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Basin-scale retrieval of zooplankton using split algorithm and MODIS data in the Arabian Sea

by

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Abstract (100 words)
Split-algorithm has been developed to estimate zooplankton in the Arabian Sea using the remote sensing inputs; sea surface temperature and particulate organic carbon. *In situ* data on zooplankton bio-volume were collected from research vessels of the Ministry of Earth Sciences of India for the period 2000-2012 representing multiple seasons round the year. An exponential increase in zooplankton concentration was observed with increase in the sea surface temperature up to 25^{o}C in the cold waters and it decreased at non-linear rate with further increase in the temperature. The results presented here highlight a critical role of temperature, rather than food, in causing distribution and abundance of zooplankton. Another feature of the algorithm is the use of particulate organic carbon instead of chlorophyll to account for feeding behavior of omnivorous zooplankton. The algorithm was implemented on Aqua MODIS data and validated for low as well as high temperature points.

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ABSTRACT

Split-algorithm has been developed to estimate zooplankton in the Arabian Sea using the remote sensing inputs; sea surface temperature and particulate organic carbon. *In situ* data on zooplankton bio-volume were collected from research vessels of the Ministry of Earth Sciences of India for the period 2000-2012 representing multiple seasons round the year and a complete range of sea surface temperature 23-29^{o}C in the basin. A pattern of variations in zooplankton was observed from the three-parameter scatter plot and it indicated a need for development of a pair of algorithms according to the prevailing sea surface temperature. An exponential increase in zooplankton concentration was observed with increase in the sea surface temperature up to 25^{o}C in the cold waters and it decreased at non-linear rate with further increase in the temperature. The results presented here highlight a critical role of temperature, rather than food, in causing distribution and abundance of zooplankton. Another feature of the algorithm is the use of particulate organic carbon instead of chlorophyll to account for feeding behavior of omnivorous zooplankton. The algorithm was implemented on Aqua MODIS data and validated for low as well as high temperature points. We have also addressed seasonal cycle of zooplankton abundance and its variability using a time-series of monthly products and found that a pattern of zooplankton variability in space and time matches with the expected trend in the study area. *Noctilica scintillans* bloom prevails in the Northern Arabian Sea during winter and *Noctilica scintillans* - zooplankton conflict is one more output of the study.

Keywords: zooplankton bio-volume, particulate organic carbon, sea surface temperature, remote sensing retrieval

Introduction

Zooplankton also known as secondary producers are tiny floating or drifting animals in aquatic system. While a few zooplankton are capable of independent vertical movement, their horizontal movements are primarily determined by water currents. This living organism forms a vital link between phytoplankton and fish in the marine food chain. Importance of zooplankton has been realized of late since they are one of the major consumers of the primary producers of the organic matter (phytoplankton) and essential prey for plankton feeding fishes and other aquatic animals. Zooplankton play a fundamental role in the food chain, linking primary producers and microheterotrophs with large consumers (Hjort, 1914;Tande and Bamstedt, 1985; Loeng and Drinkwater, 2007). Their processes of ingestion, metabolism and egestion are important in determining the size and composition of sinking particulate matter. Zooplankton produce rapidly sinking fecal pellets that can dominate the gravitational flux of biogenic material (Fowler and Knauer, 1986; Altabet and Small, 1990) and also contribute to the flux of biogenic material through their daily vertical excursions in the water column. Thus Zooplankton distribution and biomass are related to ocean productivity and biogeochemical processes. Understanding the spatial and temporal variability of zooplankton biomass and the factors controlling their distribution is important in assessing the marine ecosystem functions. Also, zooplankton have link in the "microbial loop", which mediates crucial flow of energy and matter in the sea. Knowledge of its spatial distribution and abundance as well as the variability across the seasons can facilitate efficient fishery exploration as well as determination of trophic constants in the food chain required to estimate energy transfer. In addition, the myctophids are known to feed exclusively on copepods and other zooplankton and therefore; information on this parameter can serve as an indicator of feeding ground for this fish. Likewise, zooplankton is prey for other small pelagic fishes, which ultimately sustain most productive fisheries. Apart from this, fishes usually prefer to breed in the areas of abundant zooplankton; this being prey for their larvae (Cushing, 1975). In spite of all these research needs and remote sensing capability of synoptic coverage and repetivity, generation of zooplankton product for its further use in terms of application development has not attained operational level so far. Need for the algorithm development to estimate zooplankton came from the importance realized to acquire knowledge of this parameter in order to estimate its production rate. It can eventually lead to estimation of trophic conversion efficiency from primary production to secondary production, an input for fish stock assessment. Standing stocks of zooplankton were measured from water samples collected during the ship cruises over a period of thirteen years covering all biological scenarios like the algal blooms in phased manner, upwelling, convection and the productivity forced by winter-summer monsoon winds in the coastal and oceanic waters of Northern and Southeastern Arabian Sea. Copepods were found dominating in the water samples collected from deep waters in the Northern Arabian Sea during the winter bloom. As regards the independent variables, sea surface temperature (SST) has been considered the most important factor controlling concentration of zooplankton in comparison with the food availability (Donald R. Heinle, 1969, T.R.Parsons et al, 1984). Majority of zooplankton types are omnivorous and feed in the regions of abundant chlorophyll and aggregates at high rates when the temperatures are favorable. Its concentration depends on both chlorophyll and temperature up to a limit fixed by the physiological characteristic of each species (Calbet and Agusti, 1999). However, their filtering rates increase when temperature is optimum, and then decline. When food concentrations are low, the feeding rates reduce and zooplankton can still survive (Abdel-Aziz et al., 2007). Egg hatching and postembryonic development time also show strong temperature dependence in zooplankton and these processes are largely free from the food limitation (Hirst and Bunker, 2003). Besides, it has been reported that all metabolic rates of zooplankton are dependent on temperature (Donald R. Heinle, 1969). Metabolic rates of zooplankton increase when favorable temperature is available in the environment and they feed on phytoplankton, which are available in abundance. Solanki et al. (2015) have also developed remote sensing algorithm for the Arabian Sea for copepods using SST and chlorophyll. The zooplankton algorithm developed by us is an improvement over this and uses particulate organic carbon (POC) to account for omnivorous feeding behavior of zooplankton instead of chlorophyll and SST as an environmental preference. Zooplankton data collected from the validation ship cruise were used to test the algorithm performance and the results have been included here. Moreover, a time-series images for monthly averaged zooplankton were developed and discussion of the temporal variability is also a part of the results presented here.

