Chapter 5

Primary Production Associated with Upwelling

"A theory has only the alternative of being right or wrong. A model has a third possibility; it may be right, but irrelevant."

– Egan Manfred

5.1 Introduction

Upwelling and associated advection of nutrient-rich deep water to the surface and the subsequent stabilization of the nutrient-laden water in the euphotic zone by solar heating is the fundamental mechanism supporting the high biological productivity of most of the coastal ecosystems. A predictive understanding of marine ecosystems that is useful to man will be based on a hierarchy of generalizations. The fundamental generalizations relating phytoplankton growth to the nutrient content of seawater
have been established by Redfield (1934), Sverdrup (1953), Pauly and Christensen (1995) and Santos et al., (2007). They have established that broad scale variations in primary production both temporally and spatially are related to variations in the supply of inorganic nutrients and light.

The quantity of PP helps us not only to understand matter and energy bases of PP but also to assess and predict bio-resources, particularly fishery resources. Values of PP are also indicators of environmental quality and ecological contributions in sea water. Higher levels of primary production occur in shallow coastal waters within 200m depth contour. In addition certain offshore waters are influenced by diverging fronts and other hydrographic features which can bring nutrient rich subsurface water into the euphotic zone.

High PP in the SEAS is usually related to coastal upwelling activity that injects nutrients into the euphotic zone in response to prevailing longshore winds and remote forcing from BoB. The composition of these forcings changes zonally due to the factors like varying wind field, bottom topography and orientation of the coast line. The SEAS contributes about 30-50% of the total marine fish catch in India during the upwelling period. The area is colonized by planktonivorous small pelagic fishes like Oil sardines, Anchovies, Indian Mackerals etc. The population of these
species is characterized by significant interannual fluctuations in their abundance and have major place in the SEAS, where they are exploited commercially and play a role as forage fish for numerous predators such as large pelagic fishes, demersal fishes, seabirds, mammals etc. Earlier analysis of long term time series data Longhurst and Wooster (1990) on fish landings suggest the influence of environmental parameters on large scale fluctuations in the fisheries. Especially oil sardines fluctuate highly with the intensity of upwelling. According to Bakun and Roy (1998), Krishnakumar et al., (2008), the spawning and recruitment strategies of clupeoids from the upwelling area were found to be adapted with the spatial and temporal pattern in the upwelling of the region. Longhurst and Wooster (1990) have reported that the success in recruitment of oil sardine fishery is very much depended on the upwelling in the area.

Bakun and Parrish (1982) and Cury and Roy (1989) suggested the concept of Optimum Environmental Conditions or Optimal Environmental Window (OEW) with regard to nutrient enrichment (upwelling or mixing), concentration process (convergence or stratification) and retention process that maintain eggs and larvae in the suitable habitat were found to be crucial for the successful recruitment of clupeoids in the upwelling areas. Despite of their high rate of production, the adverse environmental conditions dur-
ing the upwelling season like, turbulence, offshore advection etc., can create havoc for their larval survival and subsequent recruitment success.

The phase level of the exploitable fishery potential in the SEAS is the upwelling associated primary production in the euphotic column. In order to understand the environmental variability and its influence due to change in environmental conditions, the upwelling intensity and the total PP associated are estimated for the region between 7°N to 16°N latitude and 71°N to 78°N longitude. For a better understanding of the biological response of the process of upwelling during different years the exercise has been done for a consecutive period of seven years (2003 -2009). The objectives of the analysis are to;

1. Study the inter-annual variability in the coastal upwelling of the SEAS with regard to LTA
2. Estimate the total PP associated with the upwelling and
3. Address the inter-annual variability in PP in relation to upwelling.

