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Research Article

Upwelling phenomena in the southern coastal waters of Sri Lanka during southwest monsoon period as seen from MODIS

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Abstract

MODIS (Moderate-resolution Imaging Spectroradiometer) aqua data for 2004 has been used to explore possible coastal upwelling areas around Sri Lanka during southwest monsoon. Two very important ocean parameters, ocean colour and sea surface temperature (SST), derived from MODIS data for the waters surrounding Sri Lanka are studied to understand the variability and the relationship of the two data sets. Remotely sensed data of 1.1 km resolution obtained from MODIS were mapped using seadas software within an area of latitudes between 2.0 N - 13.5 N and longitudes between 72.5 E – 88 E. The days with heavy clouds were excluded. Daily chlorophyll *a* and SST maps were used to make composites for each week and subsequently for each month. There were between 10 – 20 daily files for each month. The southwest monsoon period arrives roughly in May and generally lasts till September. The chlorophyll concentration varies roughly in the range 0.01 – 10.0 mg m^{-3} and the sea surface temperature varies between 25 – 32°C in the waters surrounding the island during the year.

The monthly composites of chlorophyll *a* show high productive waters of over 5 mg m^{-3} average concentration in most of the southern and western coastal ocean during the months of June - August. The sea surface temperature drops by 2 to 3 degrees (centigrade) in coastal ocean waters in the south where high chlorophyll *a* concentrations are detected. Observation of chlorophyll *a* and SST maps indicate strong correlation (between 60% - 80% of negative correlation) between the two parameters in the southern coastal ocean region where high chlorophyll *a* and low SST values are detected in the months of June and July. This may be due to the upwelling phenomenon that occurs in the coastal waters. Upwelling brings cooler nutrient rich waters to the surface enhancing the production of phytoplankton near the surface waters and these high phytoplankton areas are generally attracted by large fish populations. Thus, correct identification of upwelling zones would be highly beneficial in the fishery industry.

Key words: MODIS, sea surface chlorophyll *a*, SST, southwest monsoon, upwelling

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1. INTRODUCTION

Satellite remote sensing has become increasingly helpful in studying world oceans and their many biological and physical processes. The first ocean monitoring sensor, CZCS (by USA) was launched in 1978 and was operational until 1986. Though the scanner was able to record data only in few wavelength bands and there were many technical limitations, oceanographers around the world had the opportunity to study [1,2] vast scale oceans with greatest ease. Since CZCS, ocean remote sensing technology has advanced in a rapid pace with many countries launching their own satellites such as OCTS (Japan), SeaWiFS (USA), IRS-P4 (India), etc. to monitor local and global oceans. The most recent one by United States, MODIS (Moderate-resolution Imaging Spectroradiometer) was launched in 2002. It carried most sophisticated detectors capable of measuring in 36 spectral bands, thus providing vast amount of information on land, ocean as well as atmosphere. The algorithms used to process data are superior compared to earlier remote sensing algorithms used for SeaWiFS.

In this study we obtained ocean data through NASA data archive center, in particular, sea surface chlorophyll *a* and sea surface temperature (SST), which are two very important oceanographic parameters derived from MODIS raw data. The pigment chlorophyll-a found in microscopic ocean plant, phytoplankton, affects the colour of the ocean waters. Thus, ocean colour derived from sensor data is used as an indicator of chlorophyll *a* concentration (algorithms are more applicable in open ocean waters). Upwelling is the process which brings cooler nutrient rich bottom waters to sunlit ocean surface and thereby increasing primary production. The knowledge of surface pigment concentrations and sea surface temperatures can be used in locating such upwelling areas off the coast, hence identifying possible fishing areas in the coastal ocean. Also, chlorophyll *a* is a valuable parameter in quantification of global carbon budget [3]. Knowledge of sea surface temperature is also important in quantifying changing atmospheric conditions and understanding living conditions of biological organisms.

In this paper, we have used MODIS aqua data for the year 2004 to explore the spatial and temporal variability of chlorophyll *a* concentration and sea surface temperature and the relationship between the two parameters to identify possible upwelling periods and regions along the coast of Sri Lanka.

