IJARCCE

ISSN (Online) 2278-1021
ISSN (Print) 2319 5940

International Journal of Advanced Research in Computer and Communication Engineering
Vol. 5, Issue 1, January 2016

Prediction of Coastal Upwelling Using Remote Sensing

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Abstract: South Eastern Arabian Sea (SEAS) is a unique oceanic basin within the Arabian Sea where a suite of phenomenon takes place over a year ranging from coastal upwelling during summer monsoon season along the south west coast of India to monsoon onset vortex to the Arabian Sea miniwarm pool before the onset of summer monsoon and formation of algal blooms. Seven years (2007-2013) of satellite sea surface temperature (SST) data, chlorophyll data, and wind data were used to predict the coastal upwelling in the South East Arabian Sea. Upwelling areas are determined by lower SST and higher Chlorophyll concentrations. Upwelling indices such as Latitude Temperature Gradient (LTG), Chlorophyll Extension Index and Ekman indices was computed from SST, Chlorophyll and wind data respectively, and by using those indices variations of upwelling dynamics was studied and inter-annual variability was found out for predicting the coastal upwelling in the South East Arabian Sea.

Keywords: Upwelling, Sea Surface Temperature, Chlorophyll, Latitude temperature gradient.

I. INTRODUCTION

1.1 General

Upwelling is an oceanographic phenomenon that involves wind driven motion of dense, cooler and usually nutrient rich water towards the ocean surface replacing the warmer usually nutrient-depleted water. In other words, Upwelling is an ascending motion for minimum duration, extend by which, water from subsurface layer is brought into the surface, removing the prevalent waters by horizontal flow. Deep waters are rich in nutrients, such as nitrate, phosphate and silicate, due to the decomposition of sinking organic matter and lack biological uptake. When brought to the surface, these nutrients are utilised immediately for the production of phytoplankton along with CO_2 and solar irradiation, through the process known as photosynthesis. Upwelling regions are therefore, significant for very high levels of primary production in comparison to other areas of the ocean.

1.2 Upwelling in South East Arabian Sea

Dynamic processes in SEAS are triggered by the local and remote forcing. During the summer monsoon, generally from June through to September, strong winds blow from the southwest forming an intense low-level jet over the central AS. In response to these winds a clockwise circulation evolves in AS producing coastal upwelling along the Somalia, Oman and the southwest coast of India The equator- ward eastern boundary of this anticyclonic circulation is known as the West India Coastal Current. During winter, generally from November to February, the winds blow from the northeast. During the inter-monsoon period, from March to April and October to November, weak, highly variable wind regimes occur in the Arabian Sea and the basin surface circulation dissipates. The downwelling (upwelling) Kelvin wave radiates downwelling (upwelling) Ross by waves which propagate off- shore and promote anticyclonic (cyclonic) circulation in the Lakshadweep Sea during winter (summer) monsoon. The anticyclonic Lakshadweep circulation is also strengthened by negative wind stress curl during the winter monsoon.

Upwelling along the southwest coast of India is an annually recurring phenomenon that occurs during the SWM (June to September). Though this upwelling phenomenon is less in intensity when compared to the other thoroughly studied upwelling regimes of the Arabian Sea (like those at Somalia and Oman), it has profound impacts on the coastal fisheries of India. While the west coast of India accounts for 70% fish yield of the total Arabian Sea production and the southwest coast alone accounts for 53% hence this region is of considerable importance in the Indian context.

1.3 Need for the study

- Coastal upwelling systems are highly dynamic, exhibit wide variations in hydrographic, nutrients and phytoplankton characteristics on short time scale.
- Upwelling enhances biological productivity.
- Upwelling zones accounts for high fishery yield.

1.4 Objectives of the study

- To Compute Latitude Temperature gradient (LTG) for calculating SST indices
- To Compute Ekman upwelling indices and chlorophyll indices based on wind data and chlorophyll data.
- To Determine the inter annual variability using upwelling indices.

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- To Predict and map the upwelling areas.

II.STUDY AREA

The study area covers from 8°0'00"E to 15°0'00"E latitude and 66°0'00"N to 76°0'00"N (Fig1). The Arabian Sea is approximately a triangular basin with the largest zonal extent of about 3000km and a slightly smaller meridional extent. The smaller size of the Arabian sea implies that, its coastal regime, stretched along two sides of the triangulate basin occupies up to 25% of total area and hence, the interaction between the coastal and oceanic regimes is quite important.