Materials and methods

In situ data collection and analysis:

The data base required for the algorithm development was created through organization of multiple ship cruises covering lean as well as peak period for zooplankton development. The sampling area for the zooplankton can be seen in Figure 1.

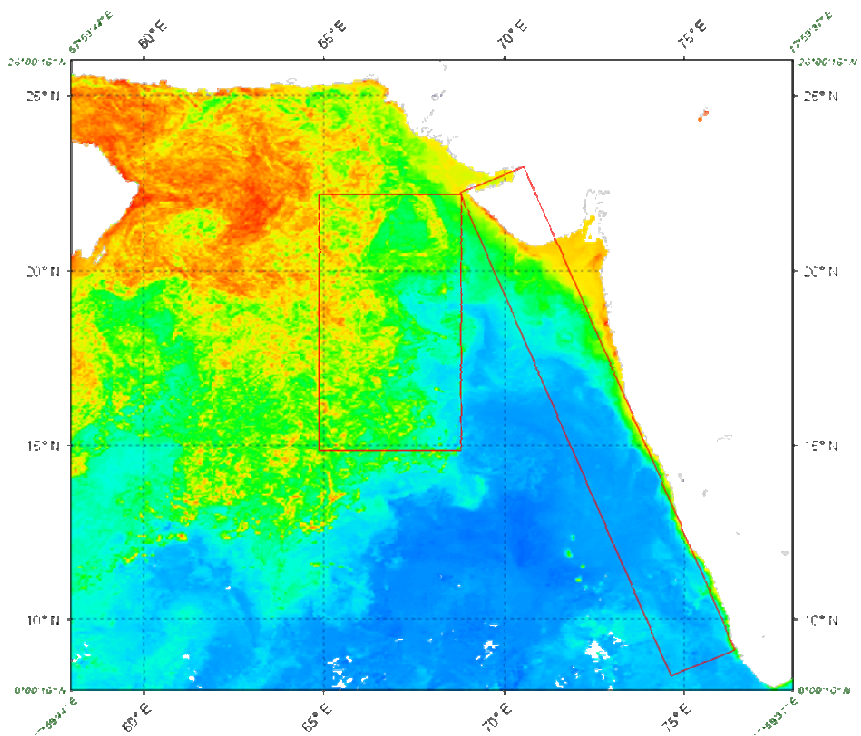

Figure 1. Sampling area for the zooplankton

Ship stations covered coastal waters of the west coast of India and oceanic waters in the Northeastern and Central Arabian Sea. Mesozooplankton samples were collected on board FORV *Sagar Sampada* from the study area. Zooplankton samples were collected from different depths including mixed layer and the bottom depths using multiple closing plankton net (Hydo-Bios, Mouth area-0.25m^2, mesh size-200µm). The net was retrieved at a speed of 1m.s^{-1} and the samples were filtered and the biomass was estimated by displacement volume method. The displacement volume was then divided by the volume filtered by the net resulting in plankton volume in units of ml.m^{-3}. The water samples were preserved in 4% formaldehyde for later enumeration and identification of different zooplankton groups. Different taxa were sorted out finally at the shore laboratory. They consisted of sarcodine, tintinids, ciliates (non-loricate ciliate), copepod nauplii etc. Input variables, SST and POC were retrieved from the MODIS data. To match these with ship based zooplankton measurements; only 40 values near synchronous to MODIS over pass were selected for the algorithm development out of over 400 zooplankton data points obtained across the seasons. More than this, the water samples collected from all the ship cruises were analyzed for phytoplankton taxonomy and cell density computations.

Satellite data analysis:

Aqua MODIS POC and SST products were downloaded from NASA's ocean color web site (http://oceancolor.gsfc.nasa.gov/) supported by Ocean Biology Processing Group at NASA's Goddard Space Flight Center. The POC(mg m^{-3}) product uses 443:555 ratio of remote sensing reflectance and its power function to establish relation with POC (Stramski et al. 2008). SST (^{o}C) is estimated using brightness temperatures from 11 and 12 µm bands of MODIS.

Algorithm development:

Zooplankton bio-volume was plotted against SST and POC as shown in Figure 2(A). Zooplankton-SST plot reveals Gaussian type distribution where zooplankton is seen increasing at exponential rate with increase in SST between 23^{o}C to 25^{o}C. A non-linear decrease in the same can be seen with further increase in SST. The plot also reveals that concentration of zooplankton is at maximum for SST value near 25^{o}C suggesting this value as a favorable temperature for its growth. Zooplankton appears to be linearly proportional to POC as can be seen from Figure 2(A). In the next step, the data set was split in the two parts, cold waters (< 25^{o}C) and warm waters (> 25^{o}C), to facilitate development of the mathematical relation. This can be seen in Figure 2(B). Two equations were developed to estimate zooplankton and the appropriate one was selected according to the SST value lower or higher with reference to 25^{o}C.