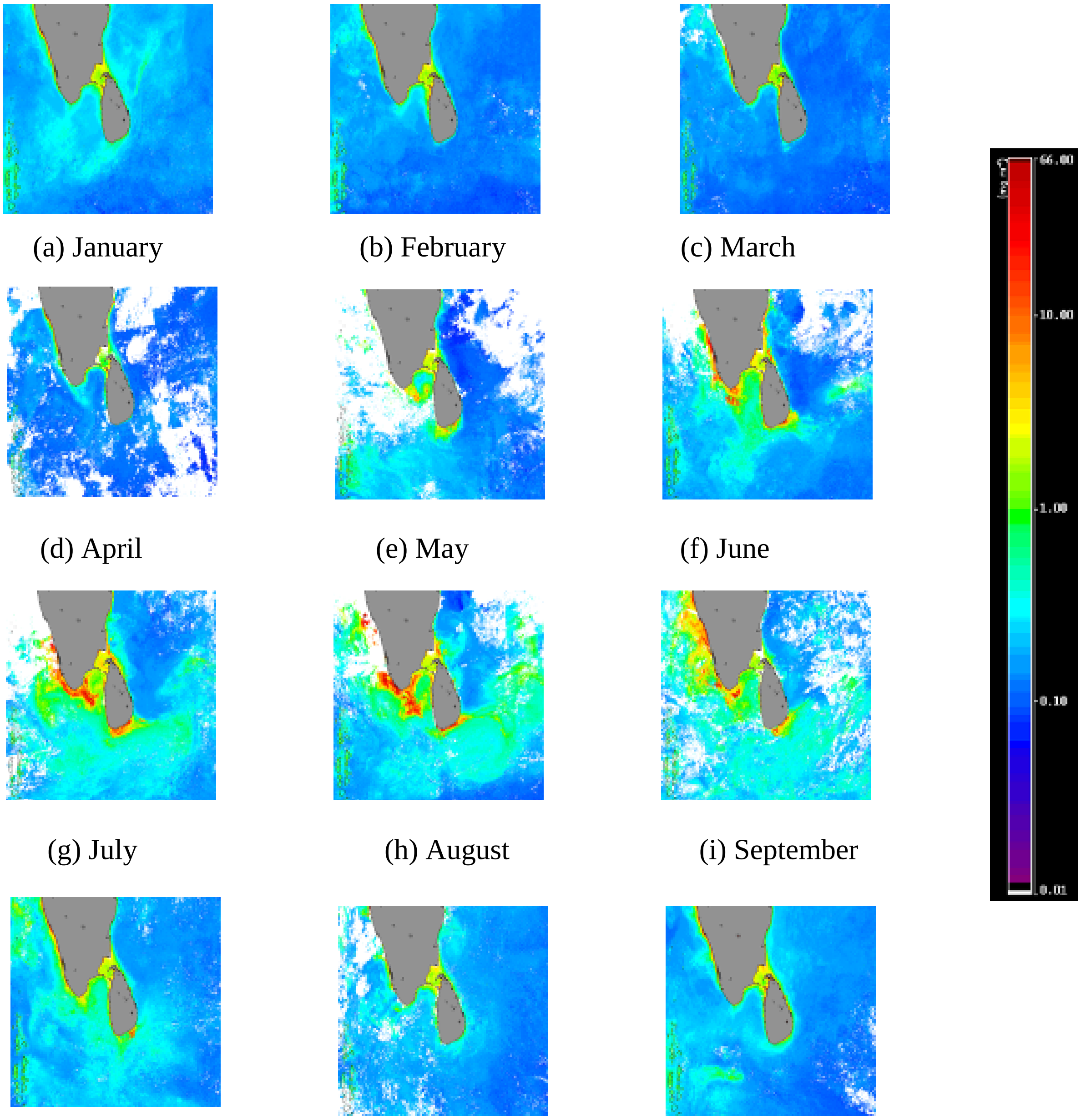
2. METHODOLOGY

MODIS provides daily local area coverage (LAC) data of 1.1 km resolution. For ocean colour observations MODIS has 8 wavelength bands in the visible region ranging from 405 nm – 683 nm, each with 10-15 nm bandwidth. The empirical algorithm [4] used to extract chlorophyll *a* (referred as CHL from this point on) concentration from MODIS is

