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# Relation Between Deep Chlorophyll Maximum and Vertical Thermal Structure in the Andaman Sea

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**ABSTRACT**

This study investigates the deep chlorophyll maximum and physico-chemical properties of the water column to delineate the underlying relation between vertical thermal structure and chlorophyll maxima. The biophysical variability in the Andaman Sea can be characterized as (i) enhanced Chl due to mixing and sediment resuspension in Northeastern Andaman Sea (ii) depressed Chl ($0 < Chl < 0.5$ mg/m$^3$) in the offshore surface waters; (iii) deep Chl maxima (DCM; $0.5 < Chl < 3.3$ mg/m$^3$) observed below the surface mixed layer in the depth range 40–80 m; and (iv) well defined oxygen minima (DO < 3 mL/L) below the DCM. The empirical relation between subsurface temperature and Chl suggests a significant correlation ($R^2$ = 0.78–0.96) indicating optimum light and nutrient conditions for deep accumulation of phytoplankton which linearly decreases down the water column. Future work has to be carried out to understand the underlying relationship between temperature and chlorophyll in coastal and shelf waters.

**Keywords:** Deep chlorophyll maximum; Temperature; Mixed layer; Andaman Sea

## 1. INTRODUCTION

Andaman Sea lies in the eastern part of the Indian Ocean (6–14° N latitude and 91–99° E longitude) between Andaman and Nicobar Islands in the west, landmasses of Myanmar, Thailand and Malaysia in the north and east, and Sumatra in the south. It is a marine regime containing internal solitary waves[1] of extraordinary amplitude (> 60 m), wavelength (6−15 km), and speed (> 2.0 m/s). The riverine discharge to the enclosed Andaman Sea is mainly controlled by major rivers (21.88 X 10$^3$ m$^3$/s) namely, Ayeyarwady, Salween and Sittang in the northern coast[2]. The physical and chemical oceanographic processes are significantly influenced by the seasonally reversing southwest monsoon (June-September) and northeast monsoon (December-February) with intense rainfall in which the circulation oscillates between cyclonic and anticyclonic currents respectively[3]. It is well connected to the Bay of Bengal through three perennial channels and South China Sea through the Malacca Strait. The northern basin of Andaman Sea is shallow (< 200 m) while the western area is deeper upto 4400 m with an average depth of 1096 m. Previous reports suggest oligotrophic waters with average primary production ranging between 300 and 600 mgC/m$^2$/d in the Andaman Sea [4].

Chlorophyll biomass is a common feature in coastal and shelf seas but the deep chlorophyll maxima (DCMs) generally occur in permanently stratified layers of tropical and subtropical waters as well as seasonally at temperate and high latitude regions[5-6]. In stratified waters, these DCMs referred as peak chlorophyll concentration, are remarkable within the thermocline where sufficient light and nutrient elements available for biological production. As warming of surface waters increase, stratification develops further which may decrease surface primary production and export of organic particulates down the water[7]. On contrary, the DCMs may occur and vary widely with respect to mixed layer depth which could improve the knowledge of warming induced stratification led by climate change in highly significant marine regimes such as Bay of Bengal and Andaman Sea[8-10]. Bay of Bengal has been extensively studied for understanding the biogeochemical processes but there have been few studies on bio-physical interactions in the Andaman Sea. Hence this study evaluates the vertical structure of chlorophyll to study the deep chlorophyll maximum in the Andaman Sea. It also investigates the temperature profile and other physico-chemical properties of the water column that can be related to the development of DCMs. Further, the objective includes the formulation of a relation between sub surface temperature and chlorophyll in the Andaman Sea.

