A survey of recent studies on chlorophyll variation in Indian coastal waters
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Abstract:
Understanding the pattern of chlorophyll in the open and coastal waters were greatly helpful for the primary productivity and the underwater light field distribution. Sensors were used for the measurements were plays a major role to quantify the amount of chlorophyll. Several studies were conducted for the analysis of chlorophyll pattern over the Indian coastal water. In this study, we conducted a literal survey on the recent studies on the chlorophyll variations. For that, first we presented the chlorophyll measurement techniques, then existing algorithms for the retrieval of chlorophyll, finally we analyzed the various studies conducted for the chlorophyll distribution and their effects. The integrated use of this survey greatly used to develop new techniques for the coastal zone management and forecasting the environmental changes.

Keywords: Chlorophyll, MODIS, Ocean Colour remote sensing, Indian Coastal waters.

I. Introduction
Chlorophyll-a or Phytoplankton is a key water constituent which play as an important biogeochemical parameter for both marine environment and coastal waters. This chlorophyll-a absorbs the earth’s incoming sunlight, carbon-di-oxide (CO₂) and maintains the ocean primary production [1] [2]. It also acts as a food web for majority of ocean living organisms by transforming the sunlight into primary production. The variation in chlorophyll-a concentration can significantly affect the underwater light fields parameters such as radiance, irradiance and reflectance in the water column [3] [4]. As the concentration of chlorophyll increases, the color of the water slowly changes from blue to green. The high values of chlorophyll concentration is an indication for increases in phytoplankton population [5] [6].

The major features of phytoplankton are its shape and size which controls biochemical functions such as plankton growth and nutrient intake. Based on the phytoplankton size structure, the total chlorophyll concentration is classified into three functional classes. The total chlorophyll size less than 2 micrometer is considered as pico-phytoplankton, 2-20micrometer is considered as nano-phytoplankton and greater the 20 micrometer is referred as micro-phytoplankton [7] [8]. Simultaneously, the size and shape of the phytoplankton affects the photosynthetic rate and sea surface temperature. Therefore, biomass with small celled and large
celled phytoplankton were responsible for the primary production and is considered as key ecological sign for ocean environment [9] [10]. The measuring technique of phytoplankton biomass is through field measurements or by ocean color satellite instruments [11] [12].

This study mainly focused on understanding the recent studies for variation of chlorophyll in the coastal waters. This analysis was done in three steps which are as follows: (1) understanding the global measurement methods of chlorophyll from the ship borne field measurements, (2) an investigation of existing chlorophyll retrieval algorithm from satellite datasets, and (3) a detailed survey on the recent studies for the analysis of chlorophyll over the Indian coastal waters.

II. Measurement techniques
For Satellite measurements, the moderate resolution imaging spectrometer (MODIS) sensors such as MODIS-Terra (1999) and MODIS-Aqua (2003) were launched by NASA and collecting the daily satellite images for till date over the ocean. MODIS-Terra capture the images from north to south and MODIS-Aqua moves from south to north. Both sensors were receiving hyperspectral data with 36 spectral bands. The captured satellite data from the top-of-atmosphere provides the remote sensing reflectance ($R_{rs}$) product after undergoing the atmospheric correction and radiometric correction. These hyperspectral $R_{rs}$ datasets were used for monitoring the seasonal and annual variation of chlorophyll and also understanding the primary productivity in the marine environment.

Another way of quantifying the ocean chlorophyll is ship borne field measurement by collecting the water and filtered for the estimation of chlorophyll pigment concentration in the Laboratory. From the collected water samples, the observation of optical properties of chlorophyll and other detrital particles were determined for each station using Niskin bottles which is a pre-rinsed bucket and filtered under low vacuum pressure through Whatman GF/F glass fiber filters (25 mm). The total absorption coefficients were computed using glass-fibre filter technique and the quantity of total particulate matter retained on the filter is represented as $OD_{tot}(\lambda)$. Subsequently, the methanol extraction method is used to determine the absorption coefficients of non-algal particles (Sundarabalan et al., 2015). The detailed estimation procedures of these absorption coefficients were provided in Ahn and Shanmugam [7].