$$\log_{10}[CHL] = a_0 + a_1 X + a_2 X^2 + a_3 X^4 + a_4 X^5$$

where $X = \log_{10}\left[\frac{(R_{rs}(443) > R_{rs}(488))}{R_{rs}(555)}\right]$

and the coefficients a_0, a_1, a_2, a_3 and a_4 are 0.283, –2.753, 1.457, 0.659 and –1.403, respectively. Here, $R_{rs}(\lambda)$ is the remotely sensed radiance at wavelength λ derived using the knowledge of optical processes in the euphotic zone and the processes in the atmosphere. The band ratio X is defined as the logarithm of the greater value of the two ratios $R_{rs}(443)/R_{rs}(555)$ or $R_{rs}(488)/R_{rs}(555)$. The SST algorithm [5] is SST = $c_1 + c_2 * T_{31} + c_3 * T_{3132} + c_4 * (\sec(\theta) - 1)*T_{3132}$ where T_{31} is the band 31 brightness temperature (BT) (cf. AVHRR channel 4), T_{3132} is (Band31 – Band32) BT difference (cf. AVHRR channel4 – channel 5) and θ is the satellite zenith angle. The coefficients c_1, c_2, c_3 and c_4 are 1.11071, 0.9586865, 0.1741229 and 1.876752 for $T_{31} - T_{32} \leq 0.7$ and 1.196099, 0.9888366, 0.1300626 and 1.627125 for $T_{31} - T_{32} > 0.7$, respectively.