## 2. METHODOLOGY

Monthly climatology of level-3 daytime 4 µm SST, Chl and POC of spatial resolution 4 km were obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) TERRA sensor between 2002 and 2019 (http://oceancolor.gsfc.nasa.gov). We used the Vertically Generalized Production Model (VGPM)[11] from the MODIS-Aqua (Reprocessing R2013.1) with a spatial resolution of 9 X 9 km$^2$ to estimate the

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monthly vertically integrated net primary production for March 2019 (http://www.science.oregonstate.edu/ocean.productivity/index.php). Monthly climatological sea surface salinity (1955–2017) were downloaded from the NODC World Ocean Atlas 2018. The Archiving Validation and Interpretation of Satellite Oceanographic (AVISO) monthly data between 1993 and 2012 was used to study the sea surface height anomaly (SSHA) to explore the mesoscale features in the region. The wind component data were downloaded from the National Snow & Ice Data Center, NASA Distributed Active Archive Center (DAAC) obtained through Advanced Microwave Scanning Radiometer-Earth observing system sensor on the NASA Aqua satellite (AMSR-E/Aqua L3 Global) with a spatial resolution of 0.25° X 0.25°. Further, the data sets are with a temporal coverage from June 2002 to October 2011.

The *in situ* data collection was carried out onboard INS Sagardhwani as part of the SAGAR MAITRI PHASE I – IIOE MISSION to study the oceanographic features of the central Bay of Bengal and Andaman Sea between 20-28$^{th}$ March 2019. The study area along with sampling locations in the Andaman Sea is given in Fig. 1. Chlorophyll measurements were carried out in conjunction with salinity and dissolved oxygen using a high vertical resolution RBR water quality profiler attached to the CTD. Temperature has been obtained from Conductivity-Temperature-Depth (CTD) profiler deployed at respective stations.

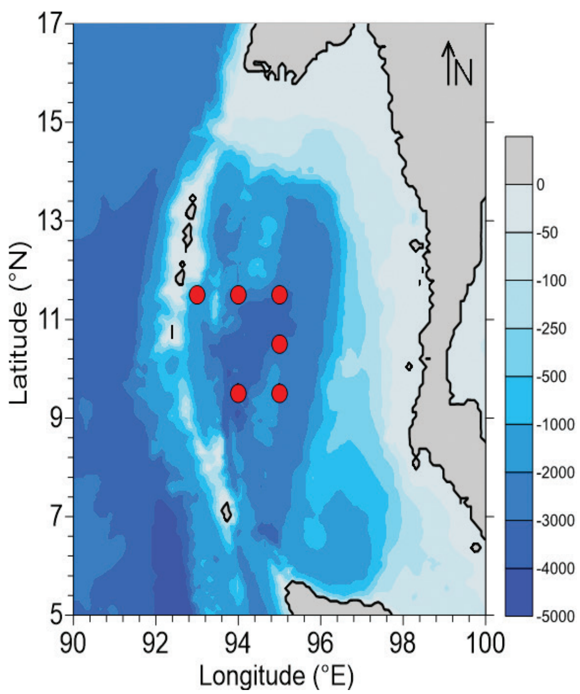


**Figure 1. Location map showing study area and sampling sites in the Andaman Sea.**

## 3. RESULTS AND DISCUSSION

### 3.1 Surface Water Properties

During the sampling period, SST varies between 27 and 29.5 °C where the SST reaches 29 °C in the central Andaman Sea. The cooling of surface waters (SST ~ 26.5–28.5 °C) was observed in the northern Andaman Sea. Sea surface salinity (SSS) varied between 30.5–34 psu in the study area. The influx of fresh water can be observed in the northern Andaman Sea and Malacca strait likely by the contribution of major rivers viz., Ayeyarwady, Salween, etc. There is evidence for the transport of less saline waters to the southern part which causes moderate salinity (SSS < 33 psu) in the central Andaman Sea. The wind speed (m/s) ranges from 1 to 6 m/s. The negative values of SSHA indicates the presence of anticyclonic structure of cold-core eddies in the Northern Andaman Sea. The southeastward path of eddies is seen as a region of high Chl patches. The low negative values of SSHA suggest lowering of the sea level which may result in the decline of thermocline depth