5.2 Data and Methodology

5.2.1 Upwelling Index from SST

Variation in SST is an accepted index for the process of coastal upwelling as it represents the responding variable of the process
irrespective of the forcing mechanism (Wooster et al., 1976, Prell and Streeter, 1982 and Naidu et al., 1999). This is based on the fact that, the difference in SST of the inshore area (where the subsurface cold water replaces the offshore transport) and the SST of the offshore area directly measures the intensity of upwelling. Though different approaches are suggested by different authors, grids separated by 3° are considered for the LTA estimation in the present study. This interval is chosen based on the analysis of different parameters like SST, surface Chlorophyll a, SSHA, SSS and based on the understanding of the offshore extend of the process in different parts of the SEAS. Also, the region along the Cape and the region between Tvpm and Goa are treated separately. In the former case, the offshore transport is southward whereas in the latter it is westward. Thus along the SW Coast, $LTA_{wc} = T_{lon-3} - T_{lon}$ and Off Cape $LTA_{kk} = T_{lat-3} - T_{lat}$, where $T_{lat}$ and $T_{lon}$ represent SST at the coastal stations between latitudes 8.5°N to 14.5°N and longitude 76.5°E to 78.5°E. $T_{lon-3}$ and $T_{lat-3}$ represents SST at 333 km away from the coast. $LTA_{wc}$ and $LTA_{kk}$ refer to LTA along the southwest coast and along the Cape. The positive LTA values suggest the coastal upwelling process.

The data for the period 2003-2009 are considered for this analysis. Monthly 9X9 km resolution data are derived from MODIS AQUA and is processed using SeaWiFS Data Analysis System (Sea-
5.2.2 Model Description

5.2.2.1 Vertically Generalised Production Model (VGPM)

VGPM is a "Chlorophyll-based" model that estimates net primary production from Chlorophyll $a$ using a temperature dependent description of Chlorophyll $a$ specific photosynthetic efficiency (Behrenfeld and Falkowski, 1997a). For the VGPM, net primary production is a function of Chlorophyll $a$, available light, and the photosynthetic efficiency. Standard products are based on SeaWiFS/MODIS Chlorophyll $a$, MODIS AQUA SST data, and SeaWiFS PAR. The euphotic zone depths are estimated from a model developed by Morel and Berthon (1989) and based on the surface Chlorophyll $a$ concentration.

\[ PP_{eu} = 0.66125P_{op}B_{E_0/E_{E0+4.1}}CSAT \times Z_{eu} \times D_{IRR} \]

The core equation describing the relationship between surface Chlorophyll $a$ and depth integrated primary production is expressed as follows:

$CSAT$ is satellite surface Chlorophyll $a$ concentration as derived from the measure-
5.2. Data and Methodology

measurements of water leaving radiance \( (mg/m^3) \).

VGPM calculations of net primary production were based on monthly average \( C_{SAT} \).

\( D_{IRR} \) is daily photoperiod (in decimal hours) calculated for the middle of the month for each pixel based on the algorithm developed by Meeus Jean (1991)

\( E_0 \) is Sea surface daily Photosynthetically Active Radiation (PAR) in \( mol \ quanta/m^2/d \).

\[ Z_{eu} = \begin{cases} 
568.2(C_{TOT})^{-0.746} & \text{if } Z_{eu} < 102 \\
200.0(C_{TOT})^{-0.293} & \text{if } Z_{eu} > 102 
\end{cases} \]

\( Z_{eu} \) is the physical depth (m) of the euphotic zone defined as the penetration depth of 1% surface irradiance based on the Beer-Lambert law.

\( Z_{eu} \) is calculated from \( C_{SAT} \) following Morel and Berthon (1989). Where

\[ C_{TOT} = \begin{cases} 
38.0(C_{SAT})^{0.425} & \text{if } C_{SAT} < 1.0 \\
40.2(C_{SAT})^{0.507} & \text{if } C_{SAT} \geq 1.0 
\end{cases} \]

\( P_{Opt}^B \) is optimal rate of daily carbon fixation within a water column \( [mgC(mgChl)^{-1}h^{-1}] \) and can be modeled according to various
temperature dependent relationships.

\[
P_{Opt}^B = \begin{cases} 
1.13 & \text{if } T < -10 \\
4.00 & \text{if } T > 28.5 \\
\text{otherwise} & 
\end{cases}
\]

\[
P_{Opt}^{B'} = 1.2956 + 2.749 \times 10^{-1}T + 6.17 \times 10^{-2}T^2 - 2.05 \times 10^{-2}T^3 + 2.462 \times 10^{-3}T^4 - 1.348 \times 10^{-4}T^5 + 3.4132 \times 10^{-6}T^6 - 3.27 \times 10^{-8}T^7
\]