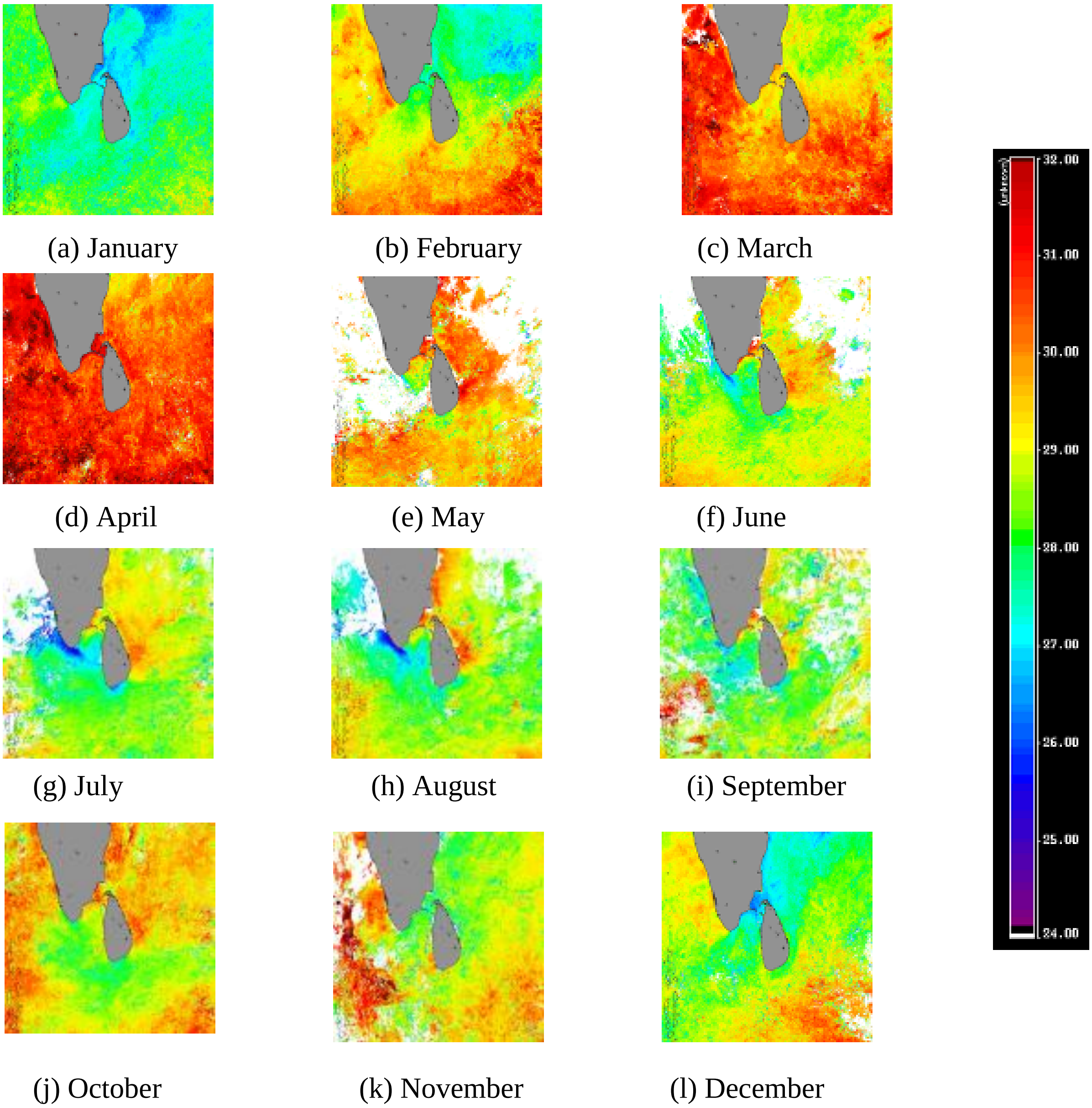
(a) January (b) February (c) March

(d) April (e) May (f) June

(g) July (h) August (i) September

(j) October (k) November (l) December

Figure 1: Monthly composites of chlorophyll *a* maps for the year 2004. The logarithmic colour scale used to represent chlorophyll *a* concentration is shown on the left.



(a) January (b) February (c) March
(d) April (e) May (f) June
(g) July (h) August (i) September
(j) October (k) November (l) December

Figure 2: Monthly composites of SST maps for the year 2004. The colour scale depicting temperature variability (24 – 32 °C) is shown on the left.

Daily maps of CHL and SST were made for the ocean waters surrounding Sri Lanka in the area of latitudes between 2.0 N - 13.5 N and longitudes between 72.5 E – 88 E. Days with heavy clouds were excluded during mapping. Weekly and monthly composites of both CHL and SST were made for each month. There were about 10 - 20 daily files available for each month. Possible upwelling areas were identified by observation of both chlorophyll *a* and SST maps and data were extracted from such locations to find correlation between the two parameters, if any.

3. RESULTS AND DISCUSSION

The temporal and spatial distribution of CHL and SST of waters around Sri Lanka are shown in Figures 1 and 2, respectively, using monthly composites. The white patches in the maps represent no data due to cloud cover. A logarithmic colour scale is used to depict CHL variability as the range varies from 0.01 mg m^{-3} to over four orders in magnitude. The scale for SST is chosen to represent values between 24 – 32 ^{o}C as over 95% of the data lie within this range. Thus, the northeastern waters can be considered as warm and more stratified throughout the year, except perhaps in January and December. During the months of May – September the waters in the south are influenced by strong southwest winds that blow across the southern part of the country and also by the strong western boundary current (Somali current) that flows northeastward via southern coastal waters. As a result, the waters in the south, west, southwest and southeast exhibit higher average CHL concentrations of over 1 mg m^{-3} during the southwest monsoon period.