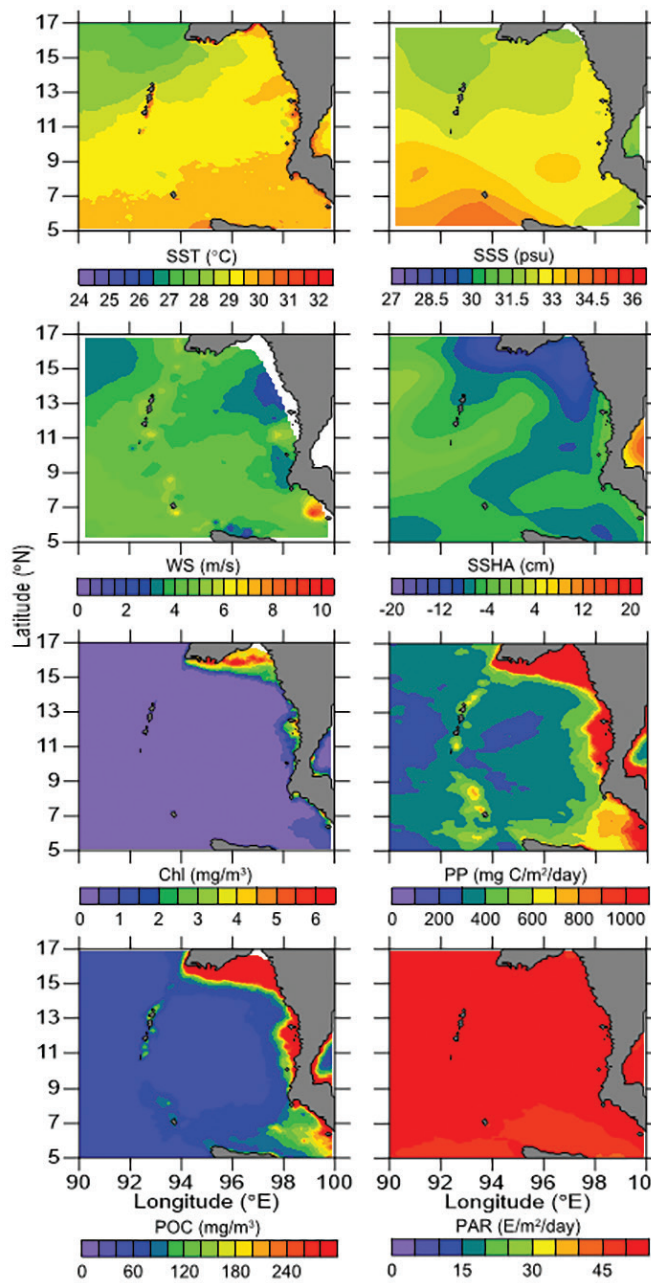


**Figure 2. Surface distribution of temperature (SST), salinity (SSS), wind speed (WS), sea surface height anomaly (SSHA), chlorophyll (Chl), primary production (PP), particulate organic carbon (POC) and photosynthetically active radiation (PAR) during the month of March.**

between January and April. It is likely by the southward flow of anticyclonic EICC to the west of Andaman island chain. The thermocline shoaling leads to entrainment of nutrients to the upper layer which enhances primary productivity in the region.