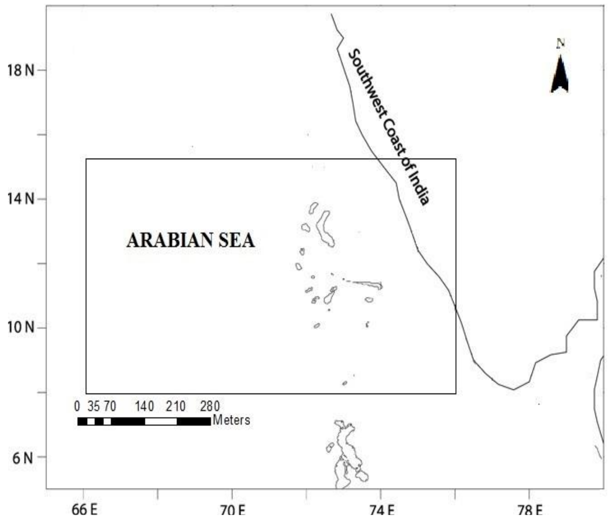

Fig 1-Study Area

The important upwelling zones in the North Indian Ocean are the Somali, the Oman systems, in addition to the SEAS upwelling system of which, the processes associated with each one are more complicated and ecologically significant. By its geographical position, the Arabian Sea can be considered as a tropical oceanic system. Physical processes in the upper 1000 m are seasonal and the upper 100 m are largely wind driven, where as vertical mixing is influenced by the changes in density. Coastal currents become more significant during monsoons.

III. DATAS USED

Monthly day time SST of Moderate Resolution Imaging Spectroradiometer (MODIS) data with 4Km spatial resolution was obtained from PO-DAAC, Jet propulsion laboratory for a period of 7 year, from 2007-2013.Monthly wind data from QuikScat (2007-2013) of 0.25×0.25 degree resolution was also obtained. MODIS monthly Chlorophyll-a concentration of 9km × 9km resolution was obtained from PO-DAAC, Jet Propulsion laboratory. Modified 2 min resolution topography for Indian Ocean was obtained from IODC of NIO, to clearly mark the 200m Isobath lines.

IV. METHODOLOGY

The adopted methodology is shown below (Fig 2)

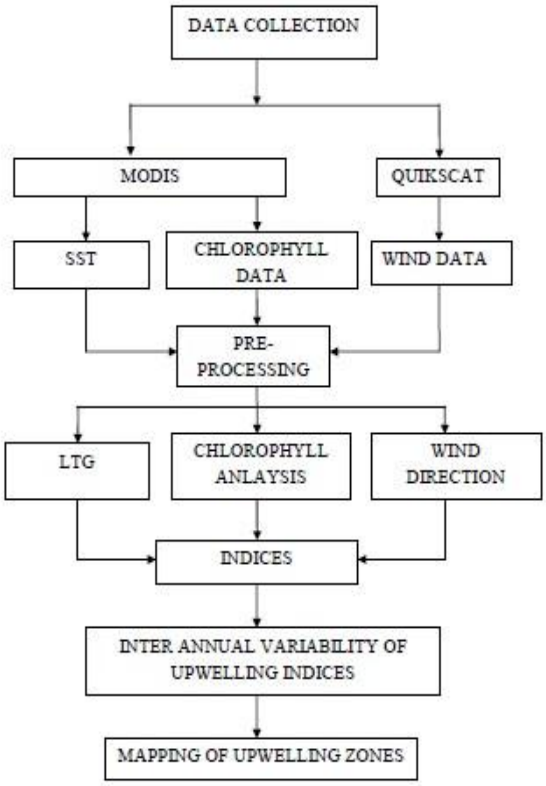

Fig 2 – Methodology-Flow chart

V. RESULTS AND DISCUSSION

5.1 Sea Surface Temperature

The response of the ocean towards upwelling can also be understood in the form of cooler SST. From the analysis, it was understood that March, April and May are the warmest months in the region. Similarly, July, August and September are the coolest.

