 (page 20)]

Authors’ comment: Distinct Chl-a characteristics for each of the identified ecological zones clearly indicates the spatial variation of Chl-a during winter is better brought out in this work (Figure R1). The temporal variability in Chl-a in the six delineated zones is an objective way to study spatio-temporal variability. This comparison clearly indicated the significance of the present classification.

Authors have correlated the surface cooling and mixed layer deepening with Chl-a production, in the delineated six ecological zones, which is required to explain Chl-a characteristics in these zones. Distinct physical and chemical characteristics within zones are identified. For the first five zones, it’s the cooling followed by MLD deepening which enhances nutrient availability resulting in increased production, in zone 6 while MLD deepening / Chl-a production is followed by maximum cooling. In the analysis section, we have used the established knowledge on driving processes of Chl-a processes in the study area based on published information. Such comparisons

are entirely appropriate for research and development. Also, the complex influence of both nutrient and DOT between north, north-east as well as south and southeast part of the study area is brought out in this work. Though, similar studies have been carried out, these have been done for smaller areas and shorter periods, while our study has covered eleven years of data covering the entire Arabian Sea. We have analysed the influence of DOT and nitrate in all zones and found that in the north and northeast production is strongly influenced by high DOT, rather than nitrate availability. Therefore, we respectfully disagree with the reviewer's opinion that this study does not provide a more comprehensive understanding of the environmental factors controlling the spatio-temporal variability of the marine chlorophyll a concentration in the northern Arabian Sea during winter conditions. We show that it does.

Furthermore, the in-situ coverage in the Arabian Sea is not great, hence we argue that the spatial and seasonal distribution of physical mechanism coupled with production in the Arabian Sea is fully known yet.

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Delimitation of marine ecosystem zones in the northern Arabian Sea using an objective method during winter

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Abstract. The spatial and temporal variability of marine autotrophic abundance, expressed as chlorophyll concentration, is monitored from space and used to delineate the surface signature of marine ecosystem zones with distinct optical characteristics. An objective zoning method is presented and applied to satellite-derived Chlorophyll a (Chl-a) data from the northern Arabian Sea (50°–75° E and 15°–30° N) during the winter months (November – March). Principal Component Analysis (PCA) and Cluster Analysis (CA) were used to statistically delineate the Chl-a into zones with similar surface distribution patterns and temporal variability. The PCA identifies principal components of variability and the CA splits these into zones based on similar characteristics. Based on the temporal variability of Chl-a pattern within the study area, the statistical clustering revealed six distinct ecological zones. The obtained zones are related to the Longhurst provinces to evaluate how these compared to established ecological provinces. The Chl-a variability within each zone was then compared with the variability of oceanic and atmospheric properties viz. mixed-layer depth (MLD), wind speed, sea-surface temperature (SST), Photosynthetically Active Radiation (PAR), nitrate and Dust Optical Thickness (DOT) as an indication of atmospheric input of iron to the ocean. The analysis showed that in all zones, peak values of Chl-a coincided with low SST and deep MLD. Rate of decrease in SST and deepening of MLD are observed to trigger the intensity of the algae bloom events in the first four zones. Lagged cross-correlation analysis shows that peak Chl-a follows peak MLD and SST minima. The MLD time-lag is shorter than the SST lag by eight days, indicating that the cool surface conditions might have enhanced mixing, leading to increased primary production in the study area.

An analysis of monthly climatological nitrate values showed increased concentrations associated with the deepening of the mixed-layer. The input of iron seems to be important in both the open ocean and coastal areas of the northern and north-western part of the Northern Arabian Sea, where the seasonal variability of the Chl-a pattern closely follows the variability of iron deposition.

1 Introduction

The Northern Arabian Sea is a dynamic ocean area, where upwelling, downwelling, convective overturning, mesoscale eddies, fronts and planetary waves commonly occur. The ocean dynamics are significantly influenced by the seasonal monsoon cycles (Rao et al., 2010; Schott and McCreary, 2001). Seasonality in marine primary production in the Arabian Sea associated with the monsoon was studied by Lévy et al. (2007), who showed that two distinct seasonal bloom patterns occur: one during winter and another during summer. During the winter monsoon period, convective overturning is common in the area enhancing nutrient supply to the ocean surface and increasing biological productivity (Madhupratap et al., 1996). Iron is found to be a limiting nutrient and is primarily supplied through atmospheric fallout of desert dust in this region (Banerjee and Kumar, 2014; Johansen et al., 2003; Moffett et al., 2015; Naqvi et al., 2010; Wiggert and Murtugudde, 2007). Under cloud-free conditions optical sensors onboard satellites measure spectral reflectance of ocean surface from which chlorophyll a (Chl-a) concentration can be derived, which serves as a proxy for phytoplankton biomass (Pettersson and Pozdnyakov, 2013; Wiggert et al., 2002). However, the accuracy of Chl-a retrieval is low in turbid waters and regions where the satellite signal is hampered by unaccounted atmospheric influences (Pozdnyakov and Grassl, 2003; Kahru et al., 2014). In this work, which focuses on open-ocean waters away from turbid coastal waters, we anticipate that such detrimental factors are not important.

Classification of the ocean into ecological zones is a useful tool to understand the interactions between physical and biochemical marine processes as well as the interactions between the surrounding water masses and zones (Longhurst, 1995, 1998, 2006; Spalding et al., 2012). Longhurst (1995, 1998, 2006) described the global ocean in terms of several ecological provinces, considering the entire plankton ecology in relation to regional meteorological and oceanographic conditions. A similar approach by Spalding et al. (2012) classified global pelagic waters into 37 large-scale pelagic provinces based on oceanographic properties. Both the Longhurst and the Spalding provinces are static representations of the global ocean based on an annual cycle. Devred et al. (2007) proposed a method of classification that allows for seasonal movements of boundaries of the ecological provinces. They used satellite measurements of Chl-a and Sea-Surface Temperature (SST) from different seasons to re-define dynamic provinces in the northwest Atlantic Ocean. Dynamic variations in global biogeochemistry based on Chl-a, surface salinity and temperature were examined by Reygondeau et al. (2013) who observed that seasonal as well as inter-annual variability influenced the delineation of the provinces.

In this study Chl-a satellite remote sensing data from the winter seasons (November to March) were used to delineate the marine ecological zones to study phytoplankton variability and its drivers in the northern Arabian Sea. Though we know that significant primary production occurs in summer in the Arabian Sea, it is also very cloudy that there are insufficient remote sensing observations to perform the analysis. The winter season was chosen as it represents the period when, due to cloud-free conditions, high quality satellite data are available and high values of Chl-a ($> 0.5 \text{ mg m}^{-3}$) prevailed in the study area. Apart from this temporal restriction, as the proposed method utilises satellite data, only surface coverage information is available. However, a significant larger spatio-temporal quantity of data is available for the delineation study, compared to usage of in situ observations. ~~The fact that during the study period (winter), deep chlorophyll maxima is weak and shallow due to light~~

attenuation by surface chlorophyll (Mignot et al., 2014) allows the usage of surface Chl-a alone as a proxy for columnar Chl-a content .

In each identified zone, Chl-a is averaged for each winter month for the study period in order to understand its variability. Similarly, the time series of zonal averages of environmental factors viz. SST, Mixed-Layer Depth (MLD), Photosynthetically Active Radiation (PAR) and wind speed are calculated and compared with Chl-a to understand their influence on marine primary productivity. To this end, we also examine time-lagged correlation of Chl-a with SST and MLD. The influence of nitrate and dust optical thickness (DOT) on phytoplankton variability is also analysed.

2 Data

This study utilizes satellite-derived data on surface Chl-a concentration, Photosynthetically Available Radiation (PAR), Sea Surface Temperature (SST) and Aerosol Optical Thickness for derivation of Dust Optical Thickness (DOT). These quantities derived by remote-sensing are supplemented with other environmental properties, including surface winds from reanalysis, modelled MLD, and climatological monthly nitrate concentrations, as described in detail below.

2.1 Chlorophyll-a data (Chl-a)

Global gridded Chl-a concentrations at 9 km spatial resolution, based on the MODIS Aqua sensor are available from NASA's ocean colour data portal (<http://oceandata.sci.gsfc.nasa.gov>). The present work uses monthly, climatological and 8-day composite Chl-a data from November to March during the winter seasons from 2002 to 2013. The MODIS Chl-a algorithm derives the near-surface Chl-a concentration (expressed in mg m^{-3}), from remote-sensing reflectance (Werdell and Bailey, 2005). The climatological dataset is used for the zoning procedure. Monthly data are used in the time series analysis and time-lagged correlations are computed using 8-day composites.

2.2 Photosynthetically Available Radiation (PAR)

PAR is the quantum energy flux from the sun in the visible spectrum (expressed in $\text{Einstein m}^{-2} \text{ day}^{-1}$). Under cloud-free conditions PAR is calculated from radiance measurements at the top of the atmosphere derived from satellite remote sensing data in the visible spectral range and corrected for the effects of clouds (Frouin et al., 1995). PAR used in this study is also available from the above-mentioned ocean-colour data portal of NASA.

2.3 Sea Surface Temperature (SST)

We used MODIS Aqua day time, 8-day, composite SST at a spatial resolution of 9 km, available from NASA's ocean colour data portal. The SST is derived from radiance signals in the thermal infra-red at $11 \mu\text{m}$ and $12 \mu\text{m}$, from the satellite sensor. The brightness temperatures are derived from the observed radiances by inversion (in linear space) of the radiance versus blackbody temperature relationship (Haines et al., 2007).

2.4 Dust Optical Thickness (DOT)

DOT used is calculated utilizing the method of Kaufman et al. (2005) and is given as:

$$DOT = \frac{AOT(f_{an} - f) - AOT_{ma}(f_{an} - f_{ma})}{(f_{an} - f_{du})} \quad (1)$$

where, AOT is the Aerosol Optical Depth, which is obtained from MODIS / Aqua (<http://oceancolor.gsfc.nasa.gov>). AOD represents total aerosol content in the atmospheric column, while DOT indicates just the dust content in the atmospheric column. Here, 'f' is the fraction of AOT contributed by fine particles. Suman et al. (2014) reported 'f' to be 0.25 over the northern Indian Ocean. The quantities f_{an} , f_{ma} and f_{du} are respectively the fine-mode fractions of anthropogenic aerosol, maritime aerosols and dust. Following the work of Nair et al. (2005) and Banerjee and Kumar (2014), f_{an} is taken as 0.90. Similarly, f_{ma} is assumed to be 0.47, f_{du} is set at 0.25. The f_{ma} value is an average value for the period of 2003–2011 over the western part of the Equatorial Indian Ocean and f_{du} is based on satellite values during dust outbreaks in the Middle East. Also, AOT_{ma} is the maritime AOT, calculated according to (Smirnov et al., 2003)(Moorthy et al., 1997), as,

$$AOT_{ma} = 0.13 * exp^{0.09*w} \quad (2)$$

where w is the wind speed in $m s^{-1}$. This study used wind at 10 metres obtained from ERA-Interim reanalysis.