Generation of zooplankton bio-volume images and validation:

The split algorithm was applied to SST and POC retrieved from MODIS data and the zooplankton bio-volume images were generated using ERDAS IMAGINE Model Maker. The product was validated by

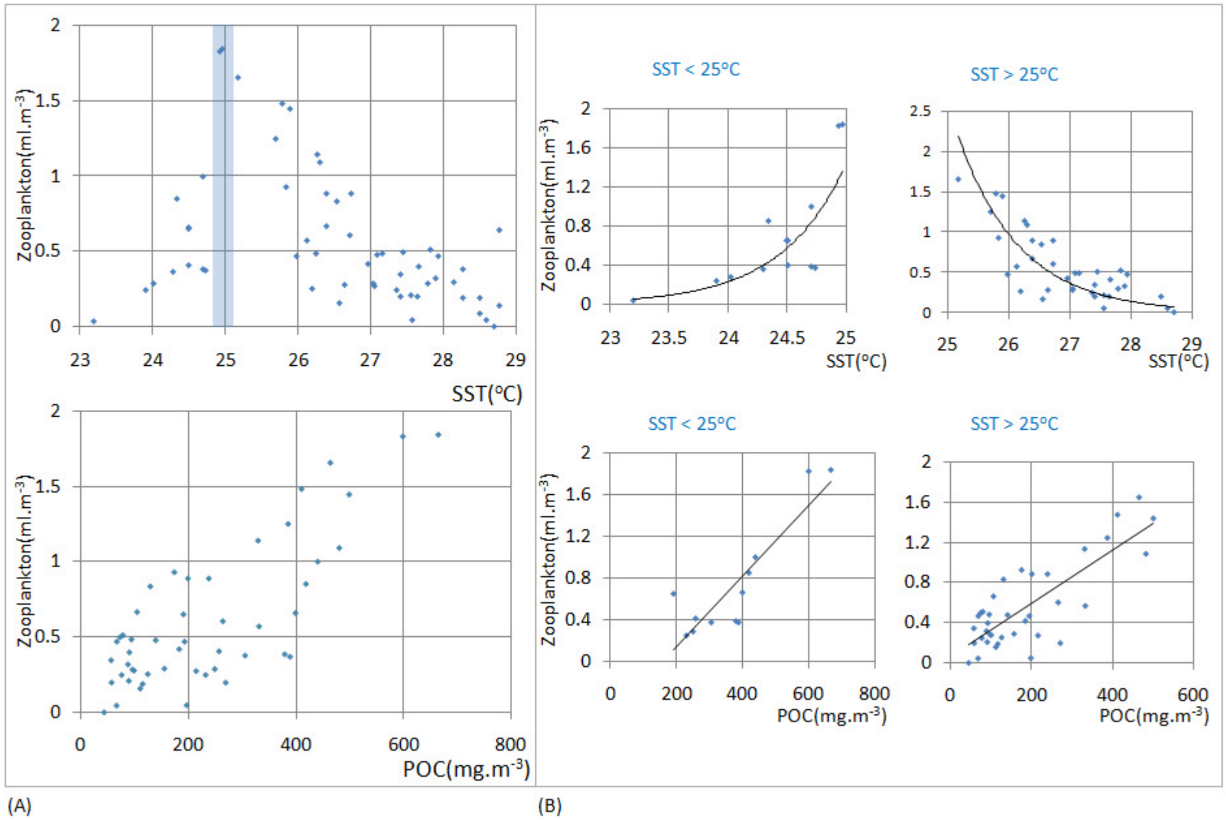

Figure 2 (A) Scatter of zooplankton (in situ) versus SST (MODIS) and POC (MODIS), (B) The scatter split in two parts for hot and cold waters

comparing model estimated zooplankton with corresponding measured values obtained from the validation cruise. Water samples corresponding to a time slot 1330 ± 1 hrs near synchronous to MODIS overpass were considered for match up.

Role of SST in determining zooplankton concentration:

Temperature alters the rates of various biological processes in copepods, such as their growth, productivity, and mortality (Hirst and Kirboe 2002). It is the most important factor controlling concentration of copepods, besides other factors like chlorophyll, salinity and pH (Abdel-Aziz et al., 2007). Filtering rates as well as metabolic and reproductive rates of zooplankton have been found to increase when temperature is optimum, and then decline. When the food concentrations are low feeding rates reduce and copepods can still survive (Donald R. Heinle, 1969). It is evident from Figure 2(B) that zooplankton is more sensitive to SST variations in view of the non-linear nature of the curve. It can also be realized from the scatter in Figure 2(A) that 25^{o}C temperature should be the most favorite environment for zooplankton to growth.

Role of POC in determining zooplankton concentration:

Copepods dominate the zooplankton community of the Arabian Sea, where over 50 species of copepods occur in the surface waters of the Arabian Sea, with roughly 11 species co-dominant during any particular season (Timonin, 1971; Madhupratap et al.,1992). Copepods are mixotrophic organisms feeding on other tiny organisms including bacteria, protozoans, insect larvae etc. as well as on tiny bits of floating plant and animal matter. A major component of mesozooplankton diets is often protozoa (e.g. Kleppel, 1992; Dam et al., 1995a; Verity and Paffenhofer, 1996; Roman and Gauzens, 1997).

Since satellite POC consists of both decayed and live organic matter and the zooplankton is mixotrophic feeding on both dead and live as well as bacteria/protozoa, which feeds on dead organic matter, the POC should be linked to zooplankton rather than chlorophyll. Heterotrophic bacteria were found to be highly correlated with particulate organic carbon (POC) and it enabled use of POC as a substitute to bacteria.

Solanki et al. (2015) have used chlorophyll in their algorithm for estimating copepods concentration and have described copepods as phytoplankton feeder. However, this class of zooplankton is omnivorous like the most zooplankton and it is not proper to relate them with chlorophyll. The rationale for using POC as an input parameter in our approach is to account for omnivorous feeding behavior of the most of the zooplankton and to obtain an estimate of total zooplankton. All adult zooplankton are omnivorous and detritivorous do not feed only on chlorophyll, Therefore, POC, which includes live as well as dead particles (detritus), should replace chlorophyll. POC-chlorophyll plot in Figure 3 reveals that though the two parameters are highly correlated the relationship is not linear.