The distribution of monthly climatology Chl pigments in the Andaman Sea during March (2002-2019) is depicted in Fig. 2. In the region of interest, the Chl variability shows large differences between coastal and offshore waters. The enclosed shallow waters in the northern Andaman Sea can be considered as eutrophic where the concentration exceeds 2 mg/m$^3$[3,12]. In the outer shelf waters, Chl varied between 0.5 and 2 mg/m$^3$ which evidences mesotrophic conditions in the surface layer. The offshore/open sea waters can be characterized as oligotrophic where the Chl varies less than 0.5 mg/m$^3$. The in situ sampling were carried out on March 2019 and the monthly average of primary production reveals a tongue of high PP in the range of 200 mg C/m$^2$/day (Fig. 2). POC concentration reveals a similar distribution trend that of Chl in the Andaman Sea (Fig. 2). POC level exceeds 80 mg/m$^3$ in the shelf of northern Andaman Sea and found to be a perennial feature likely by the resuspension of particulate matter. The patches of POC concentration (80-120 mg/m$^3$) can be observed around the Island chain of Andaman and Nicobar which indicates nutrient inputs of terrestrial origin particularly from mangrove areas[13].

The residence time of nutrient elements in the water column creates suitable environment for the production of organic matter and recycling efficiently along the coastal bays[14]. The study by Kurian[15], *et al.* suggest that the productivity in terms of foraminifera is largely affected by the sudden changes in sea surface salinity. So salinity with respect to freshwater influx might affect the productivity of Andaman Sea waters. On contrary, the fluvial load from the Ayeyarwady river as well as contribution from other river discharges in the Northern Andaman waters of about 600 Mt/y[16] plays an important role in the biological production which is clearly obtained in satellite Chl and POC data. Particularly, the Ayeyarwady continental shelf records year round productive eutrophic waters which is likely caused by the discharge of riverine inputs[17] and nutrient recycling through tidal influence. Noteworthy, the strong wind action in the coastal areas may further initiate nutrient mixing causing high concentration of Chl in the surface waters[18]. The high tidal currents and resuspension of sediments in the northern Andaman Sea induce vertical mixing compared to other parts of the study area[19]. Another important feature is the enhancement of Chl along the south of Andaman Sea particularly, from the Malacca Strait northwards during the northeast monsoon. This enhancement is due to freshwater inputs (salinity low) likely by high precipitation rate accompanied by land runoff. Interestingly, it can be attributed to larger river discharge and the intrusion of lower salinity water mass from the South China Sea[20]. Photosynthetically Active Radiation (PAR) records high values (PAR > 45 E/m$^2$/day) which provides sufficient light conditions for the production and proliferation of marine plankton in the surface and subsurface layers.

### 3.2 Water Column Properties

The downcore profile of temperature in the Andaman Sea is given in Fig. 3. The mixed layer depth has a temperature range between 28.5 °C and 29.3 °C and it extends between 10–50 m depth. The thermocline extends down to 100–150 m and the temperature reaches to 12–13 °C at 200 m depth. Salinity profile shows a rapid increase within the depth range of surface to 100 m and reaches 35 psu down the vertical column (Fig. 3). During the study, DO content varied between 4.5 and