2.5 Winds

The ERA-Interim reanalysis data of 12-hourly wind components at 10 m simulated by atmospheric model from the European Centre for Medium-Range Weather Forecasts (ECMWF) at $1.0^{\circ} \times 1.0^{\circ}$ spatial resolution was retrieved (Dee et al., 2011). These ERA-Interim wind fields were used to calculate the wind speed.

2.6 Mixed Layer Depth (MLD)

The MLD for the Northern Arabian Sea used in this work is defined as the depth where the temperature is $1^{\circ}C$ colder than that at the surface temperature (Kumar and Narvekar, 2005). In this study the vertical temperature-profile data are weekly averages from a Hybrid Coordinate Ocean Model (HYCOM) simulation for the Indian Ocean (Bleck, 2002; George et al., 2010). HYCOM combines the optimal features of isopycnic-coordinate and fixed vertical grid ocean circulation models in one framework. The adaptive (hybrid) vertical grid conveniently resolves regions of vertical density gradients, such as the thermocline and surface fronts. A detailed analysis and validation of this ocean model for the Indian Ocean can be found in (George et al., 2010). A comparison of the MLD obtained from the HYCOM modeled data using both temperature and density criteria with the Argo datasets available for winter is carried out. A total of 6256 profiles are collocated for winter for the entire study area. MLD calculated from density criteria have higher RMSD and error percentage (RMSD: 36 m and an error of 68 %) compared with that derived from temperature criteria using $1^{\circ}C$, $0.5^{\circ}C$ and $0.2^{\circ}C$ (RMSD: 20 m and an error of 28 %). This analysis showed better MLD derivation is with temperature criteria. Hence, a second analysis based on different temperature based MLD criteria (1° , 0.5° and 0.2° drop from that at surface) with the Chl-a in the six zones were carried out.

From this analysis, it was found that MLD calculated using temperature criteria of 1°C explained the Chl-a pattern in each of the six selected zones more accurately than those computed using other temperature thresholds. This is the reason for including temperature-based MLD in the present work.

2.7 Nitrate

5 Present study utilizes monthly climatological nitrate profiles available from NOAA National Centers for Environmental Information (NCEI) / World Ocean Atlas 2013 (WOA 2013) (<http://www.nodc.noaa.gov>). WOA 2013 includes global nutrient profiles at one-degree spatial resolution, which is the average of all unflagged interpolated values from all available in-situ observations (Garcia et al., 2013). Climatological data of nitrate used in this study are objectively analysed values for each winter month, such that nitrate availability in each zone is calculated by averaging nitrate values within the mixed layer determined
10 from HYCOM model.

3 Method for delineation of ecological zones

A method to delineate the study area objectively into ecological zones as per statistically distinct surface Chl-a characteristics is developed. The method is based on the sequential application of Principal Component Analysis (PCA) and Cluster Analysis (CA) to series of satellite-derived images of surface Chl-a concentration.

15 3.1 Principal Component Analysis (PCA)

PCA is a statistical method that uses orthogonal transformation to identify the principal components (PCs) contributing to the variance of a signal. This method normalizes the dataset and computes covariances, eigenvectors and corresponding eigenvalues for each PC. The eigenvectors are then sorted by decreasing eigenvalues (Abdi and Williams, 2010). The first PC is oriented in the direction of the largest variation of the original variables and passes through the centre of the data distribution. The second
20 largest PC lies in the direction of the next largest variation, and passes through the centre of the data and is orthogonal to the first PC, and so forth.

3.2 Cluster analysis (CA)

K-means clustering is a signal processing method used to partition a given set of observation vectors into 'k' number of clusters, where k can be any integer greater than one (Kanungo et al., 2002). This method generates a set of centroids, one for each of
25 the k clusters. Observation vectors are classified into clusters such that each observation vector is assigned to that cluster for which the total distance from vector to cluster centroid is minimum. For example, if a vector A is closer to centroid *i* than any other centroids, then A belongs to the cluster *textiti*.

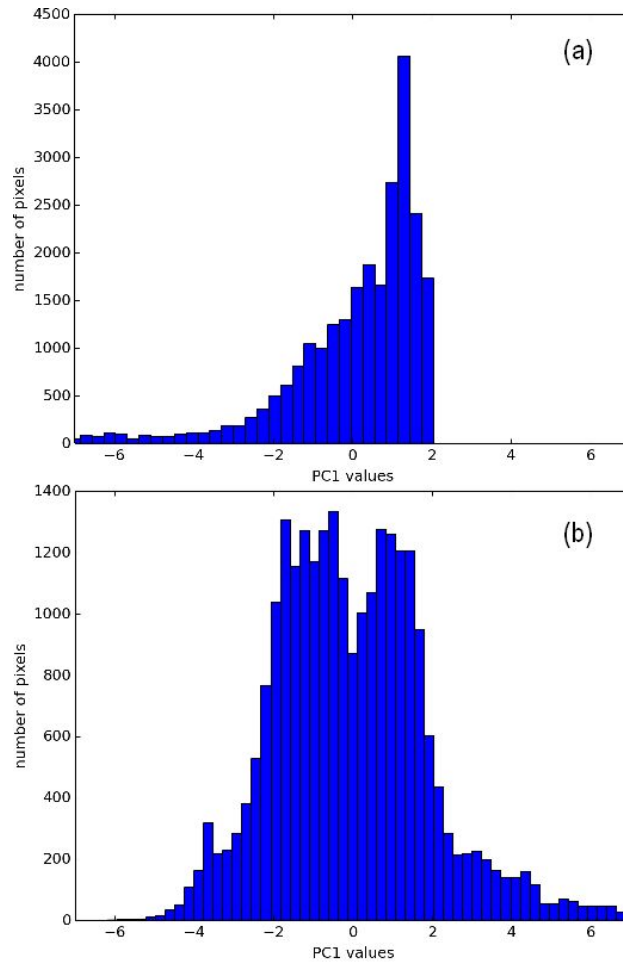


Figure 1. Probability distribution of PC1 before (a) and after the scaling and centering around the mean conversion (b).

4 Objective delineation of ecosystem zones in the northern Arabian Sea

Based on a monthly climatology (averaged over the years 2002-2013) of Chl-a concentration in the northern Arabian Sea for the winter months from November through March, five principal components of variability were obtained. The components account for respectively 80%, 13%, 7%, 4%, 2% and 1% of the variance in the monthly Chl-a distribution pattern.

- 5 Following the method of Z-score scaling (Johnson and Wichern, 1992) the values of principal components (PCs) were scaled to one standard deviation centered on the mean. In addition, values of the first PC were converted so that the probability distribution of the values is closer to the Gaussian distribution (Figure 1) using the following equation (3) and (4).

$$P_{GAUSS} = \log_{10}(\min(P_0) - (P_0)) \quad (3)$$

$$P_{NORM} = \frac{(mean(P_{GAUSS}) - P_{GAUSS})\sigma_0}{\sigma_{GAUSS}} \quad (4)$$

where P_0 denotes original value of the first principal component, P_{GAUSS} denotes value of PC1 after conversion to a Gaussian distribution, P_{NORM} denotes values of PC1 after scaling and centering around the mean, σ_0 denotes standard deviation of P_0

5 values and σ_{GAUSS} denotes standard deviation of P_{GAUSS} values.

~~Maps of principal components (PC1-5) are examined with regard to spatial distribution, information content and noise contamination (Figure 2). Ranges of P_{NORM} decay from 8 (PC1), to 4 (PC2), to 2 (PC3), to 1 (PC4) and to 0.4 (PC5) confirming that most of information about spatial and temporal dynamics of Chl-a is retained in PC1. High values associated with PC1 are observed in the southern open ocean part of the study area whereas low values are observed along coastal areas of western India and near the coast of Oman. This indicates the difference between ecosystem dynamics in the oligotrophic waters (southern open ocean) and those in the coastal eutrophic waters (coastal and northern area). Such a northwestern and southeastern gradient has been observed by Prakash and Ramesh (2007) in the study area using satellite Chl-a. Jaswal et al. (2012) have reported a north-south gradient in the study area during winter, based on SST observations. Map of values associated with PC2 (Figure 2) shows that high values appear in the Gulf of Oman (mostly oligotrophic, but with significant seasonal variations) and the shelf areas of Oman, Pakistan and western India (mostly mesotrophic, with low seasonal variations). The seasonal variation in the algal bloom pattern off Oman is attributed to iron availability (Wiggert and Murtugudde, 2007; Naqvi et al., 2010). The spatial pattern of PC3 suggests that waters in southern part of Gulf of Oman (oligotrophic) differ from the mesotrophic waters near the coasts of Pakistan and Gujarat in agreement with Naqvi et al. (2010). The map of PC4 and PC5 shows a very low range of values and very high spatial inhomogeneity meaning that it contains mostly noise.~~

20 Maps of principal components (PC1-5) are examined with regard to spatial distribution, periodicity and information content (Figure 2). Ranges of P_{NORM} decay from 8 (PC1), to 4 (PC2), to 2 (PC3), to 1 (PC4) and to 0.4 (PC5) confirming that most of information about spatial and temporal dynamics of Chl-a is retained in PC1. High values associated with PC1 are observed in the southern open ocean part of the study area whereas low values are observed along coastal areas of western India and near the coast of Oman. This indicates the difference between ecosystem dynamics in the oligotrophic waters (southern open

25 ocean) and those in the coastal eutrophic waters (coastal and northern area). The periodicity of PC1 indicates relatively constant negative values, thus PC1 is an expression of the overall pattern of low production in the southern oligotrophic gyre and high production to the north and near the coast, which dominates the signal. Such a northwestern and southeastern gradient has been observed by (Prakash and Ramesh, 2007) in the study area using satellite Chl-a. Jaswal et al. (2012) have reported a north-south gradient in the study area during winter, based on SST observations. PC2 indicates a semi-cyclic trend in Chl-a

30 production with its peak during February. The values develop from negative to positive with the same order of magnitude as PC1 and thus represents the main winter variability in the area. The strongest signal is in the northwestern Arabian Sea extending upto Pakistan coast. The periodicity of PC3 too develops from negative to positive value and back to negative values in March. This PC demarcates the regions along Oman coast, west coast of India and northern part of Persia Gulf from the other region where no significant peaks or minimums in Chl-a occur during January. PC4 and PC5 represents the intraseasonal