The \( PP_{eu} \) is the daily carbon fixation integrated from the surface to \( Z_{eu} \), (mgC/m²)

5.2.2.2 Validation Against the In Situ Data

Chlorophyll a

Depth integrated monthly composite Chlorophyll a data for the SEAS during SM, are generated in 9X9 Km spatial resolution using ocean color data. Daily photoperiod (in decimal hours) are calculated for the middle of the month for different latitudes from (Meeus Jean 1991) astronomical algorithms. Satellite derived Chlorophyll a data are then validated with corresponding in situ data on Chlorophyll a collected onboard FORV Sagar Sampada (45 stations) covering different phases of SM of the year 2009, following the methods described by Strickland and Parsons (1972). The relationship was weak (\( Chl_{sat} = 0.511Chl_{insitu} - 0.099 \))
with $R^2 = 0.507$ possibly due to the poor satellite coverage of the area due to cloud cover. SM data sets from SeaWiFS/MODIS AQUA are validated and corrected using the above formula. Calculated values of Chlorophyll $a$ are then utilised in the further computations of PP.

**Primary Productivity**

Validation of VGPM based estimates of PP with in situ PP by $^{14}C$ technique (122 UNESCO, 1994) from 25 stations of FORV Sagar Sampada cruises 235 and 237 along the EAS during different phases of SM gave $R^2$ of 0.757 (Fig.5.1) indicating good relation between the two measurements. Thus the linear validation relation between the in situ as well as satellite PP is derived as

$$PP_{sat} = 0.9PP_{insitu} + 107.3.$$
5.3 Results and Discussion

5.3.1 Upwelling- Inter Annual Variation

Inter annual variation in the process of coastal upwelling is of great concern since it contributes to variation in biological productivity. It is important in the estimation of fishery resources and thereby for an effective and sustainable management of the marine resources. The present analysis is based on the upwelling indices derived from SST, for the years 2003 to 2009 (Fig.5.2).

Considerable variability in both time and space is seen in the data with stronger upwelling in the southern regions. During the years 2005, 2006, 2008 and 2009 strong upwelling is recorded in the southernmost region of Cape, and is maximum during 2008 with LTA 3.3°C. In the remaining years, 2003, 2004 and 2007, the Cape-Kollam section showed intense upwelling suggesting a controversial result to the explanation of the shadow zone in the area.

This maximum intensity in the shadow zone can be due to the strong positive wind anomaly during the years where the average magnitude is greater than 7.2 m/s (Jayaram et al., 2010). Wind stress of weak alongshore and strong cross shore component as reported by him substantiate the strong upwelling off Cape during the years 2005 and 2006. It is noted that in all the years, the
initiation of the process of upwelling is along the Cape or within the Cape-Kollam sector (Fig. 5.2.).

The process is comparatively weak along the Kollam-Mangalore and Mangalore-Goa sectors and along the former it is observed to be starting in the end of June/July with certain lag. Whereas along the Mangalore-Goa sector, the process starts with the onset of SM in June, possibly due to the predominance of upwelling favorable winds. Considerable inter annual variability persists in these two regions, recording strong upwelling during 2003, 2004 and 2008. The process is weak along the Mangalore-Goa sector during 2006 ($LTA = 1^\circ C$), and a delayed strengthening was recorded during 2005 and 2009. Altogether, the process of upwe-
lling is weak along the northern sections compared to the southern tip as well as the Cape-Kollam sector. Also, the drastic decrease in the intensity of upwelling off Cape and off Cape-Kollam sector during September 2005 and August 2007 fails to explain the normal trend in the process along the region. The present analysis does not agree with Habeeb et al., (2008) along the Tvpm-Goa sector pointing out that upwelling and the associated production is stronger/higher off Kochi. It is assumed that the region wise grouping in the present study have accommodated the strong upwelling of Kochi.