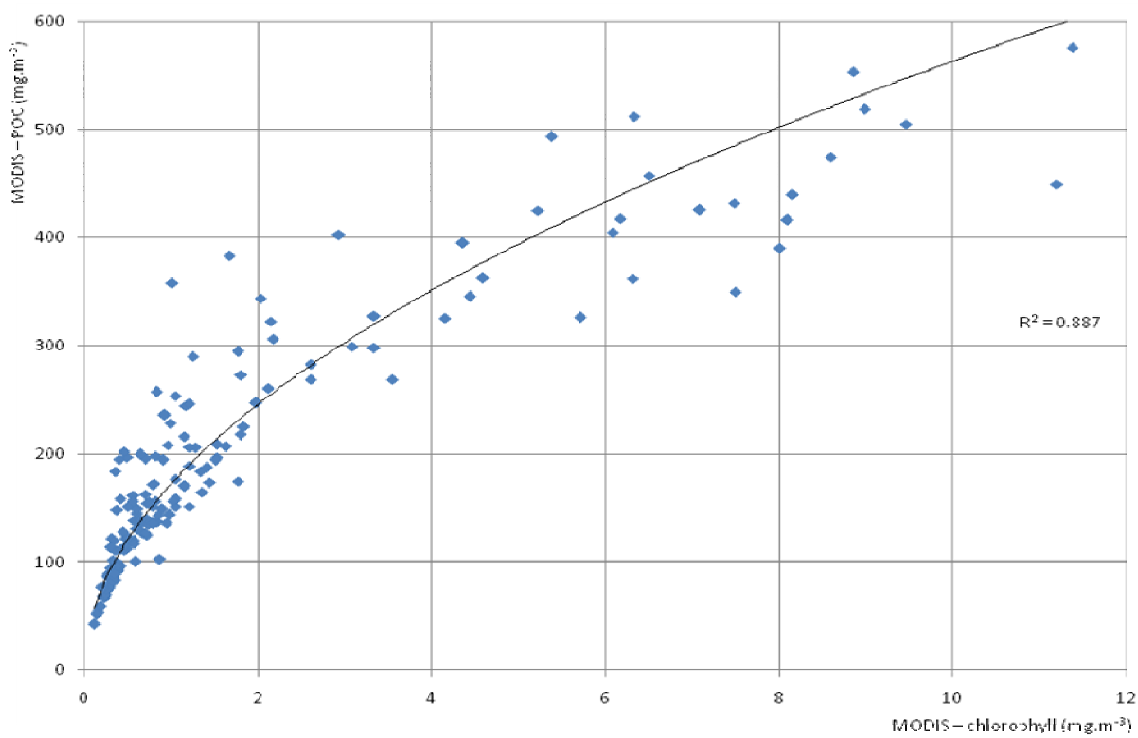

Figure 3. Relation between chlorophyll and POC

Range of chlorophyll is 0.12 - 11.38 mg.m^{-3} in the data set whereas the same for POC is greater; 42.80 - 575.71 mg.m^{-3}. It means POC is more sensitive to spatial and temporal variations and hence, zooplankton product developed using POC could reveal the variability in zooplankton distinctly. And this is another advantage of selecting POC to reflect feeding behavior in the algorithm.

Results and discussion

The algorithm:

In view of the increasing and decreasing pattern of zooplankton on either side with reference to 25°C as shown in Figure 2, two algorithms were developed, for SST < 25°C (exponential trend) and SST > 25°C (2nd order polynomial) as shown in Figure 4.