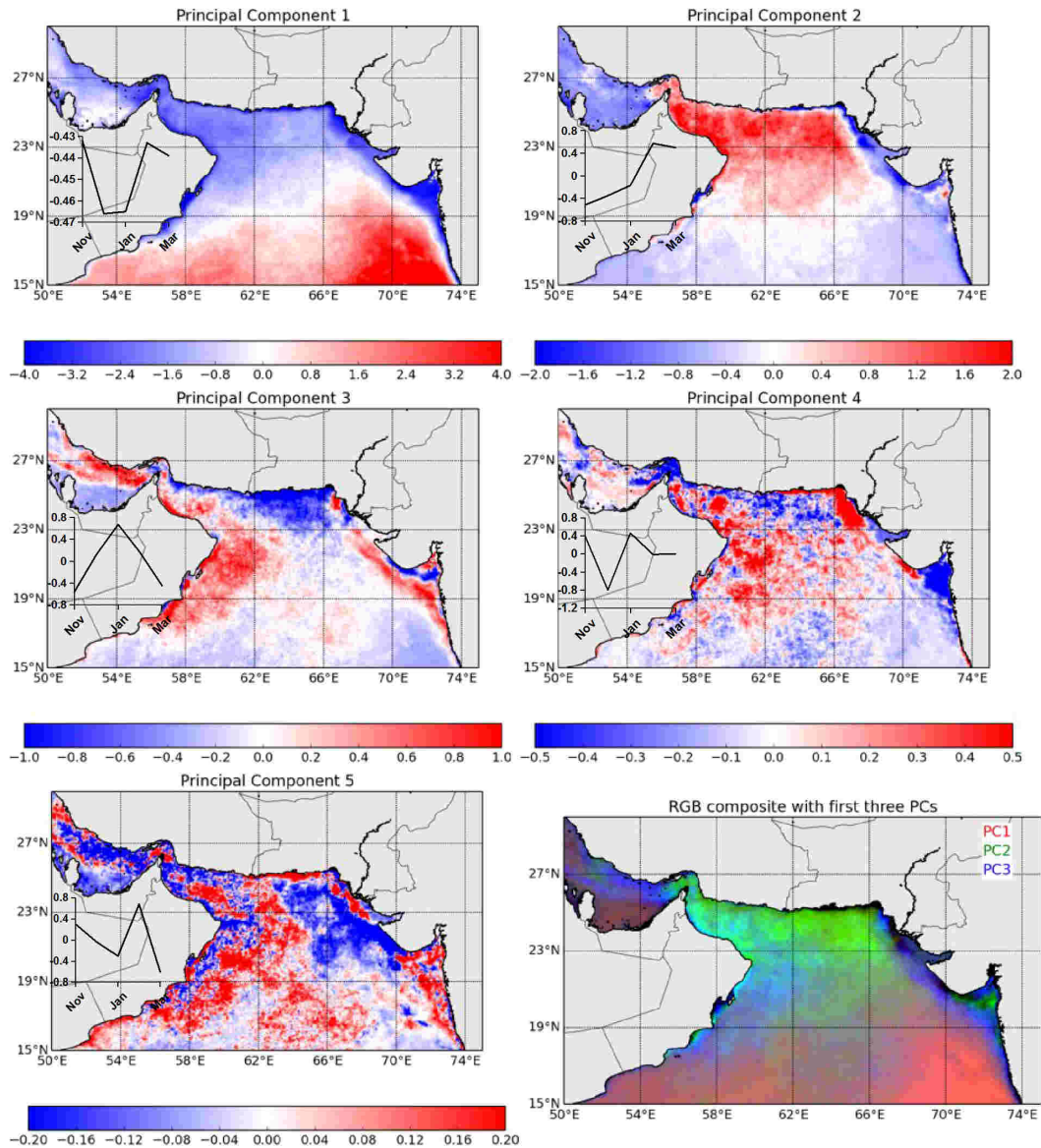


Figure 2. Individual maps of principal components (PC 1 to 5) and RGB composite of the first three statistically significant components. Corresponding to each PC, the respectively periodicity is shown.

variability, the spatial signal is highly scattered for both these PCs and it is likely that they contain a considerable amount of noise, however for PC4 we see consistent patterns along the coast of India and Pakistan and the signal is still about 10% and 5% of the PC1 for PC4 and PC5 respectively. PC5 also differentiates Persian Gulf and Pakistan and Gujarat coast from the rest of the north-central region. Based on this, PC1-PC5 was retained when considering possible zoning combinations (see Appendix

5 A1), however PC5 was not included in the final zoning.

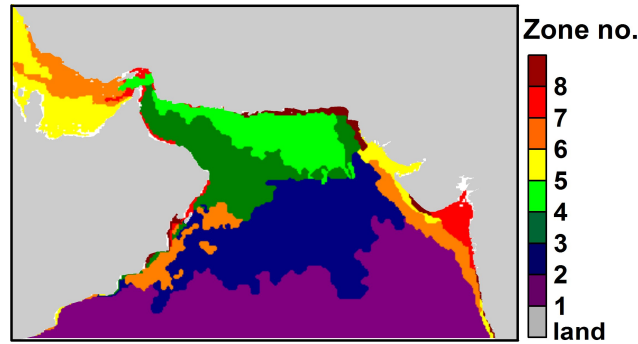


Figure 3. The identified ecological zones obtained from the combination of 4 PCs and 8 CAs.

Visual inspection of RGB composite (Figure 2f) where values of PC1, PC2 and PC3 are displayed respectively using shades of red, green and blue colours helps to identify zones with similar statistical attributes. Zones with a similar colors have similar combinations of PC values and therefore also similar seasonal dynamics of Chl-a. Such patterns allow the application of a semi-automated statistical clustering method to delineate the study region into areas with distinct Chl-a dynamics based on the values of principal components as discussed in section 3.

To bring out the significance of combined Principal Components (PCs), a map (RGB composite of the first three statistically significant components) is drawn (Figure 2f). This map is generated with the combination of first three PC's (Figure 2). First PC is represented using red, second by green and third by blue. Zones with similar colors have similar combinations of PC values and therefore this figure illustrates similar winter variability on Chl-a. This image is the application of a statistical clustering method to delineate the study region into areas with distinct Chl-a dynamics based on the values of principal components as discussed in section 3.

Several possible zoning maps were produced by varying the number of PCs and clusters in order to objectively delineate the northern Arabian Sea into ecological zones (Appendix A). The final delineation into ecological zones was obtained by combining the first 4 PCs and 8 clusters (Figure 3), based on general Chl-a pattern in the Northern Arabian Sea. Spatial smoothing was applied to the selected zone map. The methodology used in zone map selection and smoothing procedure are provided in Appendix A. Satellite-derived Chl-a values along coastal and shallow waters are found to be erroneous, hence the coastal shallow water regions under zones 5, 7 and 8 as well as the part of zone 6 inside the Persian Gulf and patches along Yemen coast are excluded from further analysis in this study. This leaves the first four zones and the region in zone 6 along Oman and the west coast of India. Zone 6 has two regions that lie on opposite sides of the Arabian Sea and the physical forcing affecting Chl-a concentration along the two regions is likely to be different (Kumar and Prasad, 1996; Kumar et al., 2001; Shetye et al., 1994). Therefore, these two regions are considered as separate ecological zones. As a result, a total of six distinct ecological zones are delineated in the study area (Figure 4a).

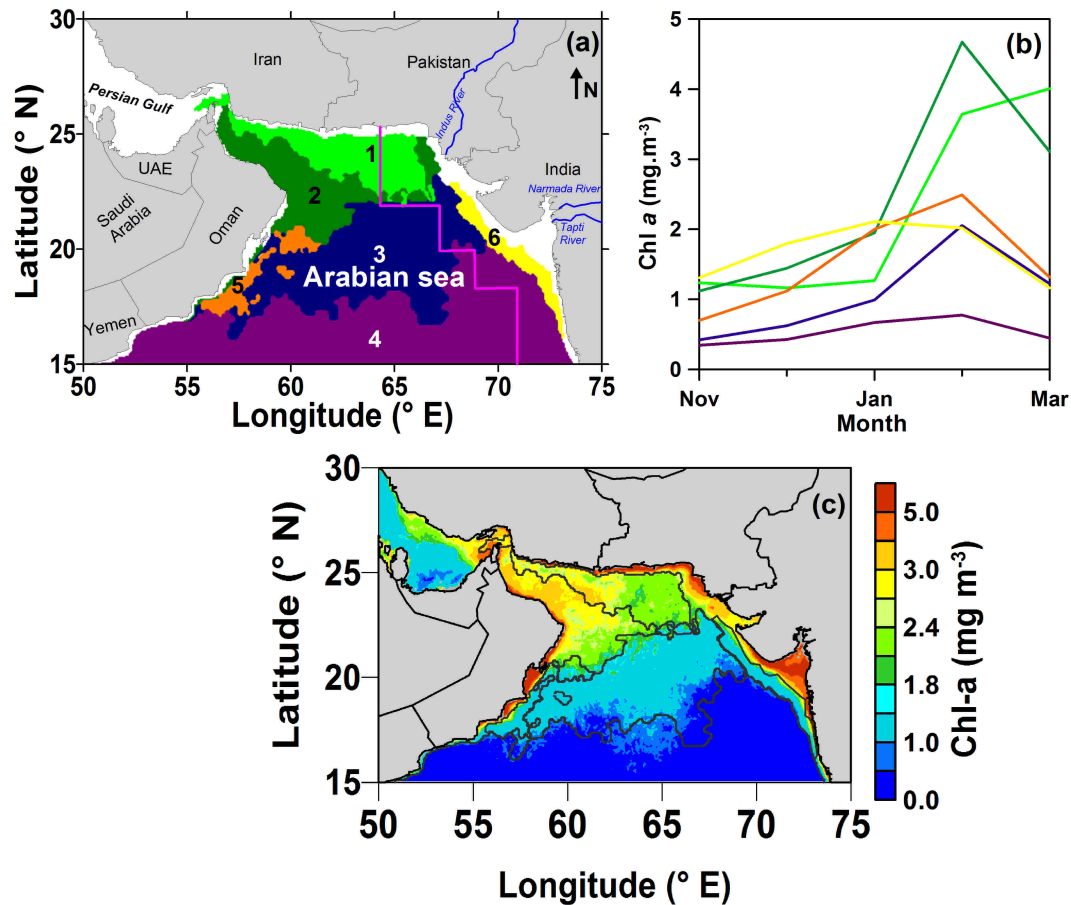


Figure 4. Map of the delineated ecological zones including the two Longhurst provinces in the Northern Arabian Sea. Pink line demarcates the border between the Longhurst provinces in the study area, respectively the northwest Arabian upwelling province to the west and the western India coastal province to the east. (b) The mean monthly climatology of surface Chl-a concentration during the winter months, for each zone, plotted using the same colours as in Figure 4(a) to represent each zone. (c) Annual winter climatography (seasonal average Chl-a values over the winter period (Nov-March) from 2002 to 2013) of Chl-a revealed from satellite data. The black lines indicated the boundaries of the delineated zones.

4.1 Comparison of ecological zones with Longhurst provinces

Chl-a winter variability revealed six distinct ecological zones in the Arabian Sea, which has been compared with the Longhurst biogeographical classification of marine provinces for the study area. The six ecological zones identified fall into the two Longhurst provinces. These are respectively the northwest Arabian upwelling province (ARAB), covering the west and central part of the study area and western India coastal province (INDW) to the east of the study area. The border between these two Longhurst provinces is demarcated with a pink line in Figure 4a.