Direct measurement of upwelling is often difficult due to logistical reasons. A method to quantify upwelling is by making use of 'upwelling indices' as a proxy for the same. SST can be made use of to deduce an index of upwelling. One of the characteristics of coastal upwelling is that the coastal surface water is of lower temperature than that of the surrounding offshore waters. The coastal upwelling index based on SST is defined as the temperature difference between the coastal waters and of those waters which are five meridians offshore, along the same latitude as described in Equation

$$SST_{index}=SST_{on} - SST_{off} \quad (1)$$

5.2 Inter -annual Variability of SST

With the onset of summer monsoon, upwelling starts from the southern tip of India with cooler SST and propagates northward along the coast. From SST climatology, progressive cooling of the ocean surface with each passing month can be observed from June to August. During all the four months [June - September], a patch of warmer waters was observed between the coastal and mid ocean.

During January, the SST in the region varied between 27.5°C at the southern tip of India and northwest corner to 29°C for rest of the region. In February, a patch of warmer

DOI 10.17148/IJARCCE.2016.5110

ISSN (Online) 2278-1021
ISSN (Print) 2319 5940

International Journal of Advanced Research in Computer and Communication Engineering
Vol. 5, Issue 1, January 2016

waters was observed along the southern coast between 8° - 10°N up to 75°E. The northwest corner of the region remained cooler between 27.5°C and 28.5°C. During March, coastal regions up to 73°E were found to be at 29.5°C with a warm patch of 30°C between 9°- 10°N. April and May recorded almost uniform temperature all over the region with temperature above 30°C. The warm patch between 9° and 10°N that was observed during March further rose to 31_C in April and moved offshore in scattered patches by May. The surface cooling signatures were observed in June at the southern tip of India with temperatures less than 28°C up to 10°N along the coast extending up to 75°E from coast. Apart from this, cooler temperatures are also observed between 70° - 71°E and 11° - 12°N. Coastal region to the north of 11°N were maintaining values around 29.5°C. During July and August, the whole SEAS was covered by SST less than 26°C. By September, these cooler temperatures turned slightly warmer to greater than 28.5°C in open ocean region, while the coastal regions remained cooler, less than 28°C. This transition indicated the terminal phases of upwelling. With the seizure of SWM, the region turned warmer by October with SST above 29°C. This warming further intensified in November and uniform temperatures of above 29°C were observed all over the region. A warmer patch of temperature greater than 30°C was observed along the coast between 11° - 14°N. By December, these warmer waters spread further up to 72°E with further reduced the surface temperatures. The inter-annual variability of SST was shown below (fig 3)

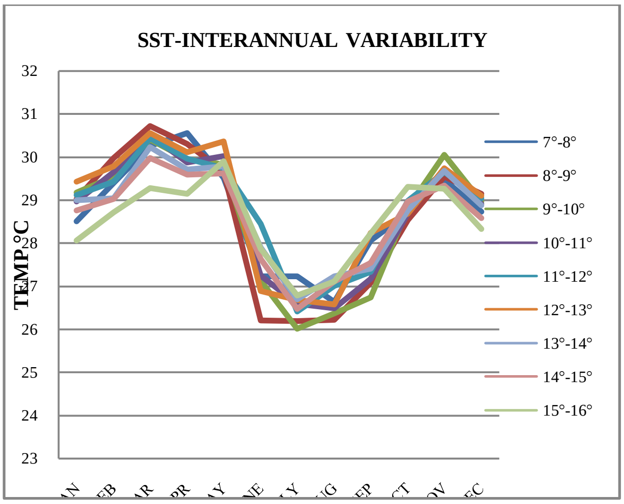

Fig 3 –Inter-annual Variability of SST

5.3 Chlorophyll-a

The response of the ocean towards upwelling can also be understood in the form higher chlorophyll concentrations. From the analysis, it was understood that non upwelling months has less chlorophyll content and during upwelling months the chlorophyll content has increased.