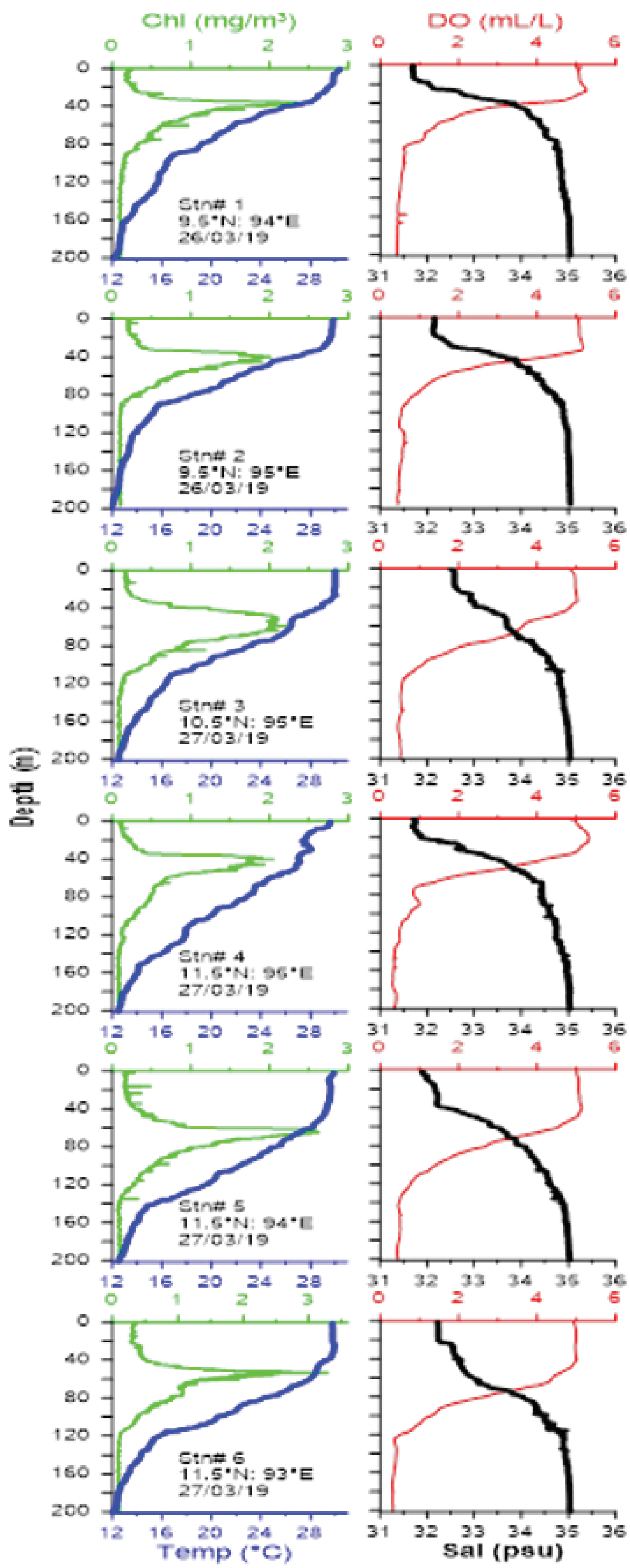


**Figure 3. Depth section of temperature, chlorophyll, salinity and dissolved oxygen in the Andaman Sea.**

5.5 mL/L in the upper 30 m water column. The surface waters were well oxygenated with similar downward trend in all the stations. DO shows a rapid decrease, less than 2 mL/L between the depth range of 50-100 m. Towards the bottom of the water column, DO profile ranged between 0.2 and 1.0 mL/L (Fig. 3).

### 3.3 Distribution of DCMs

The Chl recorded lowest concentration (less than 1 mg/m$^3$) in the surface mixed layer whereas a subsurface maxima layer was observed ranging upto 3.6 mg/m$^3$ down the profile (Fig. 3). The warm less saline surface waters are found to be nutrient poor due to less vertical mixing and the biological production is expected to be minimum at the surface layer. The DCM depth shows no regional difference and occurred between 40 and 80 m. DCM is less sharp about 25 m thick suggesting a non-upwelling region. The DCM was found to be below the mixed layer suggesting the effect of stratification and vertical mixing intensity in the formation of chlorophyll in deeper layers. The DCM shows 20 – 30 times increase than the upper layer Chl in the Andaman Sea.

Chl concentration declined to minima below the DCM in all the stations likely by reduced solar insolation. At certain stations, the DCMs were as deep as 60 m which can be attributed to stratification thereby limiting the upward movement of nutrient elements. The deep Chl maximum is often observed in stratified oligotrophic areas where nutrient depleted upper surface waters occur[21]. The vertical mixing as a result of internal waves may act as a potential source of nutrients for the development of phytoplankton in the sub surface water column[22]. The deep Chl maximum can be traced as nutrient rich deep waters that cause high biological production and the associated remineralization and downward flux of organic matter results in the development of oxygen minimum zone at intermediate depths. Previous study in the Andaman Sea demonstrated that the DCM is obtained as a result of high nutrient levels in the sub surface than the surface waters[23].