III. Algorithms
In optical remote sensing, there are several algorithms were existing for the retrieval of chlorophyll from remote sensing reflectance. The detailed review of some selected bio-optical algorithms was discussed in this section for the retrieval chlorophyll concentration.

*Ocean Color (OC) Algorithm:*
OC is the band-ratio based bio-optical algorithms to retrieve the chlorophyll-a concentration from remote sensing reflectance developed by O’Reilly et al. (1998). The study suggests that the minimal error in chlorophyll retrievals due to the CDOM absorption in case-1 waters. The model
shows limitation in coastal waters due to presence of other sea water constituents. The model performance was improved in the revised OC6version in O’Reilly et al. (2019). The fourth order polynomial expression for the chlorophyll retrieval algorithm is as follows,

\[
\log_{10}(\text{CHL}) = a_0 + a_1 X + a_2 X^2 + a_3 X^3 + a_4 X^4
\]

Here, the coefficients \(a_0 = 1.22914\), \(a_1 = -4.99423\), \(a_2 = 5.64706\), \(a_3 = -3.53426\), and \(a_4 = 0.69266\). Also, blue and green bands were used for the estimation of intermediate \(X\) values.

**Cannizaro and Carder Chl model:**

The model for the retrieval of Chlorophyll in shallow waters from remote sensing reflectance is developed by Cannizaro and Carder (2006). In shallow water, bottom reflectance plays a major role which is reduced by the usage of four different bands for the chlorophyll retrieval. The model also has limitation when applied to global waters. The explanation of the model is as follows,

\[
\log_{10}\left(\frac{\text{CHL}}{\lambda_{555}}\right) = 2.198 - 4.58 \log\left(\frac{R_{rs}(\lambda_{510})}{R_{rs}(\lambda_{670})}\right) + 3.24 \log\left(\frac{R_{rs}(\lambda_{510})}{R_{rs}(\lambda_{670})}\right)^2 - 1.11 \log\left(\frac{R_{rs}(\lambda_{510})}{R_{rs}(\lambda_{670})}\right)^3
\]

**Zhang Chl model:**

This model is developed Zhang et al. (2009) especially for the case-2 waters where the CDOM and sediments were dominated in the water. This Chl model utilize the red and NIR bands in the algorithm which minimize the contribution of CDOM content in the chlorophyll retrieval. The model was validated in lake Taihu which are dominated by high chlorophyll content. The equation is as follows,

\[
\log(\text{Chl}) = 372.4 \times \left\{ \frac{1}{R_{rs}(690)} - \frac{1}{R_{rs}(703)} \right\} \times R_{rs}(759) + 27.6
\]

**Shanmugam Chlmodel:**

This technique is mainly developed for both case-1 and case-2 water by Shanmugam (2011) for the retrieval chlorophyll from remote sensing reflectance in optically complex waters. The model is more suitable for SeaWiFS and MODIS-Aqua data. The performance of this model shows less error compared to other models. The name of model is ABI chlorophyll model, where ABI tends to algal bloom index.

**HuChl model:**

This model combines four visible bands for the retrieval of chlorophyll and model is known as three-band reflectance algorithm which is developed by Hu et al. (2012). This model solves several issues in the existing models. Since three bands used in the algorithm, the model is less sensitive to noise and other sea water constituents. The expression of the model is as follows,

\[
\text{Chl} = R_{rs}(555) - \left[ R_{rs}(443) + \frac{555-443}{670-443} (R_{rs}(670) - R_{rs}(443)) \right]^{0.4909 - 191.659 \times CI}
\]

Where \(CI = R_{rs}(555) - R_{rs}(443)\).
The above described models are well known, these algorithms were tested for the global waters and the results are very closely matching with the in-situ datasets for open and coastal waters.