Zone 1 appears in the northern part of the study area (Figure 4a). During winter, moderate ($5-10 \text{ m s}^{-1}$) northeasterly winds ~~blows~~ blow over the area. Intense cooling is reported in this region, which enhances primary production (Madhupratap et al., 1996; Kumar and Prasad, 1996). Similar to zone 1, intense cooling and high production also occur in zones 2 (Madhupratap et al., 1996). First three zones have similar Chl-a pattern, such that peak values occur either during the month of February or March and for January Chl-a concentration is always half than its peak value. These three zones are ~~strong upwelling regions with high values of Chl-a concentration during the winter~~ regions where strong convective mixing occurs during winter, which enhances Chl-a concentration in these region (Banse and English, 2000). The cool and dry northeasterly winds blowing onto the region from the adjacent land territories enhance cooling at the ocean surface. Consequently, increased evaporation leads to a decrease in surface temperature and increase in surface salinity and density, creating convective mixing (Kumar and Prasad, 1996; Prasad and Ikeda, 2002; Shetye et al., 1992). All these three ecological zones are stretched across both the Longhurst provinces, with the majority of the area located in the ARAB province. It is to be mentioned here that the ARAB province with upwelling in the Arabian Sea according to Longhurst's classification represent provinces with strong upwelling during summer and with strong convective cooling during winter. The southern part of the study area includes zone 4, where winter cooling is less intense and less marine production occurs, compared with zones 1-3 (Jyothibabu et al., 2010). However, similar to zones 1-3, zone 4 also is split across the two Longhurst provinces, with the western and central parts of zone 4 falling into the northwest Arabian upwelling province and the eastern part of the zone into the west Indian coastal province. Zone 5 includes the coastal area along the Oman coast between 18°N - 22.5°N and the coastal region along the west coast of India from 16°N to 23°N is included under zone 6. These coastal areas are highly productive during winter (Kumar and Prasad, 1996; Kumar et al., 2001).

The physical mechanisms in the northern and northwestern part of the Arabian Sea are very different from those in the eastern part. Strong convective mixing prevails in the northern and northwestern parts of the study area. The strong stratification in the east, due to the presence of low salinity and high temperature water limits convective mixing in the eastern part of the study area (Naqvi et al., 2006). The eastern part comprises the zone 6, a part of zone 3 and zone 4. Among these three zones, zone 6 is a coastal area and is vulnerable to coastal complex processes. ~~Zone 6 is also an upwelling region (Shalin and Sanilkumar, 2014; Sudheesh et al., 2016). Nutrient supply from Narmada and Tapi rivers as well as atmospheric deposition of nitrogen enhances marine production in zone 6 (Singh et al., 2012; Singh and Ramesh, 2011).~~

For comparing Chl-a in six zones with Longhurst's province, we have classified zone 1, zone 2, zone 3, zone 4 and zone 5 in the Longhurst ARAB province and zone 6 as the INDW province (Figure 4a). Maximum Chl-a observed during February is consistent in both provinces of Longhurst as well as the present six zones. During winter, ARAB ($0.5-0.8 \text{ mg m}^{-3}$) and INDW ($0.4-0.6 \text{ mg m}^{-3}$) have low values of Chl-a with similar range of variability (Longhurst, 2006). ~~However, our study has identified high values of Chl-a concentration ($>0.5 \text{ mg m}^{-3}$) with significant gradients between various parts of the study area.~~ However, we have identified high Chl-a concentration ($>0.5 \text{ mg m}^{-3}$) in the entire study area, with significant differences between various parts, particularly higher values to the waters closer to the coast. From our analysis, it is clear that the northern parts has higher concentrations of Chl-a, which decreasing concentrations towards south. Also the variation between each zone is identified higher concentrations of Chl-a in the western parts compared to the more easterly located zones. With

only two Longhurst provinces such a spatial difference is not detectable. This spatial difference is due to the difference in physical mechanisms as mentioned in the above paragraph. Longhurst classification is based on 1° resolution global Chl-a maps in the context of regional meteorological and physical oceanographic variability (Longhurst, 1995). It also uses Chl-a observations from different time periods. In contrast, the present study utilises primarily Chl-a concentration obtained from satellite sensors at about 100 times the resolution used by Longhurst for regional mapping and classification of ecological zones in the northern Arabian Sea. Hence, this regional classification could delineate the spatial Chl-a variability better and the obtained zones contain more detailed regional information. This study is restricted to the analysis of data for the winter season. This work intends to characterise a more complete delineation of ecological zones and the mechanisms driving marine production in the study area during winter. Therefore, the influence of other ecological factors such as SST, MLD, PAR, wind and nutrients, on Chl-a production is included in the interpretations of the Chl-a pattern in each of the ecological zones. The Longhurst classification accounts for the differences in physical conditions between the northwestern and eastern parts. However, according to Naqvi et al. (2006), downwelling in the eastern part in winter cannot extend to the northern boundary of West Indian coastal province of Longhurst. Since the present zonal classification limits zone 6 from extending to the entire northern portion of the Longhurst province, our zones seem to be realistic in capturing regional Chl-a variability during winter season.

The annual winter climatology (seasonal average Chl-a values over the winter period (Nov-March) from 2002 to 2013) of Chl-a distribution revealed distinct features for each of the identified ecological zones (Figure 4 (c)). Based on the variability of Chl-a concentrations, zone 1 experiences maximum bloom intensity between 1.5 to 9.6 mg m⁻³ with a mean of 2.6 mg m⁻³ and standard deviation of 0.7 mg.m⁻³. Next to Zone 1, high Chl-a prevails in Zone 2, with a range of 1.4 to 7.0 mg m⁻³ and a mean 2.8 mg m⁻³. Standard deviation observed in Chl-a are same for both zones. Moderate values of Chl-a (1.3 to 1.9 mg m⁻³) are observed in Zone 3, Zone 5 and Zone 6. Though similar range are observed for these three zones, the temporal evolution are different. In zone 3, Chl-a varies between 0.5 to 4.2 mg m⁻³, with 0.3 mg m⁻³ standard deviation. Among coastal zones, zone 6 Chl-a standard deviation is higher (0.8 mg m⁻³) with a range of 0.9 to 6.8 mg m⁻³ than for zone 5 (0.6 mg m⁻³) between 1.0 to 4.3 mg m⁻³. Minimum value of Chl-a for the winter is observed in zone 4 (0.2 to 1.2 mg m⁻³), also in this zone least mean (0.5 mg m⁻³) and standard deviation (0.2 mg m⁻³) is observed. The Chl-a geo-spatial statistical variation in the study area clearly demarcates different ecological zones.

5 Time series analysis

Based on the magnitude of Chl-a in each zone, time series data of Chl-a and other environmental parameters (wind speed, MLD, PAR and SST) are examined to understand better the relations between physical and biological processes within each zone. Note that, the influence of water temperature on primary productivity through control of metabolism and respiration is a highly non-linear process (Wetzel, 2001) and cannot be accounted for in the present study. Monthly climatology of Chl-a concentrations in the identified ecological zones have all moderate to high values (0.3-5.0 mg m⁻³). Also, Chl-a follows a semi-cyclic seasonal variation pattern during the winter months with maximum values in February (Figure 4b). In zone 6, peak

Chl-a is observed during January. Variability in the northern, most productive, part (zones 1 and 2) is discussed first and then the southern, least productive, zones (zones 3 and 4) are considered. Finally, the time series along coastal and continental shelf zones including zones 5 and 6 are examined. The mean and standard deviation for each of these parameters are calculated for each winter month (November to March).

5 5.1 The ecological zones in the northern and most productive part of the Arabian Sea

In general, Chl-a concentration in zones 1 and 2 follows a typical wintertime cyclic variability with its peak values during the month of February (Figure 5c). Throughout the study period, the Chl-a concentration during February is at least double the concentration during January in these two zones. SST follows an inverse pattern compared with that of Chl-a, such that SST minima coincide with Chl-a maxima. Surface waters are relatively warm ($>27^{\circ}\text{C}$) during November and cool as winter progresses, with stronger cooling in zone 1 and 2 (Figure 5b). By January, SST has reduced by $2.5\text{-}3.0^{\circ}\text{C}$ in both zones with a minimum of $\approx 23\text{-}24^{\circ}\text{C}$ occurring in February. In March, the SST increases to $23\text{-}26^{\circ}\text{C}$. Although the Chl-a range is approximately the same for both zones, comparatively SST is lower in zone 1 than zone 2. The inverse relationship between SST and Chl-a have weak correlation coefficient ¹ in zone 1 ($r = 0.39$, $n=60$) and zone 2 ($r = 0.55$, $n=60$).

A deepening of the MLD during winter is seen in both zones (Figure 5b). During November, the MLD is shallow (≈ 35 m), and as winter progresses, MLD deepens to ≈ 80 m in January and in zone 1 to $90 - 110$ m during February. In general, MLD in zone 2 is 10 m shallower than in zone 1 during January and February. The MLD starts to shallow again in March. The peak concentrations of Chl-a coincide with the deepest MLD. However, MLD and Chl-a in zone 1 and 2 are moderately correlated (correlation coefficient, $r = 0.28$).

During winter in the study area SST cooling initiates MLD deepening. Decrease in SST is mainly due to evaporation, which has dual effects i.e., increase in salinity and reduction in temperature, causing increased density of surface water (Naqvi et al. 2006), as a consequence of which convective overturning takes place. As winter progresses, SST drops and convective overturning occurs (salinity and temperature effect), increasing the MLD (Shankar et al., 2015). MLD also influences SST variability. For example, when the MLD deepens, SST will decrease as cool water is mixed toward the surface. On the contrary, during a shallow MLD, SST is generally higher (Cronin and Kessler, 2002). Hence, both of these environmental parameters are dependent on each other and both influence marine primary production in the study area. ~~Mean wind speed in zone 1 is highest during January ($\approx 3\text{ m s}^{-1}$) and in zone 2 during December ($> 3\text{ m s}^{-1}$) (Figure 5a)~~. Wind speed fluctuates strongly for zones 1 and 2. In zone 1, the maximum variability ($0.5\text{-}3.0\text{ m s}^{-1}$) is seen during November and December and for zone 2, the wind varies strongly throughout winter, with maximum wind speed ($0.5\text{-}3.0\text{ m s}^{-1}$) for December and January months (Figure 5a). High inter-annual variability is seen in wind speeds along the two zones, with peak wind speed in any one of the months between November and February. Only in certain years, moderate wind ($< 3\text{ m s}^{-1}$) coincided with high Chl-a and the correlation coefficient confirms that Chl-a and wind speed are not correlated in zone 1 and 2 ($r = 0.09$, $n=60$).