5.4 Inter- annual Variability of Chlorophyll

The satellite measured surface CHLA provides an estimate on the biomass of the region of interest. On examination of the CHLA monthly climatology, it is observed that similar to SLA, CHLA too has a distinct annual cycle. The region shows feeble variability with respect to the CHLA during non upwelling months. For this period, CHLA remained less than 0.5 mg/m^3 all over the region except very near to the coast during the months of January, February, March, April, November and December. For May and October, i.e., during the initial and terminal phases of upwelling, CHLA of 2 - 3 mg/m^3 was observed all along the coast. By June, a strong patch of 5 mg/m^3 CHLA was observed at the southern region of the coast and which spread about 100 km from the coast. This patch extended further north by July coinciding with the peak phase of SWM and the resultant upwelling, northwards. These highly productive waters spread 200 − 300 km offshore, while a maximum concentration was noted between 8° - 10°N during July - September. Two distinct productive fronts can be noticed: one, between 8° - 9 °N and the other between 11°- 12°N. These are also the regions of high river run-off during the rainy SWM season. By August, the frontal regions were subdued and rather uniform CHLA content was observed all over the coast. In the entire open ocean region, CHLA up to 1 mg/m^3 was observed during this period. The same scenario prevailed in September too but with depleted offshore values to the west of 72 °E and south of 12°N. The CHLA content reduced considerably by October, all over the region, and was present only very near to the coast. The entire region stands deprived of measurably productivity by November and December based on CHLA and this was shown in the graph (fig 4).

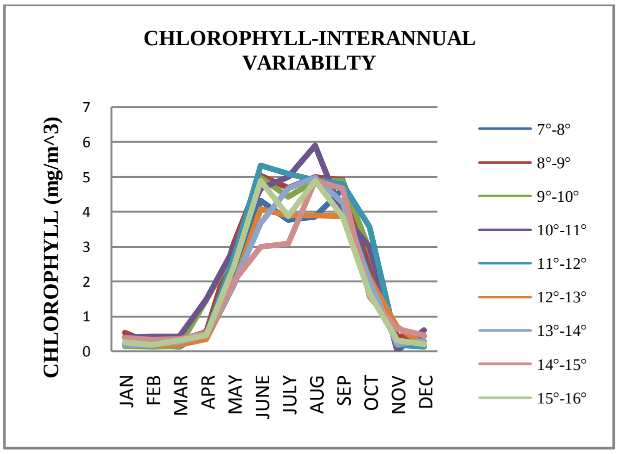

Fig 4-Inter-annual Variability of Chlorophyll-a

5.5 Wind Data

The monthly variability of the wind pattern in the region was obtained for seven years (2007 - 2013) as per the quality data record of QuikScat measured sea surface winds. The resultant 25km x 25km resolution monthly climatological product was utilized to ascertain the mesoscale variability of the wind for the region.

`It can be stated that the wind direction near the coast was northerly (equatorward) irrespective of season. Despite this fact, coastal upwelling in the region was taking place only during the SWM. This is because the alongshore winds that were prevailing during the northeast monsoon does not have adequate strength to drive Ekman transport away from the coast, also the absence of divergent circulation pattern to generate upwelling. Another

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important fact to be reckoned is that the zonal component of the wind varies once a year i.e., during SWM, whiles the meridional component has bi- modal variability and this component of wind functions importantly in coastal upwelling for the region.

5.6 Variability of Wind

The meridional wind stress was predominantly southward near to the coast all most throughout the year. During January and February, the meridional wind stress had a similar pattern with only slight variability in magnitude; maximum northerly stress was noted at the northern end of the region. A small patch of higher order stress was observed near to the coast between 8° and 10°N extending up to 73°E. The meridional (alongshore) wind stress, very near to the coast, was northerly for a significant part of the year. However, the strength of such an along shore wind stress was relatively weak unlike in other places of notable eastern boundary upwelling zones around the world.

5.7 Correlation Between Sst And Clorophyll

From the graphs (figure 5 & 6), it is clearly found that SST and chlorophyll data are less correlated and it satisfies the upwelling condition i.e., SST should be low and meanwhile chlorophyll should be high in the upwelling regions.