IV. Chlorophyll Over Indian Coastal waters

There are several studies were conducted in the Indian coastal waters to understand the variation of chlorophyll in the coastal waters. Some of the selected studies were literally surveyed in this section. This survey leads to understand the major reasons behind the different pattern and fluctuation of chlorophyll in the Indian coastal waters.

Tholkapiyan et al. (2012) estimated the radiometric calibration coefficient for the OCM-2 sensor onboard IRS satellite. This coefficient used in the CAAS atmospheric correction algorithm and the results shows better performance when compared with the standard SeaDAS atmospheric correction algorithm. The dataset used for this analysis was obtained from the field measurement conducted from off-Point Calimere and Gulf of Mannar, Bay of Bengal. These analysis results suggest that the coefficients from Tholkapiyan et al. (2012) can be used in CAAS AC algorithm were improve the results of OCM-2 captured dataset for the better extractionof Chlorophyll in various coastal waters (including algal bloom) around India.

Arthi and Shanmugam (2012)developed an algorithm for the classification of four algal blooms using the MODIS-Aqua sensor and monitor the spatial variation of those blooms in Arabian sea. The major four blooms and their color are namely, Erythareum, Trichodesmium, Noctilucascintillans/miliaris (green/brown), and Cochlodiniumpolykrikoides (red)). The validation of the algorithm explains that the retrievals are almost matching with the in-situ datasets. The increasing occurrence and effects of algal blooms are highly important in coastal waters around India. These analyses are highly useful for the various departments in the fisherman and local public health officials.

Sundarabalan et al. (2013)developed a technique for the estimation of underwater light field parameters in coastal and shallow water in Off-Point Calimere. The method uses a standard Hydrolight software and understand the effect of bottom reflectance. The study clearly explains shows that the chlorophyll based optical parameters such as absorption due to phytoplankton are directly involved in the changes of underwater light field. The analysis shows the variation of hase function along the depth due to variation of chlorophyll.

Tholkapiyan et al. (2014) worked on a time series analysis of the MODIS-Aqua-derived ocean surface algal bloom index (OSABI) for the years from 2003 to 2011. The seasonal merged images explains new information about the blooms and their development stages over the Indian coastal waters. The analysis upwelling along the coast of Oman leas to the initiation and development of algal bloom. Anlaysis conducted in southern part of Indian coastal water shows that the anomalies of sea surface height along the coast leads to algal bloom patches in the Off-Point Calimere. The study confimed that the MODIS-Aqua shows the reliable observations of variatioin in the ocean algal bloom in coastal waters around India.
Sundarabalan et al. (2015) analyzed the vertical profile of the chlorophyll for the study of underwater light field in coastal water of off-Point-Calimere, south east India. Off-Point-Calimere is a chlorophyll dominated waters with shallow water region. The analysis shows that the chlorophyll concentration at the surface is very low and depth where the chlorophyll maximum is shifted exponentially to the seabed. This scenario explains that the light reaches almost near to the seabed. This maximum chlorophyll may move vertically upward due to the presence of benthic resuspension initiated by tides and currents.

Varunan and Shanmugam (2015) worked in the size classification of phytoplankton, namely pico, nano and micro. This classification was based on the optical signature of the different groups of phytoplankton. The new model was developed and validated using the three different in-situ datasets from global and regional coastal and eutrophic waters. The developed model was applied to the satellite MODIS-Aqua images and observed the spatial pattern of blooms which shows different pattern for the cyclonic eddies. This study was highly useful for understanding the chlorophyll pattern for the global waters.

V. Conclusion
This study summarizes the recent studies on the variation of chlorophyll along the Indian coastal waters. The survey starts with the measurement techniques of chlorophyll based on ship borne and space borne. Further description based on the exiting model for the retrieval of chlorophyll from the satellite based remote sensing reflectance. Finally, the studies conducted on the chlorophyll estimation and analysis in the coastal waters of India were analyzed. These analyses explain that the primary production by chlorophyll can be indirectly affected by several factors such as surface winds, water temperature and other environmental factors. These studies highly important for the oceanographic community and coastal zone management.

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