PAR follows the seasonal cycle of incoming solar radiation (Arnone et al., 1998). PAR is the waveband of light that is used in photosynthesis, and it is closely correlated with total incoming solar radiation heating the water column. Hence an

¹Correlation coefficients mentioned in this work are statistically significant at 95% confidence interval

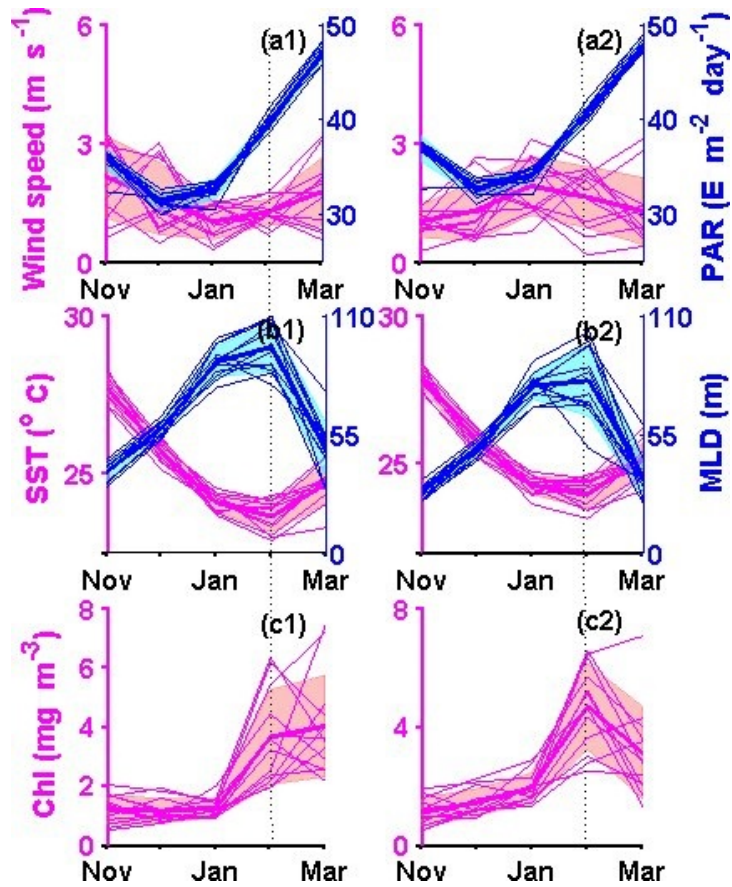


Figure 5. Time-series of the monthly-average concentration of wind speed and PAR (a1 and a2) SST and MLD (b1 and b2) and surface Chl-a (c1 and c2), in zone 1 (left, a1-c1) and zone 2 (right, a2-c2) during the winter period for the years 2002–2013. Thick lines represents mean and the shaded areas the standard deviation. The time-series from individual years are shown using thin lines. Vertical dotted lines represent the timing (month) of peak algae blooms. Temporal variability of wind speed and PAR (a), SST and MLD (b) and surface Chl-a (c) averaged for zone 1 (left, denoted by suffix 1) and zone 2 (right, denoted by suffix 2) during the winter period for the years 2002–2013. Pink colour is used to represent Chl-a, SST and wind speed and blue to represent MLD and PAR. Thick lines represents mean and the shaded areas the standard deviation for each parameter. The time series for the individual years are shown using thin lines. Vertical dotted lines represent the timing (month) of peak algae blooms in each zone.

increase in PAR is accompanied by higher surface temperature and associated with enhanced stratification, which results in reduced mixing and vice versa (Lee et al., 2014). During November to December, low PAR ($33\text{--}36 \text{ E m}^{-2} \text{ day}^{-1}$) prevailed in the study area, corresponding to low temperature and enhanced mixing, deepening the MLD. Decreasing PAR ($33\text{--}36 \text{ E m}^{-2} \text{ day}^{-1}$) prevailed in the study area during November to December for both zones, which corresponds to a decreasing trend in temperature and deepening MLD cycle. Contrarily, when PAR increased after December, surface temperature started increasing and mixing was reduced. However, there is a one-month time lag between the onset of increasing PAR and the onset

of increasing SST. The increase also coincides with a reduction of the MLD. This is due to the high heat capacity of water and the large amount of energy required to heat the water column when the MLD is deep. Low SST and deep MLD favours increased nutrient supply to the euphotic zone (Madhupratap et al., 1996; Wiggert et al., 2000) and hence production increases in these zones by February. These transitions in terms of a reduction in SST and peak MLD initialise algal blooms. Hence, PAR influences production also indirectly, by affecting the stratification that controls nutrient availability. There is stronger correlation between Chl-a concentration and PAR in zone 1 ($r = 0.69$, $n=60$) and compared to zone 2 ($r = 0.49$, $n=60$).

Peak Chl-a concentrations occurring for the month of February, coincided with lowest SST (< 25 °C) and deepest MLD (90-110 m). Thus, the increased amount of Chl-a is found to be directly related to sea surface temperature variability (i.e., cooling) and the deepening of the mixed layer. Similar inverse relation between productivity and SST is observed in the Indian Ocean by Singh and Ramesh (2015). PAR was found to have an indirect influence on primary production in these zones. PAR increases surface temperature as a result mixing gets reduced and vice versa. During the month of January, PAR enhancement coincides with SST reduction / MLD deepening. This coincidence occurs with a one month lag between PAR increase and SST reduction / MLD deepening. SST reduction and MLD deepening increases nutrient supply to the mixed layer thus enhancing production. Nitrate is high at 100 m depth ($> 12 \mu\text{mol l}^{-1}$), thus a deepening of the mixed layer beyond 100 m will mix up nutrients towards the surface (Garcia et al., 2013). This suggests that the highest Chl-a concentrations are due to the increase in nutrients by a deepening of the MLD triggered by cooling (Figures 5, 6, 7, 9) in December and January. Wind influence is not strong in these zones. Though the wind speed is relatively low ($< 2 \text{ m s}^{-1}$) during most years, certain cases with moderate wind speed ($\approx 3 \text{ m s}^{-1}$) are observed in these zones. Moderate wind (5 m s^{-1}) occurring during January to February could have enhanced mixing and thus production in zone 2.

5.2 The ecological zones in the southern and western Arabian Sea

Chl-a, SST, MLD and PAR in zones 3 and 4 followed similar seasonal patterns of variability as in zones 1 and 2 (Figure 6). However, the range of values are different in these zones, compared with the ecological zones further north. The magnitude of Chl-a concentration in zone 3 is two to three times less than in zones 1 and 2 and Chl-a in zone 4 is about half of the Chl-a concentration in zone 3. Thus, high differences in Chl-a concentration occur in zones 3 and 4, compared to the first two zones. The inter-annual variability of SST, MLD and PAR are higher in the third and fourth zones compared to the two zones further north. In zone 3, as it is closer to the equator, PAR is $3\text{-}4 \text{ E m}^{-2} \text{ day}^{-1}$ higher, SST is 1.5° C warmer and MLD ≈ 10 m to 15 m shallower than in zones 1 and 2. Furthermore, PAR in zone 4 is $2\text{-}3 \text{ E m}^{-2} \text{ day}^{-1}$ higher, SST is 1.0° C higher and MLD 10 m shallower than in zone 3. The fact that Chl-a concentration in zone 3 is less compared to that of Chl-a in zones 1 and 2 and Chl-a in zone 4 is still lower than that in Zone 3, affirms that variation in Chl-a production in the northern Arabian Sea is strongly related to physical parameters viz. SST, MLD and PAR. SST is an indirect indicator of favourable conditions for algal blooms. Low SSTs can be the result of intensified convection, which will also be manifested by increased mixed layer depth and entrainment of waters rich in nutrients (Morrison et al., 1998). SST in zone 3 is 1.5° C warmer than in zone 1 and 2 and SST in zone 4 is 1° C warmer than in zone 3. Hence, the rate of convection is most likely weak in zone 3 and even weaker in zone 4, compared to zones 1 and 2. This indicates that phytoplankton production in these zones could be linked to

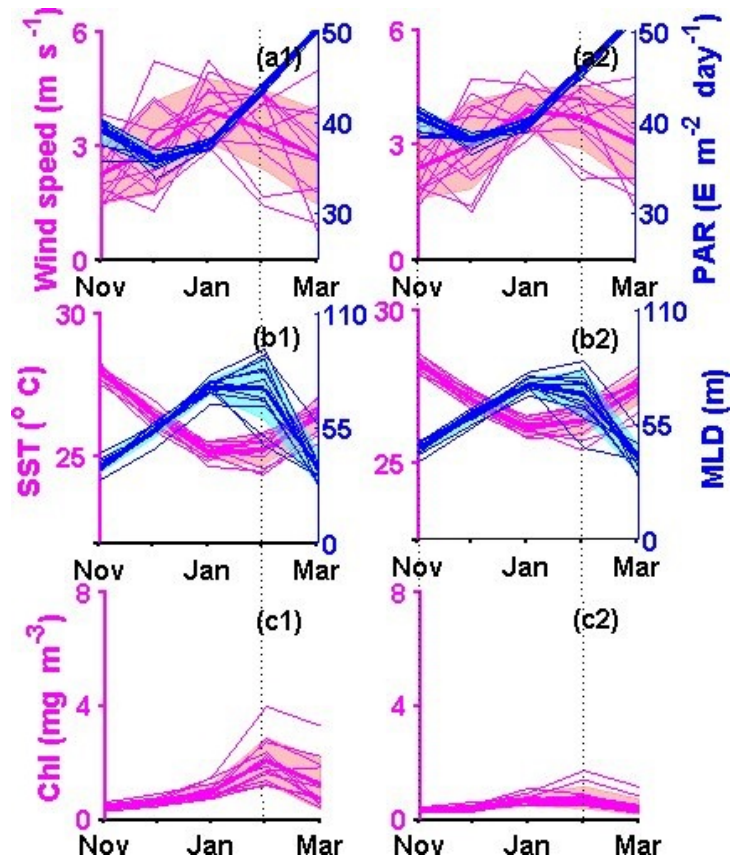


Figure 6. Time-series of the monthly average concentration of wind speed and PAR (a1 and a2) SST and MLD (b1 and b2) and surface Chl-a (c1 and c2), in zone 3 (left, a1-c1) and zone 4 (right, a2-c2) during the winter period for the years 2002–2013. Thick lines represents mean and the shaded areas the standard deviation. The time-series from individual years are shown using thin lines. Vertical dotted lines represent the timing (month) of peak algae blooms. Temporal variability of wind speed and PAR (a), SST and MLD (b) and surface Chl-a (c) averaged for zone 3 (left, denoted by suffix 1) and zone 4 (right, denoted by suffix 2) during the winter period for the years 2002–2013. Pink colour is used to represent Chl-a, SST and wind speed and blue to represent MLD and PAR. Thick lines represents mean and the shaded areas the standard deviation for each parameter. The time series for the individual years are shown using thin lines. Vertical dotted lines represent the timing (month) of peak algae blooms in each zone.

the convective strength and increase in nutrients and that the production is limited by nutrient in the period before and after the bloom. In zone 3 and zone 4 the inverse correlation between SST and Chl-a is stronger, compared to zone 1 and 2, with $r = 0.62$ and -0.70 , respectively.