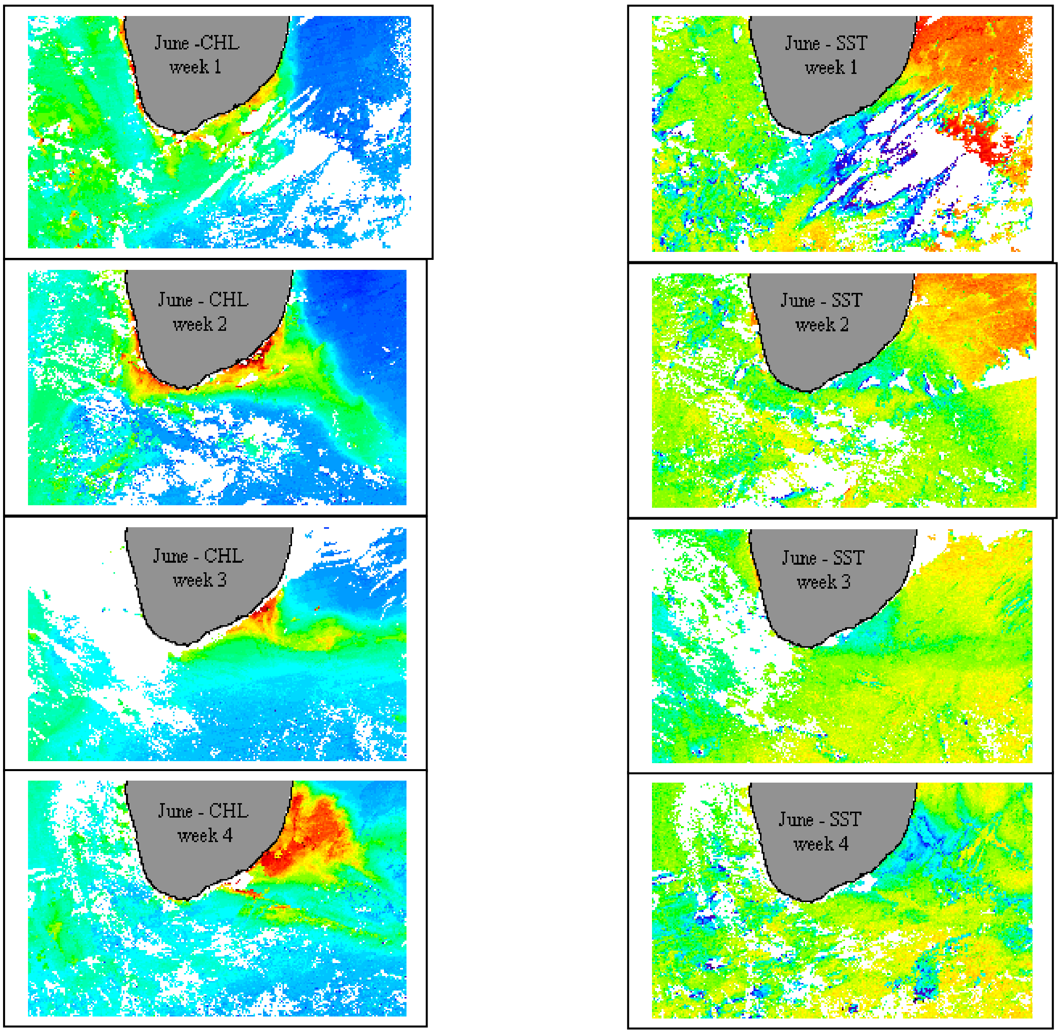


Figure 3-a: Time sequence of MODIS CHL and SST composites in the southern waters of Sri Lanka depicting development of coastal upwelling during the month of June, 2004.