Ecosystem averaged upwelling measures are computed for this period and compared with the seven years climatological average. This is derived from the upwelling indices calculated separately for each latitudinal transects for the four SM months and averaged to a single entity to get a representative figure for the entire ecosystem. The average index for the ecosystem for a period of seven years is found to be $0.64^\circ C$ (Table 5.1). Stronger upwelling is recorded in 2008 ($0.68^\circ C$) followed by $0.67^\circ C$, $0.66^\circ C$ and $0.65^\circ C$ for the years 2004, 2005 and 2009 respectively, which are above the normal value of $0.64^\circ C$. Whereas an index value of $0.59^\circ C$, $0.62^\circ C$, and $0.58^\circ C$ represents the weak upwelling years of 2003, 2006 and 2007. The weak upwelling recorded during 2003 can be due to the weak SM wind as reported by Vinayachandran.
Table 5.1: Upwelling Indices (LTA)-Average for the SEAS

(2004) particularly in the onset phase. In contrary, 26 Gopalakrishna et al., (2008) reported that the upwelling during 2005 is the strongest and prolonged one for the period of his study (2002-2006). This contradiction may be due to the restriction of his study region to Kochi transect, with which the whole ecosystem of SEAS cannot be represented.

5.3.2 Primary Production - Inter Annual Variation

The monthly average PP per day associated with the SEAS upwelling (VGPM derived using satellite data) for the years 2003 to 2009 for each sub regions and the total PP for the whole ecosystem in million ton Carbon (MtC) are presented in Table 5.2. Considerable inter annual variation is noticed in all the four regions and preliminary analysis indicate the existence of one-to-one relation...
Table 5.2: Year wise/sub region wise and total PP for the SEAS

between PP and the ecosystem averaged upwelling indices. Maximum PP estimate of 39.76 MtC is recorded in 2004, associated with the second strongest upwelling period. During other years, the values fall in the range of 24.78 MtC (2003) to 29.97 MtC (2006), with two abnormal values of 39.76 MtC (2004) and 20.54 MtC (2008). The unexpected low PP value associated with the strong upwelling year of 2008 is due to the non-availability of data during June, August and September and so is not considered in the present analysis.

Interannual variation is prominent in the region wise average PP per day (Table 5.2) recording high values off Cape, followed by Cape-Kollam region. Maximum value recorded off Cape is 1047.65 mgC/m²/d, during 2004, followed by 926.11 mgC/m²/d, in
2005 and 772.85 mgC/m²/d, during 2009. The minimum PP measure of 555.38 mgC/m²/d, recorded during 2007 is associated with the weak upwelling. Along Cape-Kollam sector, maximum PP is 793.19 mgC/m²/d, recorded in 2004, followed by 764.91 mgC/m²/d, in 2005 and 761.88 mgC/m²/d, during 2009. The value of 578.34 mgC/m²/d, recorded during 2007 is the lowest in the section. The pattern is different along the Kollam-Mangalore sector except that, the year of maximum production was same as that of the other regions (2004 with PP values 930.44 mgC/m²/d). In this region the second highest PP of 666.35 mgC/m²/d, is recorded during the year 2006 followed by 635.59 mgC/m²/d, during 2007, which coincides with the below normal upwelling years. High PP of 743.42 mgC/m²/d, during 2004 is observed along the Mangalore - Goa sector followed by 734.25 mgC/m²/d, in 2007 and 702.07 mgC/m²/d, during 2006. Also, this region recorded minimum production of 293.38 mgC/m²/d, during 2003.

Region-wise month-wise PP averaged for 2003 to 2009 is shown in Table 5.3. The values varied in a small range between 600.37 mgC/m²/d, and 808.94 mgC/m²/d, except during the onset phase along the two northern sectors off Kollam - Mangalore (367.02 mgC/m²/d,) and Mangalore - Goa (594.65 mgC/m²/d,). This clearly indicates the northward progress of the process of upwelling with the advancement of the SM winds.
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<table>
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<tr>
<th>Sub-region</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Sep</th>
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<td>808.9438</td>
<td>792.1396</td>
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<td>636.3794</td>
<td>636.4887</td>
<td>600.3704</td>
<td>617.2899</td>
</tr>
</tbody>
</table>

Table 5.3: Region wise - month wise long term averaged PP ($mgC/m^2/d$)

Both along the Cape and Cape-Kollam sectors, enhanced PP are observed in the start of the SM month itself showing PP values of 782.52 $mgC/m^2/d$, and 686.97 $mgC/m^2/d$, respectively. The high values of PP recorded during July and August indicates that the upwelling is well established in all the sections by July. All the four sub-regions showed high rate of production during July-August and starts to decrease during September. The region off Cape is marked as the high productive zone with a seasonal average of 796.48 $mgC/m^2/d$, followed by Cape - Kollam (690.79 $mgC/m^2/d$), Mangalore - Goa (617.29 $mgC/m^2/d$) and Kollam - Mangalore (592.30 $mgC/m^2/d$).