The availability of nutrients is the prime factor influencing production. A deepening of the mixed layer will increase nutrient availability, but the magnitude depends both on the depth of the MLD and on concentration of nutrients below the mixed layer. The relatively shallow MLD and high SST in zones 3 and 4, compared with zones 1 and 2, suggests low transport of nutrients into mixed layer in zones 3 and 4, compared to the other two zones. MLD and Chl-a productivity in zones 3 and 4 are correlated

($r = 0.50$, $n=60$ and $r = 0.56$, $n=60$, respectively). The indirect influence of solar radiation in maintaining SST and MLD and thus nutrient availability is evident from higher PAR, higher SST and more shallow MLD values in zones 3 and 4, compared with zones 1 and 2. Hence, a direct dependence of SST cooling and deepening of the MLD and indirect dependence of PAR with the primary production is evident in the first four zones. In zone 3, a weak correlation exists between PAR and Chl-a ($r = 0.41$, $n=60$) and in zone 4, these two parameters are not correlated at all. The increasing wind speed pattern prevalent during winter indicates that wind mixing could be the prime factor governing the ecological dynamics in this zone during winter. Chl-a has a weak positive correlation with the wind speed in zone 3 ($r = 0.30$, $n=60$) and moderately correlated in zone 4 ($r = 0.47$, $n=60$). Relatively warm surface and shallow mixed layer in zone 4 indicate weak convective overturning (Naqvi et al., 2006). Hence, wind induced mixing in this zone can influence production.

10 5.3 The ecological zones in the coastal and continental shelf waters

Elevated values of Chl-a ($> 2.5 \text{ mg m}^{-3}$) persist in zones 5 and 6 throughout the winter season, with high levels of variability. This suggests that the dynamics in the coastal and continental shelf zones 5 and 6 are more complex than open ocean waters (zones 1, 2, 3 and 4). Chl-a in zone 5 shows significant inter-annual variability for the winter period with its peak value during February. In zone 6 there is low variability of Chl-a for the winter period in January, while the range of variability is high for both December and February months. In zones 5 and 6, MLD maxima and SST minima occurred either during January or February in each of the studied years (Figure 7b). During January and February, in zone 5 MLD varied between 70 to 80 m, and in zone 6, MLD varied between 80 to 100 m. A comparison between MLD values in zones 5 and 6 with those in zones 1 and 2 shows that MLD is shallower in zone 5, whereas the variability of MLD in zone 6 is comparable to that in the first two zones. MLD variability for the winter is consistent with Longhurst's observations, however, the range of MLD in Longhurst is smaller (range from 40 to 70 m) compared to present study (40-110 m) for the winter period. Additionally, SST is higher during January – February in zones 5 and 6 ($>24.5^\circ\text{C}$), compared to SST values in zones 1 and 2 ($23.5\text{-}24.5^\circ\text{C}$). The correlation coefficient between MLD and Chl-a is lower in zone 5 ($r = 0.53$, $n=60$) than in zone 6 ($r = 0.69$, $n=60$). On the other hand, the inverse relation between SST and Chl-a concentration is higher in zone 5 ($r = -0.64$, $n=60$) compared to zone 6 ($r = -0.54$, $n=60$). PAR ranges for December and January in zones 5 and 6 are almost equal to PAR ranges in zones 3 and 4 ($36\text{-}38 \text{ E m}^{-2} \text{ day}^{-1}$) and are higher compared to zones 1 and 2 ($30\text{-}34 \text{ E m}^{-2} \text{ day}^{-1}$) for the same period. A weak inverse correlation ($r = -0.27$, $n=60$) exists between PAR and Chl-a in zone 6, while in zone 5 these parameters are not correlated ($r = 0.12$, $n=60$). For zone 5, wind and Chl-a production are weakly correlated ($r = 0.30$, $n=60$), while in zone 6, these parameters are not correlated ($r = -0.09$, $n=60$).

In zone 5, low SST prevails which is an indicator of strong convective activity. Again, in zone 6, high SST coincides with deep MLD, and strong wind. Wind is reported has the one of the main forcing factor in the INWM by Longhurst (2006), which is consistent with our present study. Comparative warm surface water indicates convective overturning is weak, in addition the presence of strong wind suggests production in this zone could be controlled by upwelling induced by wind. ~~Discharge from the rivers Narmada and Tapi are an additional source of nutrient supply to this region. Hence, the highly varying production in this area can be attributed to this enhanced nutrient supply (Singh and Ramesh, 2011). In addition, in zone 6 it could also~~

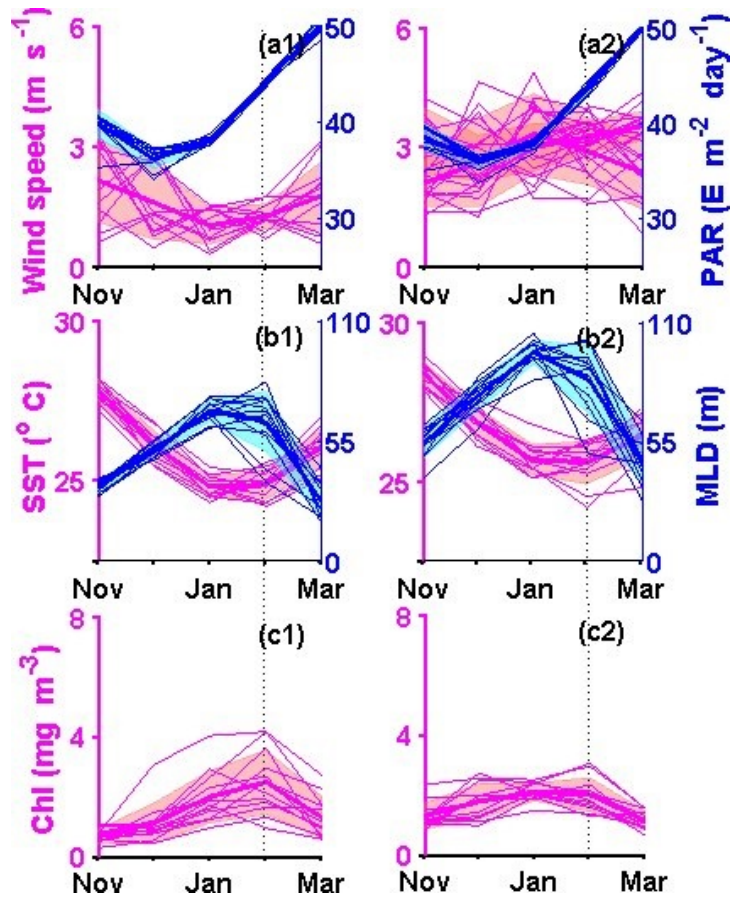


Figure 7. Time series of the monthly average concentration of alongshore wind speed and PAR (a1 and a2) SST and MLD (b1 and b2) and surface Chl-a (c1 and c2), in zone 5 (left, a1-c1) and zone 6 (right, a2-c2) during the winter period for the years 2002–2013. Thick lines represents mean and the shaded areas the standard deviation. The time series from individual years are shown using thin lines. Vertical dotted lines represent the timing (month) of peak algae blooms. Temporal variability of wind speed and PAR (a), SST and MLD (b) and surface Chl-a (c) averaged for zone 5 (left, denoted by suffix 1) and zone 6 (right, denoted by suffix 2) during the winter period for the years 2002–2013. Pink colour is used to represent Chl-a, SST and wind speed and blue to represent MLD and PAR. Thick lines represents mean and the shaded areas the standard deviation for each parameter. The time series for the individual years are shown using thin lines. Vertical dotted lines represent the timing (month) of peak algae blooms in each zone.

be attributed to higher rates of nitrogen fixation (Gandhi et al., 2011; Singh et al., 2012). Production in zone 6 was found to be more complex with influence of wind. (Gandhi et al., 2011; Kumar et al., 2017) indicates that nitrogen fixation may be a significant contribution to production in zone 6. However, the results are based on experiments with limited temporal coverage.

Table 1. Multiple-linear regression analysis

Zone	Multiple-linear regression equation	r
Zone 1	Chl-a = 0.18 - 0.23 SST+ 0.47 PAR- 0.04 MLD- 0.01 WND	0.73
Zone 2	Chl-a = 0.18 - 0.24 SST+ 0.41 PAR+ 0.27 MLD- 0.13 WND	0.71
Zone 3	Chl-a = 0.10 - 0.09 SST+ 0.39 PAR+ 0.40 MLD- 0.03 WND	0.75
Zone 4	Chl-a = 0.26 - 0.37 SST+ 0.09 PAR+ 0.10 MLD+ 0.09 WND	0.71
Zone 5	Chl-a = 0.10 - 0.21 SST+ 0.28 PAR+ 0.44 MLD- 0.06 WND	0.69
Zone 6	Chl-a = 0.58 - 0.36 SST- 0.19 PAR+ 0.28 MLD- 0.11 WND	0.73

5.4 Multiple Linear Regression Analysis

Multiple linear regression analysis is carried out to understand the combined effect of all chosen environmental parameters on Chl-a production. Multiple linear regression (MLR) is performed here on normalised values of selected parameters, such that individual values are subtracted from minimum value of observation and then divided by the range of observation. MLR equations with r value are tabulated in table 1. MLR equations for the six zones done in this work are found to be statistically significant and are carried out using 60 data points. In zone 5 and 6, WND represents alongshore wind component.

In general, MLR analysis confirms that production is controlled by surface cooling, enhancement of PAR, deepening of MLD. However, the dependence of each of these variables varies differently within each zone. A negative impact of wind is observed in first three zones and a positive influence of wind in last three zones. As for zone 5 and 6, alongshore wind component are considered, southward component enhances production in these case. However, the negative wind speed coefficient observed for first three cases may be due to the fact that the time span considered in this work is monthly and the effect of wind occurs much less than this time scale. In the first zone, for each 1 % increase in light availability as well as each 1 % cooling enhances Chl-a production by 0.47 mg m^{-3} and 0.23 mg m^{-3} respectively. In second zone PAR (for each 1 % increase production enhances by 0.41 mg m^{-3}) has major influence on production, followed by MLD and SST. For the third zone, MLD and PAR has the highest influence on Chl-a. Cooling has major influence in fourth zone. While in fifth zone, MLD, PAR and SST has major control on production, similar to zone 2, however, the rate of enhancement differs between these zones. In zone 6, too cooling has major influence, which is followed by PAR decrease and MLD deepening. An inverse relation of PAR to Chl-a is observed in this zone. It is to be mentioned here that apart from other five zones, two peak are observed on Chl-a maxima, SST minima and deepening of MLD with initial peak during December. PAR has its minima during this initial bloom month and increasing trend corresponding to the second peak of Chl-a i.e., during its minima and maxima value of PAR winter cycles bloom occurs. This implies PAR is not a limiting factor for production in this zone.

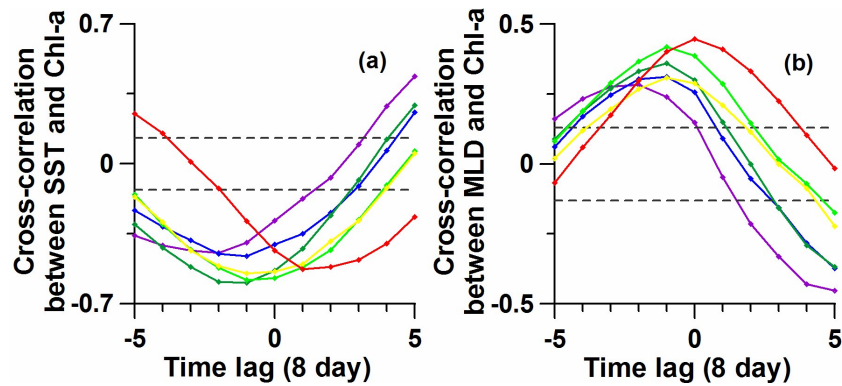


Figure 8. Cross-correlation of (a) SST and (b) MLD with Chl-a in six zones. Grey dashed horizontal line represents the 99 % confidence interval. Each tic on X-axis represents an 8-day period. Zones 1 - 6 are represented by violet, blue, green, light green, yellow and red lines respectively.