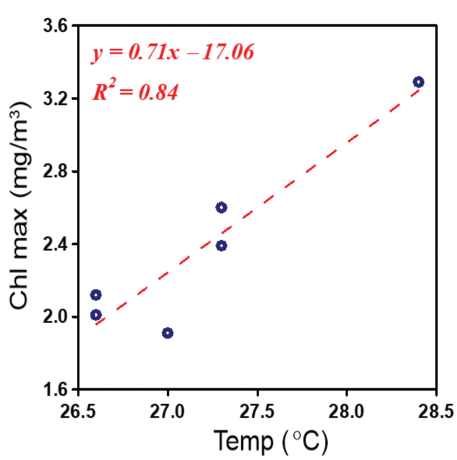


**Figure 4. Linear regression plot of chlorophyll maximum and corresponding temperature in the Andaman Sea.**

### 3.4 DCM relation to vertical thermal structure

All DCMs throughout the study region are closely associated below the mixed layer at the top of the thermocline. The cross-correlation between the temperature of the water column corresponding to the Chl maximum specifically in the Andaman Sea is depicted in Fig. 4.

The results showed linear relation between temperature and Chl maximum ($R^2$ = 0.84) suggesting optimum light conditions for sufficient phytoplankton accumulation in the sub surface water column. Further, the linear regression between sub surface temperature and chlorophyll using the temperature data pertaining below the DCM upto 20 °C isotherm and the corresponding Chl concentration (Table 1) has been generated. The linear relations suggest a significant correlation between sub surface temperature and chlorophyll in the Andaman Sea ($R^2$ = 0.78 – 0.96).

**Table 1. Result of linear regression analysis**

| Station | Linear Regression | $R^2$ |
|---|---|---|
| 1 | Chl = 0.21*Temp –3.99 | 0.92 |
| 2 | Chl = 0.24*Temp –4.40 | 0.96 |
| 3 | Chl = 0.26*Temp –5.00 | 0.93 |
| 4 | Chl = 0.19*Temp –3.83 | 0.81 |
| 5 | Chl = 0.26*Temp –5.29 | 0.82 |
| 6 | Chl = 0.18*Temp –3.36 | 0.78 |

Increase in stratification and oligotrophic conditions results in low nutrient levels leading to lower Chl maximum[24]. Previous studies in the Southern Bay of Bengal reported the dominance of picophytoplankton in the DCM since low light and low nutrient conditions favours the growth of smaller phytoplankton[25-26]. The study by Garg[24], *et al.* reported thick DCM with the dominance of dinoflagellates in the Andaman Sea. Thicker DCM could be attributed to optimum light and increased nutrient inputs from the bottom. Moreover, the variability of DCM and its relation to temperature has got implications for understanding the vertical thermal structure dynamics through the absorption of short wave radiation.

## 4. CONCLUSIONS

Present study describes the relationship between DCM and vertical thermal structure in the Andaman Sea. This study confirms that DCMs are a typical feature in the stratified waters of the Andaman Sea. DCMs are located in the euphotic zone between 40 and 80 m depth but they are generally connected to the upper thermocline and separated from the mixed layer. Chl concentration in the surface waters was low, whereas the sub surface maximum at about 40–80 m is caused by optimum light and nutrient conditions. The biological response related to physical features can be characterized as follows (i) efficient nutrient recycled eutrophic waters due to physical response in the northeastern margin (ii) poorly mixed oligotrophic surface waters in the central Andaman Sea (iii) high saline cold sub surface Chl maximum in the offshore water column, and (iv) mid depth oxygen minima (≤ 0.5 mL/L) below the DCM layer. The linear regression between subsurface temperature and chlorophyll reveals a significant correlation ($R^2$ = 0.78–0.96) which suggests that the DCM formed below the mixed layer decreases linearly with the temperature gradient within the euphotic layer. This relation can be used to model the temperature profile in strategically significant marine regimes.

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