Further, detailed analysis of the monthly average PP for all the years between 2003 and 2009 (Fig.5.3) has been done separately for each sub-region. The interannual variation was evidenced in monthly pattern along different sub regions. The analysis was done subjected to the three phases of upwelling in different sub-regions considering June as the onset phase, July-August...
5.3. Results and Discussion

as peak phase and September as the withdrawal phase.

Along the Cape, PP during the onset phase of June was considerably less in 2003 (470 mgC/m²/d) as compared to the remaining years. Along the Cape-Kollam section the values were in the range of 480-800 mgC/m²/d, which is less as compared to Cape region. Along Kollam-Mangalore section the range was still less (400 mgC/m²/d to 720 mgC/m²/d) and the maximum value is recorded during 2004. In the northern most sectors along Mangalore - Goa it further decreased to the minimum range of 200 mgC/m²/d to 600 mgC/m²/d during 2003 and 2004 respectively.

The months of July and August were observed as the maximum production (600 mgC/m²/d to 1000 mgC/m²/d) period in all the sub regions except for the year 2003. Less production is marked during July 2003 (average for all the sub regions was 487 mgC/m²/d), compared to other years. This can be due to the delayed SM winds during the onset 2003, as explained by Vinayachandran (2004). Cape and the Cape-Kollam sections are the high production zone during all the years, except the weak upwelling year of 2007 where the high production is marked in the Mangalore-Goa stretch.

During September, the production showed a general decreasing trend except during 2006 and 2008 indicating the weakening of the process of upwelling has not taken place during these
years. The average PP for all the sub-regions during the month recorded between 350 \( mgC/m^2/d \) to 800 \( mgC/m^2/d \). And the highest value of 1100 \( mgC/m^2/d \) is recorded along the Cape during 2004. As observed in the other months, maximum production observed during September is along the Cape followed by Cape-Kollam sector, except the year 2007.

In brief, there exists a one-to-one relation with the intensity of upwelling and the total PP associated with it. The northward progression of the process of upwelling with the advancement of SM wind is evidenced in the PP pattern also. The southern sections (Cape and Cape-Kollam region) are shown as high productive regions among the four except during 2007, the weak upwelling year where the northern transects showed high PP values.

The relation between the UI and the corresponding PP for each latitudinal transects and for the SM months (June-September) were made to regression analysis, and the relation is found to be relevant with \( R^2 = 0.575 \) (Fig. 5.3) for an optimum values of UI and PP and the relation is \( PP = 179.2UI + 287.4 \). In detail, the relation does not hold well for anomalous PP values and for very strong LTA values which may be associated with algal blooms or the strong offshore transport.
Figure 5.3: Distribution of monthly averaged PP in \( \text{mgC/m}^2/\text{d} \) for SM months in each sector during 2003-2009.

Figure 5.4: Relation between UI and PP for 2003-2009.
5.4 Conclusion

Many studies have come out with emphasize on the physical processes and associated chemical and biological implications. This study attempts an integrated approach relating the physical forcing and biological responses associated with the SEAS. It is shown that there exists a one-to-one relation with the intensity of upwelling and the total PP associated with it. The northward progression of the process of upwelling with the advancement of SM wind is evidenced in the PP pattern also. The Cape and Cape-Kollam sub-regions are shown as high productive areas among the four sub-regions considered. In addition, an attempt to derive theoretical basis of the relation between the response variable $LTA$ and the biological production PP has been done by analysing seven years of satellite/model data on UI and PP. Thus it can be estimated that for an optimal upwelling period, the PP associated with it can be formulated as $PP = 179.2UI + 287.4$. The estimation was done after validation/correction of satellite Chlorophyll a and the modeled PP data against the in situ data collected. Furthermore, the study explored the extensive possibilities of satellite measurements on ocean color (Chlorophyll a) and PP, as the in situ PP data available are of low resolution with regard to space and time. It recommends the reliability and usability of satellite-modeled PP data in the region.