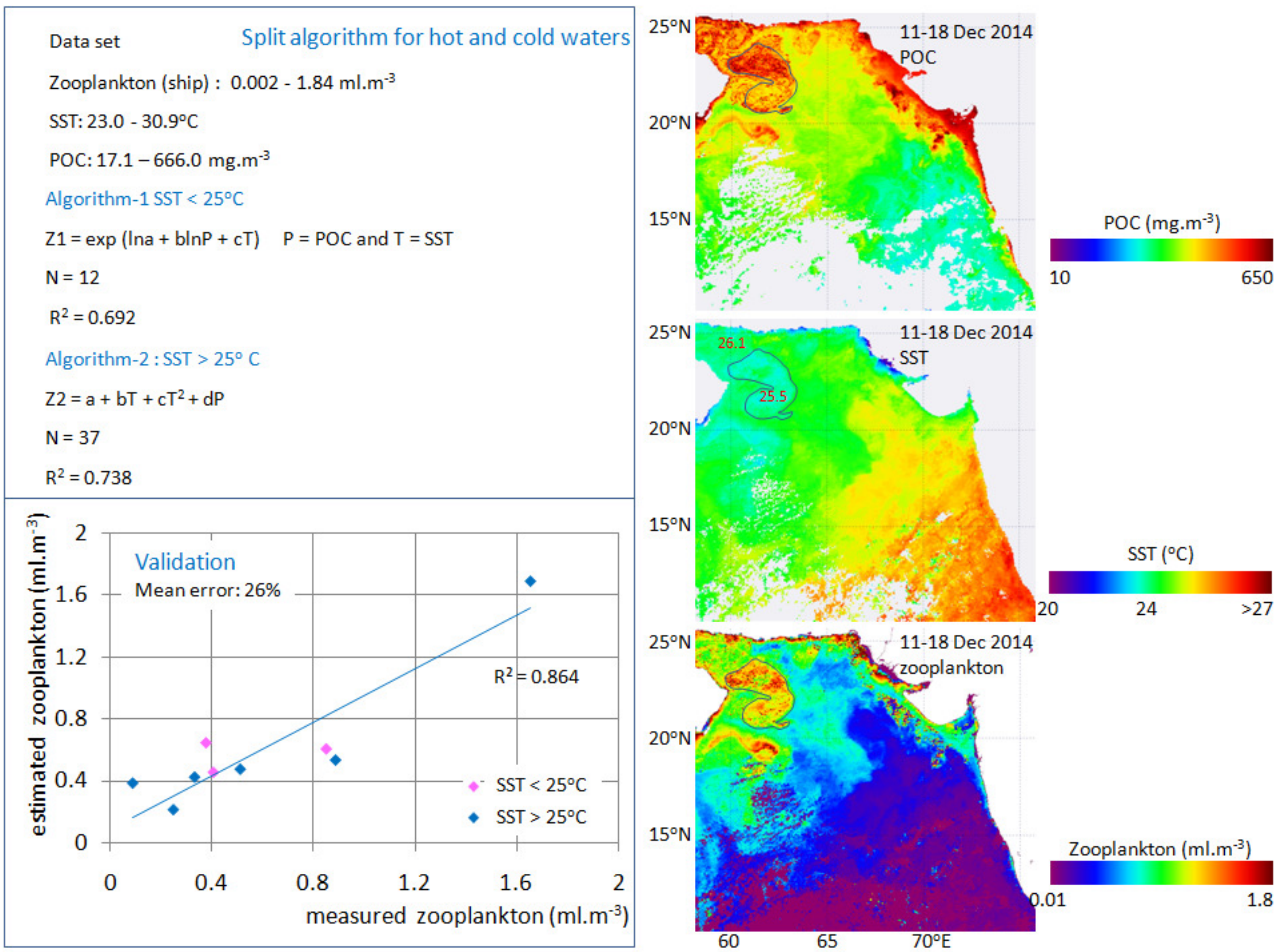

Figure 4. The algorithm for zooplankton and its validation (Left), the end-product (right)

While implementing these algorithms on MODIS data every pixel of SST image was checked to decide an appropriate algorithm. Zooplankton image generated using these two algorithms can be seen in Figure 4 along with POC and SST images for the same period. A prominent patch of high zooplankton bio-volume is delineated in zooplankton image. It can be seen from SST image that favorable temperature (25.5^{o}C) prevailed at this location. Also, POC image reveals high concentration i.e. food availability within this patch. It can be seen that POC is also high in extreme top corner of the POC image just outside the delineated patch. However, temperature is also on higher side (26.1^{o}C) here. It is an unfavorable temperature for zooplankton according to Figure 2(A,B) and the estimated zooplankton is relatively lower. This substantiates the logic of temperature preference of zooplankton for its growth as described above. Apart from this, zooplankton concentration is seen lower in lower right corner (zooplankton image) corresponding to warm waters of unfavorable temperature (SST image). Recently a validation cruise was conducted where the water samples were collected and analyzed to measure the normalized zooplankton bio-volume. Zooplankton images were generated for the corresponding dates using the algorithms under test. A plot of estimated versus *in situ* zooplankton in Figure 4 presents the comparison. Care was taken to include the match up pints from cold and hot waters to assess performance of both the algorithms. The parameter was found to be estimated with an average accuracy of 74%. We have performed polynomial fitting using the inputs, POC and SST, from MODIS data so that bias in the satellite inputs gets absorbed in the regression co efficient to some extent. Moreover, the data base for zooplankton included water sample collections from a column and round the clock. Out of this, only surface measurements matching with satellite over pass were selected. Though the treatment for estimating zooplankton is changed according to SST; there may still be some field uncertainty like heavy predation of POC just before the satellite over pass besides the inherent error in algorithm.

Merit of split algorithm:

Zooplankton images generated using a common algorithm (Soalnki et al. 2015) and the split algorithm have been presented in Figures 5(A) and 5(B) respectively. A common algorithm (Soalnki et al. 2015) is chlorophyll bases input and uses exponential function with SST and negative sign. This equation will tend to overestimate zooplankton in cold waters, whereas Figure 2(A) reveals that low SST, below 25^{o}C, is unfavorable condition for zooplankton growth and the algorithm is expected to yield low estimate. It can be seen from Figure 5(A) that zooplankton is overestimated at top left of the imaged as marked with the circle. SST reads 21-24^{o}C in this patch as shown in Figure 5(C). Zooplankton image obtained from the split algorithm is shown in Figure 5(B) and relatively lower concentration can be seen within the circle. Though units of zooplankton are not same in both the images, a pattern of high or low concentration can be inferred through spatial comparison with remaining area in a given image. Secondly, a patch of high zooplankton is delineated in Figure 5(B) corresponding to the ideal temperature 25-25.5^{o}C. The chlorophyll based zooplankton image of Figure 5(A) does not reflect this pattern and reveals the low concentration.

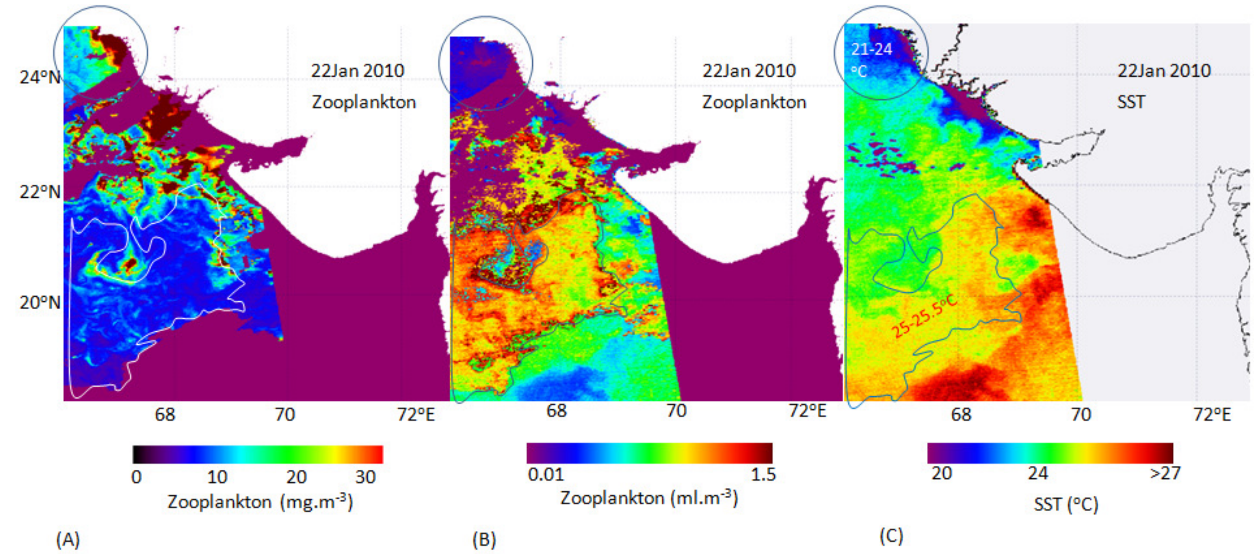

Figure 5. (A) Zooplankton image generated with an algorithm of Solanki et al (2015), (B) Zooplankton image generated with split algorithm (C) Corresponding SST image

A time-series of monthly SST and zooplankton images is shown in Figure 6.