6 Time lag between SST and MLD variability to peak algae bloom

It is evident from the above analysis that Chl-a production depends strongly on cooling intensity (variability of SST) and MLD development. To quantify the eventual lag between SST minimum and MLD maximum to Chl-a maximum, the time-lagged correlations of each of these parameters with Chl-a are calculated (Figure 8). As, these parameters induce algal blooms at much shorter time scale than a month, these analyses are carried out using 8-day composite data. Cross-correlation analysis shows (Figure 8 and Table 2) that zones 1 to 5 reveal a strong and significant ($p < 0.01$) correlation between Chl-a and SST occurs with lag of -3 to -1 time interval (a scale = 8 days), i.e., dip in SST occurs before the peak in Chl-a. A similar situation is observed for MLD but the lag is shortened by one time step i.e., 8 days. In zone 6, SST maximum is observed 1 time step later than Chl-a maximum (lag = 8 day) and MLD peaks simultaneously with Chl-a (lag = 0). These observations enable us to put forth a hypothesis that the prevailing cool conditions must have enhanced mixing in the study area, which led to increased algae production.

Table 2. Lag between peak Chl-a, SST and MLD in 8-day intervals.

Zone number	Lag between Chl-a and SST	Lag between Chl-a and MLD
1	-3	-2
2	-1	-1
3	-2	-1
4	-1	-1
5	-1	-1
6	1	0

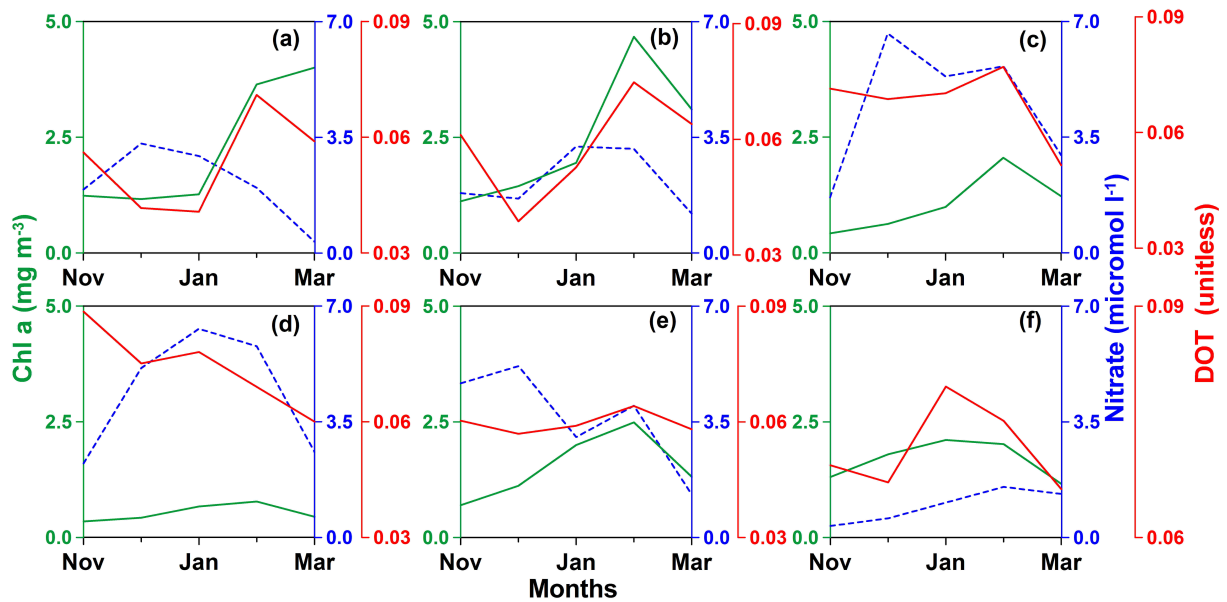


Figure 9. Averaged variability of surface Chl-a, nitrate and DOT in six ecological zones. Viewports (a), (b), (c), (d), (e) and (f) represents variability along first, second, third, fourth, fifth and sixth zones, respectively.

7 Impact of nutrients and iron on Chl-a production based on the analysis of climatological nutrient and dust optical thickness

Time lag between Chl-a maxima and MLD maxima suggests that enhanced nutrient availability in the water column due to a deepening of the mixed layer could lead to increased primary productivity. However, the time lags between MLD and Chl-a varied for the six zones, implying productivity is not only dependent on nutrient availability, but also on other environmental variables (Table 2). Naqvi et al. (2010) reported that iron limits the marine productivity along the Oman coast, which corresponds to the northwestern part of the study area. Similarly, Banerjee and Kumar (2014) have also reported marine production limited by availability of iron in central Arabian Sea. Hence iron supply to the ocean surface have been analysed using the Dust Optical Thickness (DOT), where high DOT indicates more iron deposition from the atmosphere. The temporal variability of nitrate in the mixed layer and DOT from the atmosphere is compared with the Chl-a variability in each ecological zone (Figure 9). Nitrate and DOT show significantly different patterns of seasonal variability in each zone. Wiggert et al. (2006) parameterized nitrogen half saturation constants in the northern Indian Ocean to $0.4 \mu\text{mol l}^{-1}$ for small phytoplankton and $0.8 \mu\text{mol l}^{-1}$ for large phytoplankton. The climatological data show that nitrate $< 0.8 \mu\text{mol l}^{-1}$ was observed only in March (Zone 1) and November (Zone 6), which shows that usually nitrate is not a limiting factor.

High amounts of nitrate can contribute to the production of large algal blooms (Appendix A2 and Figure A2). These can also be harmful, which are abundant in the eastern Arabian Sea (Singh et al., 2014). However, our observations indicate that higher nitrate does not always correspond to elevated Chl-a concentrations. For example, during the months of December and

January high nitrate availability ($> 2 \mu\text{mol l}^{-1}$) prevails for zones 1-5, while biological activity is moderate ($\text{Chl-a} < 3.0 \text{ mg m}^{-3}$), suggesting that additional variables play a role in determining primary production. The fact that, during each of the algal blooms ($\text{Chl-a} > 1.5 \text{ mg m}^{-3}$) both nitrate ($> 3 \mu\text{mol l}^{-1}$) and DOT (> 0.11) had high values, confirms that the co-occurrence of high concentrations of these two nutrients is necessary to enhance primary production. Interestingly, Chl-a and DOT followed similar pattern of variability from January to March for zones 1-3 and 5. The fact that Chl-a follows a similar temporal pattern as DOT in zones 1, 2, 3 and 5, strongly indicates that iron is a limiting factor for productivity in these zones. This result is in agreement with Wiggert et al. (2006) and Naqvi et al. (2010), who show that iron limits production in the northern and northwestern parts of the Arabian Sea. In zones 4 and 6, which lie to the south and southeast, the relationship between iron and Chl-a is not evident. Aerosol in the south and east has much lower iron content, compared to the western part (Appendix A2).

To quantitatively analyse the impact of atmospherically deposited iron in the study area, comprehensive in-situ measurements of the iron content at the sea surface are required, and these are presently not available.

8 Summary and Conclusions

In this study a statistical objective zoning methodology was applied to remotely sensed Chl-a data for the northern Arabian Sea and eight homogeneous ecological zones were delineated. In six of these zones Chl-a variability is studied in relation to physical-chemical parameters. The identified six ecological zones give a more comprehensive picture of the variability of marine ecosystems during winter in the Arabian Sea than the Longhurst classification in two provinces for the entire northern Arabian Sea (Longhurst, 2006). The Chl-a variability followed a semi-cyclic pattern during the winter period, with the mean of peak observations for the study period observed during February in zones 1 to 5 (Figure 4). For zone 6, there is no distinct peak value between December to February. Zones 1 and 2 in the northern part of the Arabian Sea were highly productive (Chl-a values ranging from 1 to 7 mg m^{-3}), while zone 3 ($1 - 4 \text{ mg m}^{-3}$) and zone 4 ($1 - 2 \text{ mg m}^{-3}$) were found to be less productive, i.e. a north-south gradient in the phytoplankton productivity is observed. Contrary to the open ocean zones, the coastal and continental shelf water zones, zone 5 and zone 6, have high levels of variability with elevated Chl-a values throughout winter ($> 2.5 \text{ mg m}^{-3}$). In addition, the inter-annual variability for the winter season is well captured in the present study and is not seen in Longhurst's case. This is because in the present analysis delineation is done considering winter period alone, while in case of Longhurst the annual variation is considered for delineation. Moreover, this study is assessed for eleven years, while Longhurst's is for about four and a half years (Longhurst, 2006).

~~The increased amount of Chl-a production in the open ocean zones are found to be directly related to sea surface temperature variability (ie. cooling) and the deepening of the mixed layer. Similar inverse relation between productivity and SST is observed in the Indian Ocean by Singh and Ramesh (2015). PAR was found to have an indirect influence on primary production in the study area. PAR increases surface temperature as a result mixing gets reduced and vice versa. During the month of January, PAR enhancement coincides with SST reduction /MLD deepening. This coincidence occurs with a one month lag between PAR increase and SST reduction /MLD deepening. SST reduction and MLD deepening increases nutrient supply to the mixed layer thus enhancing production. Production in zone 6 was found to be more complex with influence of wind, river discharges from~~

Narmada and Tapi river (Figure 4) and also attributed to higher rates of nitrogen fixation (Gandhi et al., 2011; Kumar et al., 2017; Singh and . MLR analysis confirms production is controlled by surface cooling, increase in PAR and deepening of MLD, with the varying dependence for each of these variables within each ecological zone. To understand wind dependence on Chl-a, much shorter time scale is required, with variability on scales less than a month. Low SST and high MLD prior to onset of the winter algal blooms suggest that nutrient supply from below the thermocline could trigger their onset. However, the temporal variability of the algal blooms in the identified ecological zones could not be explained exclusively in terms of nitrate supply or iron availability, as resolved in the variations in DOT. The combined analysis of DOT and nitrate suggests that the variability of the algae blooms depend on both sources in these zones. The variability of Chl-a in the northern and northwestern parts of the Arabian Sea is correlated strongly with the atmospheric deposition of iron from January to March. The combined analysis of DOT and nitrate suggests that the variability of the algae concentration depend on both sources of nutrient supply in all six identified ecological zones. However, the variability of Chl-a in the northern and northwestern parts of the Arabian Sea (zones 1, 2, 3 and 5) is predominantly correlated with the atmospheric deposition of iron during the period from January to March.