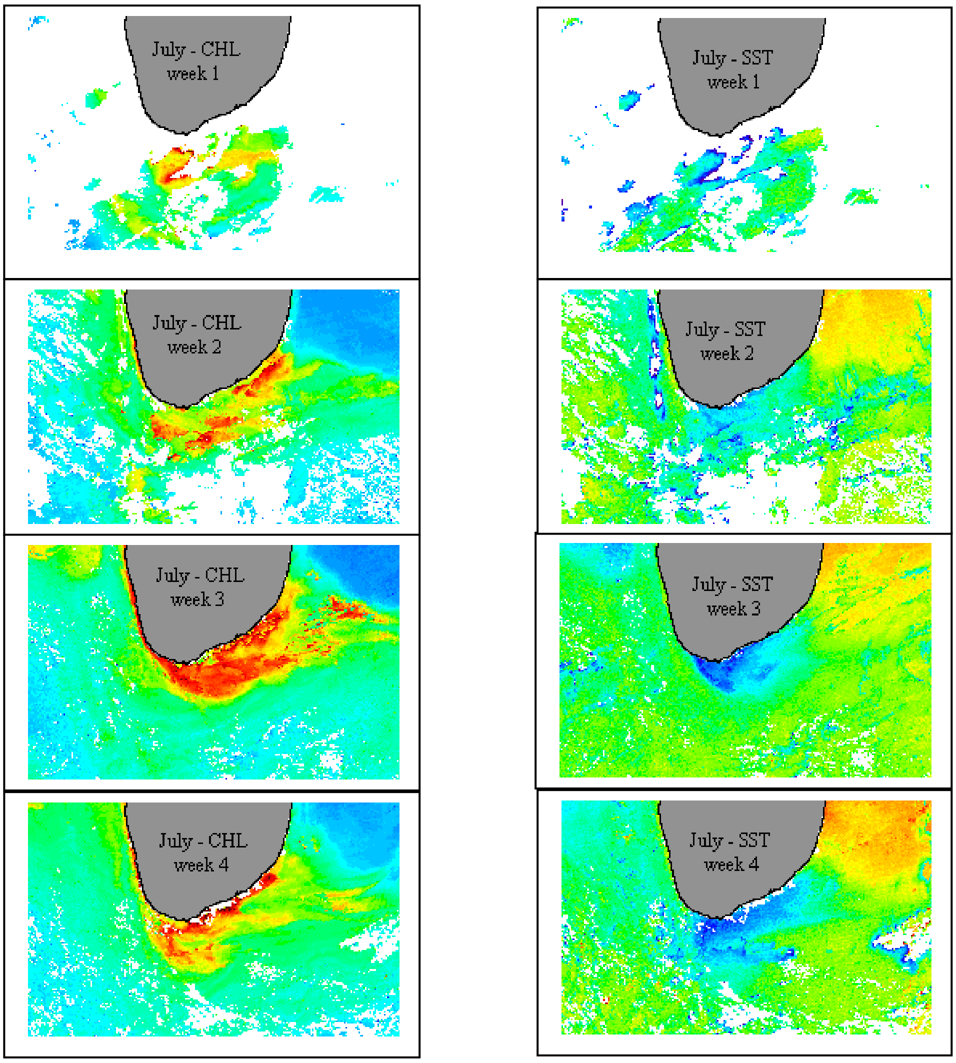


Figure 3-b: Time sequence of MODIS CHL and SST composites in the southern waters of Sri Lanka depicting development of coastal upwelling during the month of July, 2004.

As southwest monsoon starts in May, southern waters begin to show interesting features; high CHL patches (between 1 – 10 mg m^{-3}) develop along the southern coast and become stronger as the month progresses. The SST maps show lower temperatures (about 25 - 26^{o}C) in corresponding regions. Development of this feature can be seen well in the weekly time series composites of CHL and SST for the months of June and July shown in the Figures 3-a and 3-b. During the second week of June the southeastern coastal waters starts to develop high CHL values as seen in the Figure 3-a. It peaks around the fourth week showing a very strong CHL patch spreading to an area of about 2^{o} x 2^{o} (latitudes between 5.5N - 7.5N and longitudes between 81 E – 83 E, roughly). The corresponding SST maps for the 3rd and 4th weeks show cooler temperatures in the south eastern coast exhibiting coolest waters in the 4th week. A similar feature can be observed in the month of July as well (Figure 3-b). By the second week of July southern waters develop an elevated CHL patch, peaking around the 3rd week and spreading into a large area along the southern coast (latitudes between 4.5N – 7N and longitudes 80 E – 83 E, roughly). Cooler

SST values of around 26°C are observed in the area during the peak period. High CHL patches (with matching low SST values) start appearing in two spatially distinct areas and can be considered as two separate upwelling phenomena developed during the southwest monsoon period.

Strong upwelling conditions and eddying motions [6] develop in the coast of Somalia during the southwest monsoon. The Somali current [7] which flows along the south of Sri Lanka towards northeast may also bring these favouring upwelling conditions into the south and southeast coasts, thus enhancing upwelling phenomena along the southern coast.