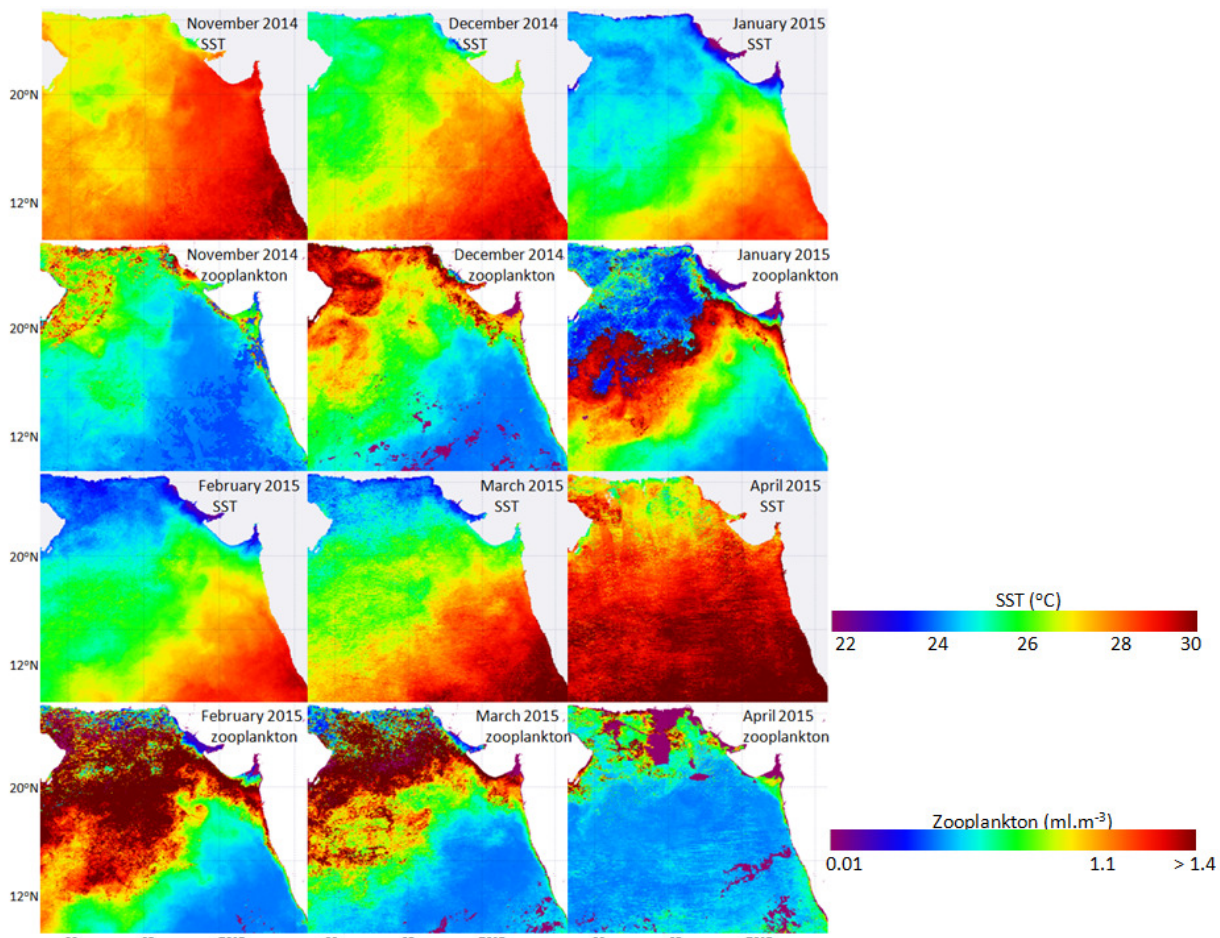

Figure 6. A time-series of monthly zooplankton image

It was realized from the zooplankton-SST plot (Figure 2) that zooplankton distribution is dependent on temperature within a range of 24.5-25.5 ^{0}C, the most preferred temperature of about 25^{0}C. Light blue and adjacent green colour in the step wedge represents this value. A pattern of zooplankton in the time-series indicates that they aggregate in the areas of this temperature. SST images of November and December reveal this temperature in the top left corner and correspondingly zooplankton is higher. With onset of winter, cooling signature can be seen in January image in the Northern Arabian Sea. This temperature is unfavorable for zooplankton growth and it is found relatively lower concentration as compared to the same in November and December. A belt of high zooplankton concentration can be seen in the Central Arabian Sea in red colour during this period. After January, cool water area is found shrinking in the Northern Arabian Sea and a shift in 25^{o}C waters (light blue) can be seen from the Central Arabian Sea towards north. This is as indication of warming of winter mass with approaching decay of winter. High zooplankton patch is also found shifting to north corresponding to the change in SST pattern.

A mixed species of algal bloom, diatom and green *Noctiluca scintillans* (*N. sci.*), is known to occur in the Arabian Sea during convective mixing season in spring-winter during NE monsoon when productivity is high in the Arabian Sea. Green *Noctiluca* follows diatom and is restricted to a temperature limit of 24^{o}C or less (Parab et al. 2006). It was a relatively weak development of these blooms during the current year as compared to the previous year in 2015. SST, zooplankton and phytoplankton species (Dwivedi et al. 2015) images for 2015 and 2016 were generated for the peak bloom period 2-9 February. This is sown in Figure 7. Our intension was to observe if inter-relation between green *Noctiluca* and zooplankton was there.