Chl-a production in the delineated zones within the study area are controlled by surface cooling, increase in PAR and deepening of MLD. MLR analysis confirms the varying dependence for each of these three variables within each ecological zone. However, the influence of wind speed is not visible from monthly data, to understand wind dependence on Chl-a, much shorter time scale is required, as wind dependence occurs at scales less than a month. The combined analysis of DOT and nitrate suggests that the variability of the algae concentration depend on both sources of nutrient supply in all six identified ecological zones. However, the variability of Chl-a in the northern and northwestern parts of the Arabian Sea (zones 1, 2, 3 and 5) is predominantly correlated with the atmospheric deposition of iron during the period from January to March. The satellite based Chl-a concentration utilized in this work is a proxy of marine primary production, and the results obtained in this work are consistent with those of Singh and Ramesh (2015). Their paper states nutrients and solar radiation are predictors that can explain most of the variability in the marine productivity, and observed a strong inverse relation of primary production with SST.

This study provides a more comprehensive understanding of the environmental factors controlling the spatio-temporal variability of the marine chlorophyll a concentration in the northern Arabian Sea during winter conditions. Considering the availability of long time series of high-resolution satellite ocean colour data and biogeochemical numerical ocean models today, this study is timely. Additionally, this study reveals the need for better understanding of factors controlling the marine primary productivity in other coastal upwelling zones. The north Arabian Sea is not well sampled and more in-situ observations are needed in order to validate remote sensing products and initialise numerical models and establish more reliable databases. Biogeographical studies of the lower trophic level of the marine ecosystem, such as this one, could be used to design new sampling programs and strategies.

Appendix A

A1 Various combinations of PC and cluster number for performing zoning

As the first three PC's account for 97% of the total Chl-a variability in the study area, it is compulsory to consider at least the first three PC's for zoning. Hence, in the present study various possible combinations of PC's viz., first three PC's, first 5 four PC's and first five PC's are selected to map Chl-a zones. Varying complex coastal dynamics including high Chl-a along the Arabian Peninsula coast; river discharge from Indus river along Pakistan and western Indian coast and high sediment distribution and river discharge from Narmada and Tapi rivers along Gujarat coast suggests at least three ecosystem zones along the coastal regions (Chandramohan and Nayak, 1991; Singh and Ramesh, 2011). High-saline waters in the Persian Gulf have different dynamics compared to the rest of the study area, suggesting at least one zone in the Persian Gulf. Furthermore, in the open ocean at least two zones are proposed: one in the north and another in the southern sectors (Gomes et al., 2008). Thus, based on the dynamics in the area, at least six distinct zones are identified in the study area. Initial preliminary images showed cluster number nine and above, has insufficient clustering and therefore, cluster number (c) chosen here, is six to eight (Figure A1).

Various combinations of PC's and clusters are carried out using 3 to 5 PC's and 6 to 8 clusters. The number of PC's selected is hereafter suffixed using letter 'pc' and number of cluster by 'c'. The selected nine combinations of PC's and cluster numbers include (1) 3pc 6c, (2) 4pc 6c, (3) 5 pc 6c, (4) 3pc 7c, (5) 4pc 7c, (6) 5pc 7c, (7) 3pc 8c, (8) 4pc 8c and (9) 5pc 8c (Figure A2). In general, zone maps obtained from the nine selected combinations classified Persian Gulf into two zones, offshore area into four zones and the areas within bathymetry depth 150 m as coastal zones (Figure A3). Open ocean areas are demarcated using blue and green part of the spectrum, while coastal areas by yellow, orange and red colours. In seven out of the nine zone maps ((1) 3pc 6c, (2) 3pc 7c, (3) 4pc 6c, (4) 4pc 7c, (5) 5pc 6c, (6) 5pc 7c and (7) 5pc 8c) the lower portion of Persian waters and southern part of the area as a single zone. However, the dynamics of these two regions are entirely different (Bower et al. 2000; Shankar et al. 2002). This fact suggests, these zone maps does not differentiate surface ocean Chl-a and hence these zone maps are not selected for the present study. In case of zone map with 3pc 8c combination, red patches, which in general represent coastal region, is not restricted within 150 m depth. Hence, this zone map is also discarded, leaving the zone map with combination 4pc 8c to be selected for the present study.

A2 Spatial smoothing on the selected zone map

In the selected zone map, overlapping zones are observed especially in the central study area. Zone 1, zone 2, zone 3 and zone 4 and the orange patch along the Oman coast are highly scattered and hence each of these are overlapped one over the other. Simple averaging will remove the characteristics feature along highly overlapping regions and hence smoothing i.e., border of each of these highly scattered zones are identified, before averaging. Smoothing considers an area with 5 x 5 pixel (Figure 4). Each middle pixel is replaced by the zones with major pixel characteristic. Along the coastal area, pixels with more than five consecutively similar values are considered, others are replaced with the main zonation along the area. After smoothing,

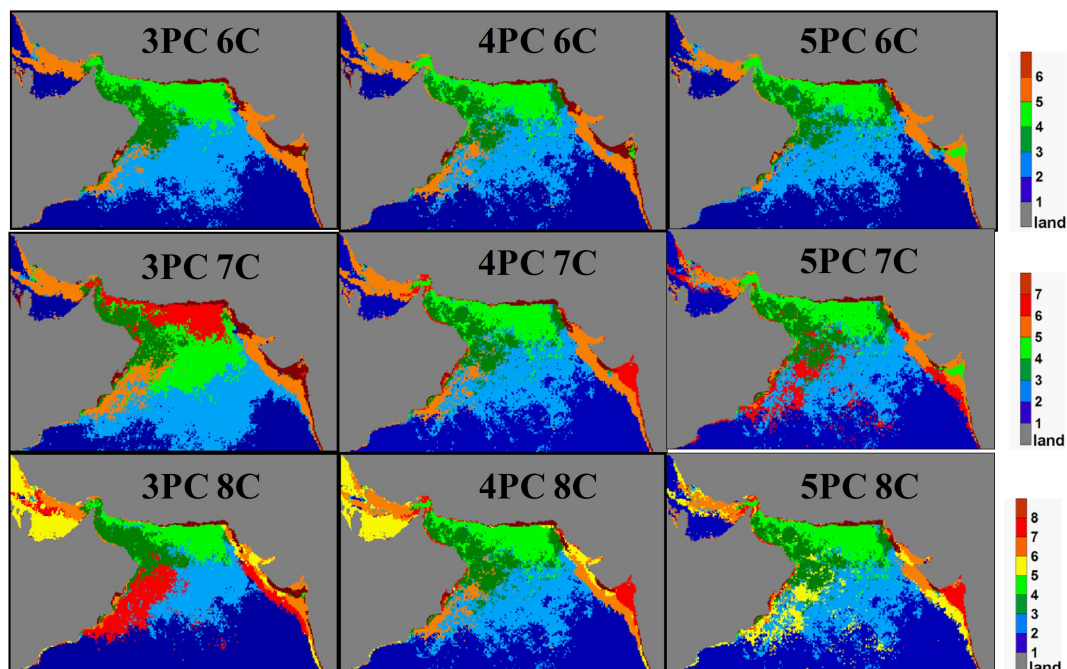


Figure A1. Various combinations of PC and CA tried out for achieving better zonation.

averaging is applied, around a 3 x 3 pixel area; such that characteristics of pixels with half or more strength are considered, otherwise they are replaced by the main zone.

A3 Winter wind roses

In order to better understand why in some parts of the sea DOT is higher than in the others, wind rose is plotted alongside with DOT over the study area (Figure A2). It is to be mentioned here that Arabian desert in the west and Thar desert to the east are the major dust contributing deserts to the study area. As suggested we have plotted the wind roses for the respective zones in order to reveal the possible source locations of DOT. For Zone 1, both the Thar desert and Arabian desert contribute to DOT, as the strong winds have directions between northerly to north-westerly. Similarly for zone 2, both these zones can be significant. While, for zone 3, its the Arabian desert contribution more to DOT enhancement as revealed from wind rose diagram. While for zone 4, it's the continental wind from Indian sub-continent available in the area. This is consistent with Patel et al. (2017).

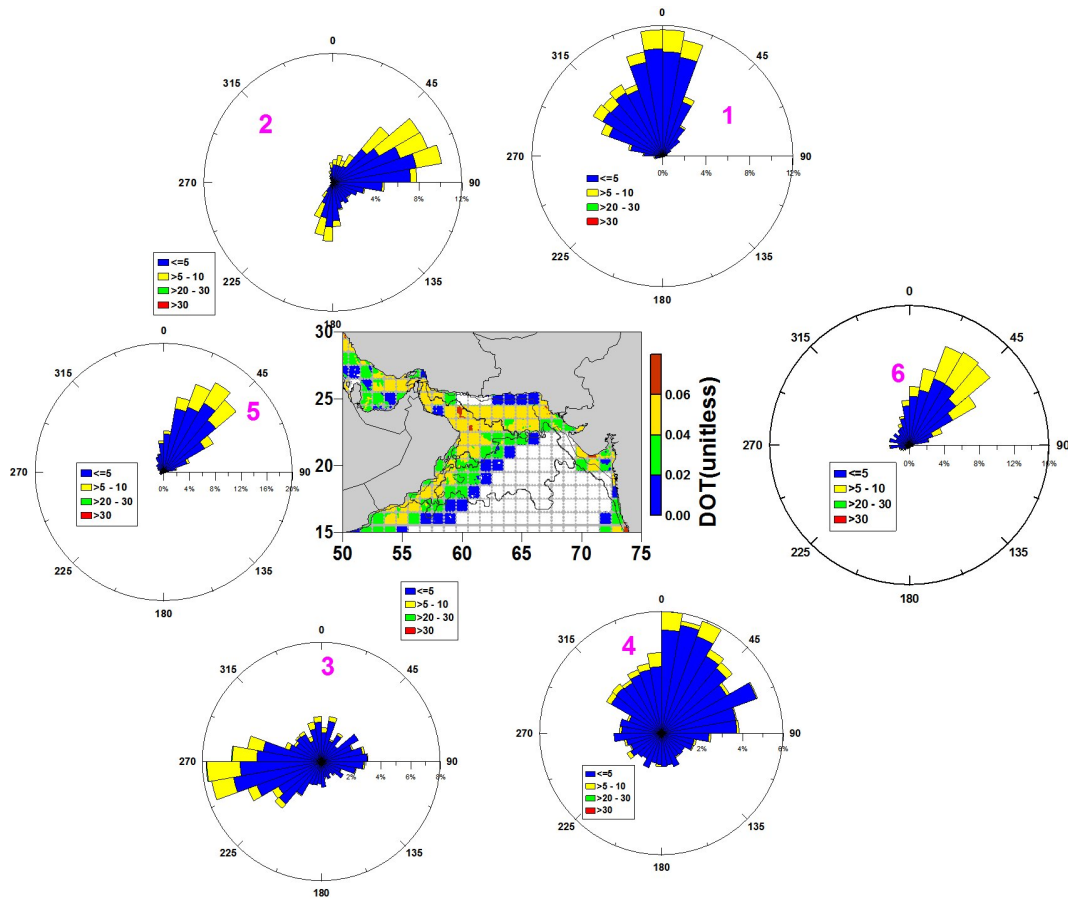


Figure A2. Wind rose diagram for the six zones. Zone number corresponding to wind rose plot is provided in pink colour.

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