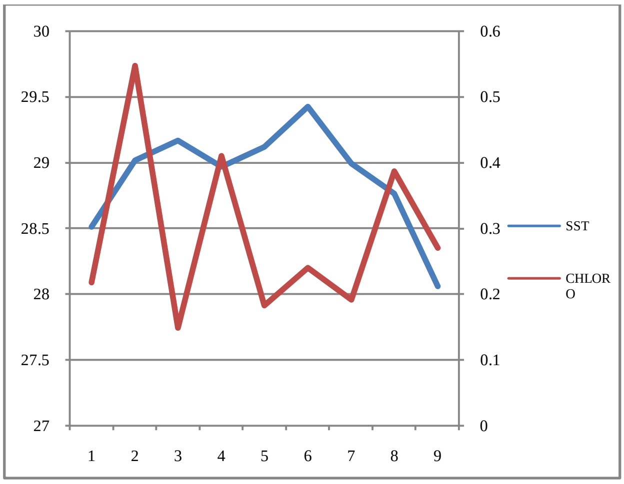

Fig 5- Graph between SST and Chlorophyll

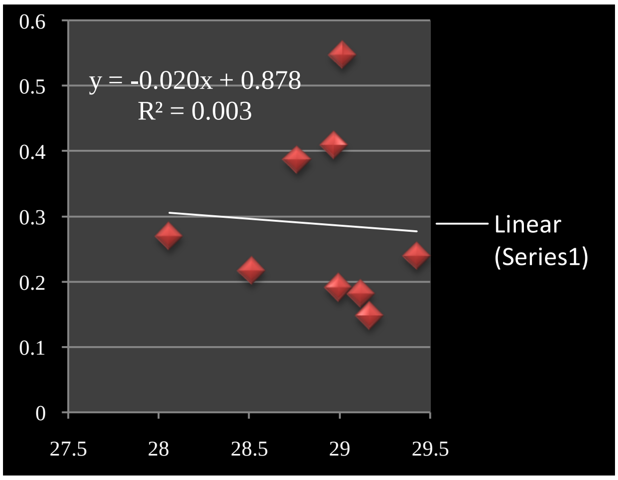

Fig 6- Correlation between SST and Chlorophyll-a

5.8 Upwelling Zone

Through the analysis of series of SST, Chlorophyll-a and wind data, upwelling was found to be predicted at the 8°-12°N latitude and 73°-76° E longitude and the upwelling region is shown in the map (fig 7).

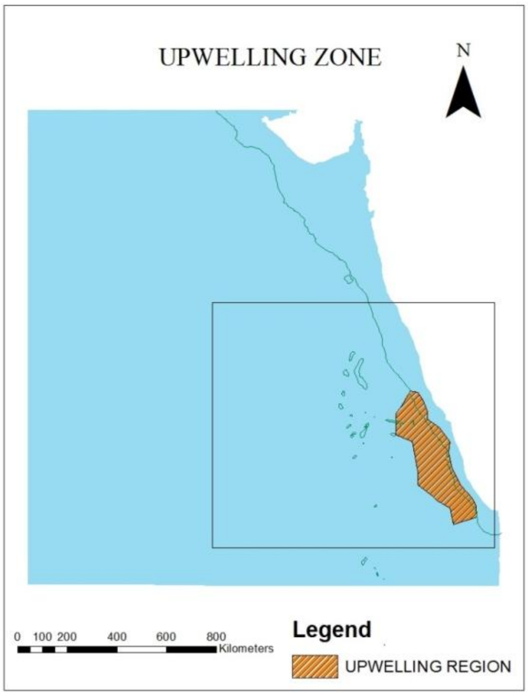

Fig 7 – Upwelling Zone

VI. CONCLUSION

Satellite remote sensing is being effectively used in monitoring the oceans and their variability hitherto unknown, augmenting the in-situ measurement techniques. Advancements in sensor physics as well as in retrieval algorithms have made satellite oceanography an indispensible tool in oceanic research, today. The signatures of upwelling facilitated through remote sensing are cooler sea surface temperatures, high chlorophyll-a concentration, and along shore wind stress. Upwelling along the southwest coast of India is an annually recurring phenomenon that occurs during the southwest monsoon (June to September).

Upwelling in south eastern Arabian Sea commences around May from near the southern tip of India. This extends northward with time and by July, the whole of southwest coast of India from 8°N to 15°N is an up welled region. A fall of 4°C in sea surface temperature is often observed in this region. Factually, the average chlorophyll-a concentration in the region is approximately 4 - 5mg/m^3 during the upwelling season (compared to less than 0.5 mg/m^3 during other seasons). The inter-annual variability of these signatures has also been studied, based on upwelling indices computed from sea surface winds and sea surface temperature. It was observed and reported herein that the maximum extent of upwelling in the south eastern Arabian Sea along the southwest coast of India is approximately up to 300kms from the coast.

ACKNOWLEDGEMENT

I would like to thank PO-DAAC, Jet propulsion laboratory for providing the SST, Chlorophyll-a data for global level. And I also express my gratitude to Institute of Remote Sensing, Anna University for giving me the opportunity to do this project and for their kind support.

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