There is a possibility that *N. sci.* may affect zooplankton communities by competing for food resources. However, the detailed studies so far have indicated that this conflicting food requirement is not an issue because the grazing rate of *N. sci.* is apparently low compared to same-sized zooplankton (Nakamura, 1998). It is further reported that the ecological conditions causing the decrease in the other-zooplankton biomass by *N. sci.* blooms are difficult to confirm. Though nutritional conditions do not restrict zooplankton growth in presence of *Noctiluca* there are reports that during *N. sci.* spring blooms, the high abundance seemed to suppress the other-zooplankton biomass. (Daan, 1987; Quevedo et al., 1999). Kuninao Tada et al. (2004) observed large numbers of copepods when *N. sci.* abundance was low. Le Fevre and Grall (1970) also reported that the minimum abundance of copepods corresponds to the maximum abundance of *N. sci.* and, inversely, the maximum abundance of cope pods was found in an area where *N. sci.* was least abundant.

Remote sensing of these two parameters as shown in Figure 7 substantiates these observations. There was a weak bloom in 2016 in comparison with the same in 2015 as a consequence of weaker convection. It resulted in insufficient cooling (25-25^{o}C) of surface waters in the Northern Arabian Sea. temp warmer in North, ~ 25 deg, favorable for zoo. Our earlier observations and the reports indicate that *N. sci.* does not

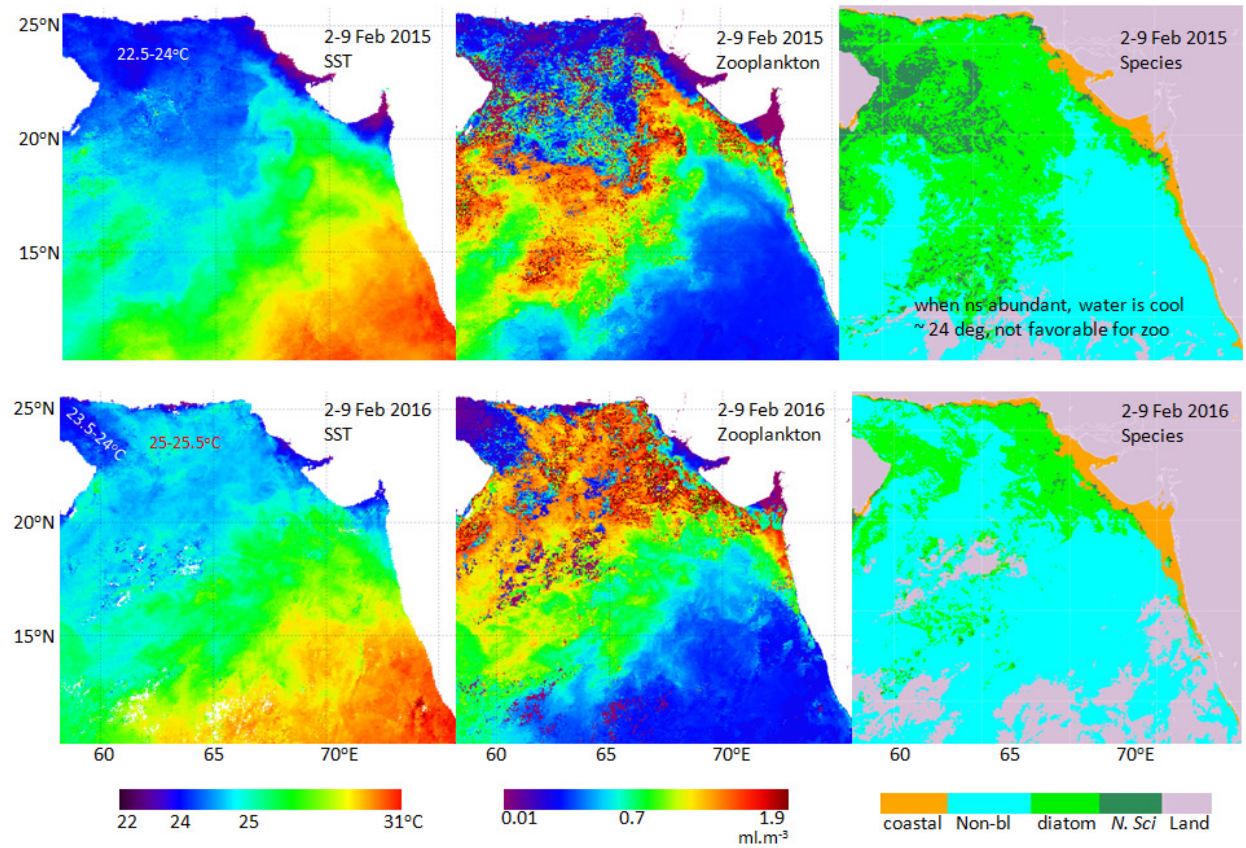

Figure 7. SST, Zooplankton and phytoplankton species images for 2-9 February (peak bloom period) of 2015 and 2016.

proliferate in this warm waters. Species image of 2016 confirms this through missing signature of NS (dark green colour). However, this temperature is favorable for zooplankton and can be seen in high concentration. In a contrasting situation to this, 2015 was a strong bloom year, sufficient cooling (22.5-24^{o}C), which is favorable for *Noctiluca* growth. Corresponding to this zooplankton concentration is relatively less in the NAS, prevailing SST not being ideal for zooplankton growth. Thus, the observed complementary scenario of *N. sci.* and zooplankton may because of favorable/unfavorable SST condition. This is supplemented by a plot of zooplankton bio-volume versus *N. sci.* cell density in Figure 8. Over all, an inverse trend between zooplankton and *N. sci* can be seen indicating low concentration corresponding to high abundance of *N. sci.* and vice versa.