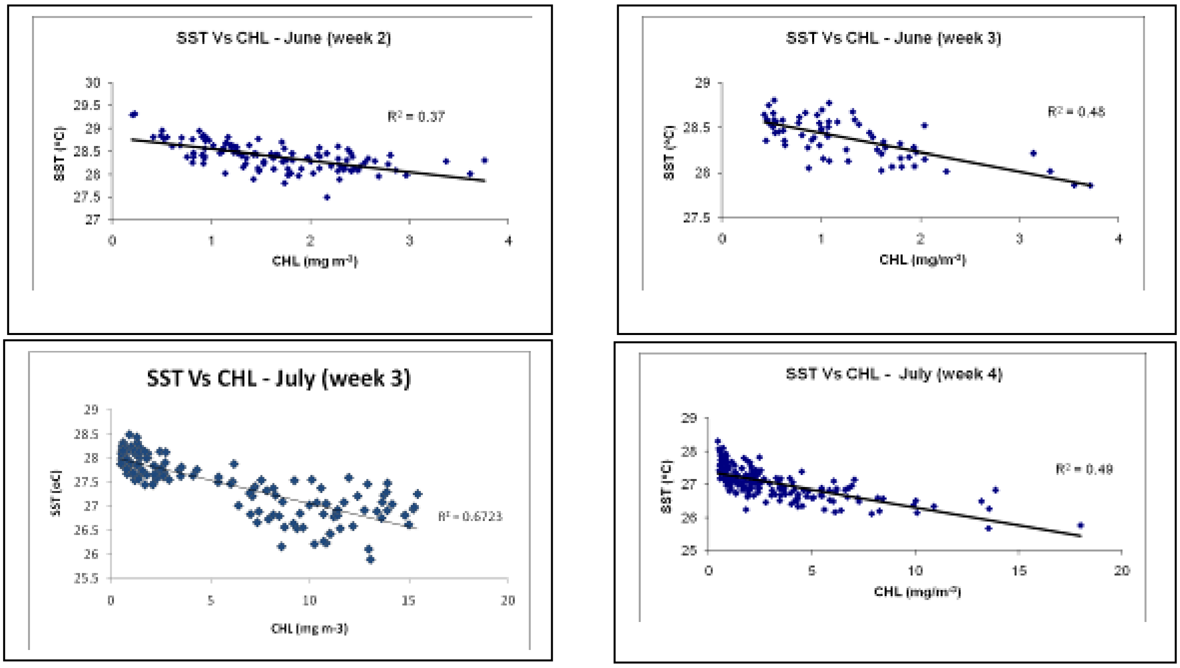


Figure 4: Inverse relation between SST and CHL for the upwelling regions in the southern coastal area

The inverse relations between CHL and SST shown in the plots in Figure 4 are made using data extracted from the regions that exhibited strong upwelling phenomena during the months of June and July. The data used for the plots are from sub areas of sizes about 1° x 1°. The correlation coefficients for each data set shown in the plots are between –0.6 to –0.80. From these plots it is clear that even though the differences in temperature of upwelled waters are only few degrees (maximum of 3 - 4 °C) compared to SST of surrounding waters, CHL concentrations are increased to very high values. Accordingly, we can expect enhanced phytoplankton populations in these regions.

4. CONCLUSION

Remotely sensed ocean colour and sea surface temperature data from MODIS are analyzed here to identify possible upwelling zones around the coast of Sri Lanka. Ocean colour is used as a tool to locate as well as a measure of areas of enhanced biological production. This is a valuable tool in fisheries management since fish population is known to spawn and feed in these biologically productive waters. Sea surface temperature explains the environment suitable for high productivity.

The study confirms that the northeast monsoon is a gentle phenomena, with low CHL concentrations and moderate to high SST values in the northern waters and rest of the oceanic region around Sri Lanka. During southwest monsoon, two distinct high CHL patches develop in the south and southeast coasts, in June and July, respectively. The optical features seen in CHL maps match the thermal features in the SST maps. Cooler temperatures indicate nutrient rich waters and those two areas have higher probability of enhanced production. Good inverse relation of CHL and SST suggests strong coupling between physical and biological processes in these upwelling zones. Use of both these parameters simultaneously would explain ocean environment and food availability in the areas of such persistent colour and thermal features. Therefore, coincidence of colour and thermal features in remotely sensed ocean data can be utilized for exploring fishery resources. Fishery forecasting [8] is utilized satisfactorily in India, for example, reporting two to three fold increase in fish catches in the northwest coast during northeast monsoon period. A major problem that we may face using satellite ocean data for fishery forecasting would be the heavy cloud contamination in the daily maps seen throughout the year, more so during the southwest monsoon period.

Further work is underway to study these features further using current MODIS data with other physical parameters such as surface winds, ocean currents, etc. Derived CHL concentrations from remotely sensed data are not restricted to the two dimensional processes on the sea surface since radiance arriving the sensor carry information from biological, chemical and physical processes in the euphotic zone. A thorough analysis of different parameters, physical and biological, would explain the oceanic environment and its processes well, for exploring fishery resources and also enhancing capability of fishery forecasting.

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