Signature of southwest monsoon upwelling can be seen off Somalia, Oman and southern tip of India in the SST images of July and August 2015 in Figure 9. Zooplankton image of 2015 reveals that like chlorophyll; zooplankton image also can be used as a tracer of advecting water mass due to Ekman transport. Bio-volume of zooplankton can be seen elevated within the area of upwelling off Cochin and south of Cochin covering southern tip of India during the southwest monsoon.

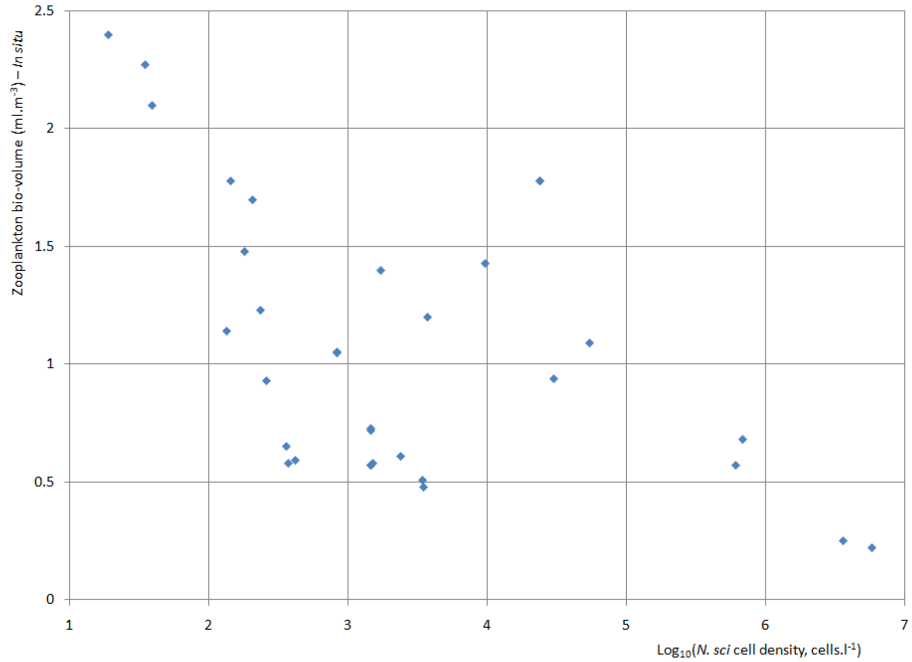

Figure 8. Inverse trend between zooplankton concentration and N. sci cell density

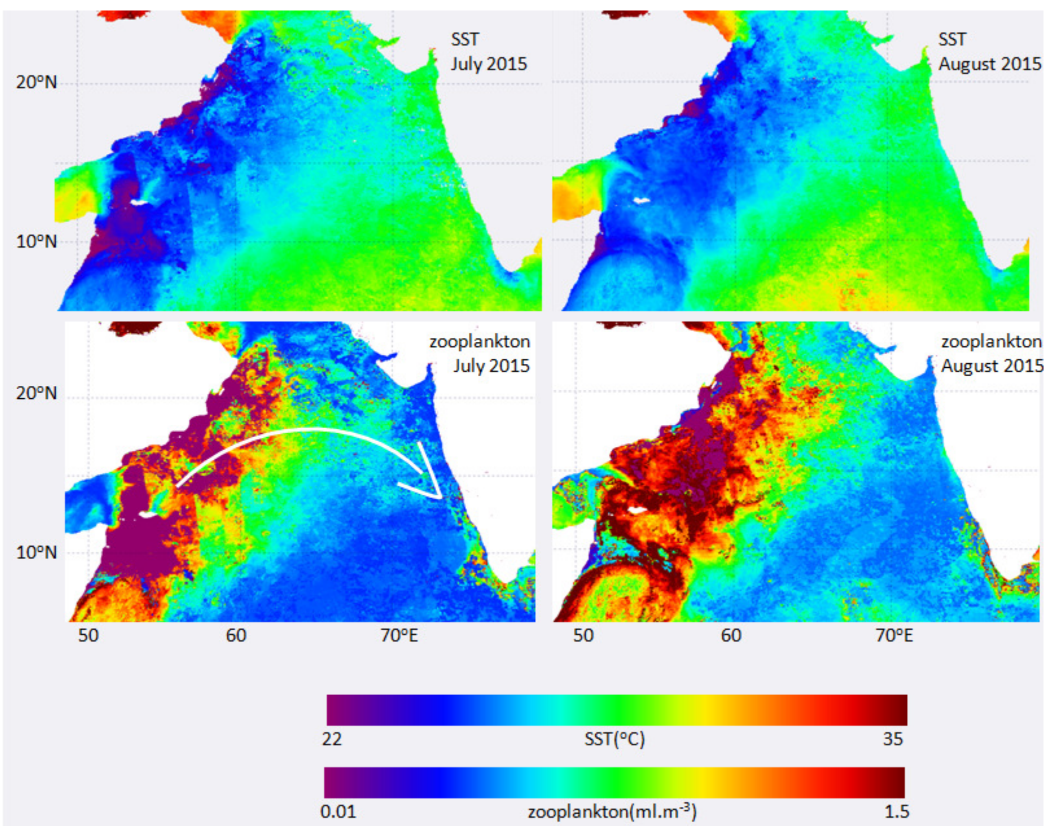

Figure 9. SST and zooplankton images during southwest monsoon upwelling

Conclusion

The split algorithm to retrieve zooplankton in the Arabian Sea from MODIS data developed here is found to perform better as regards its sensitivity in extreme cold and hot temperatures. Also, it is a basin-scale algorithm and accounts for a complete range of SST. POC was used as another input besides SST. It includes live phytoplankton as well as detritus and hence, supports omnivorous zooplankton. Temporal variability in the time-series of zooplankton was followed a pattern of SST. An inverse trend was observed between the cell density of green *Noctilca* and zooplankton.

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