

**Step-up Multiple Regression Model to explain Chlorophyll *a* production
in the coastal waters off Cochin, southwest coast of India**

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Abstract

The interacting effects of abiotic processes in explaining variations of phytoplankton biomass in a coastal marine region off Cochin are evaluated. The control of environmental forcing on phytoplankton production and its relation on various interaction effects are reinforced to outline a predictive ecosystem model for the southwest coast of India. The first-order interaction effects between parameters are found to be highly critical since in biological activities, competition between abiotic species, which is difficult to measure directly, can be replaced by interaction between nutrient-factors. The present study by multivariate statistical analysis shows that the inter-relationships between phytoplankton variability and nutrient factors are highly sensitive to seasonal periodicity. The step-up multiple regression model explain chlorophyll *a* up to 77% variability for non-monsoon periods and show that these coastal waters sustaining vertical gradients, are capable of inducing primary production through a variety of direct as well as interaction effects among the environmental variables. This study also indirectly suggests that grazing of zooplankton and supply of particulate organic matter either from the adjoining watershed or the periodically activated mudbanks of this region regulate the nutrient dynamics of these coastal waters, and their contribution should be duly considered for an effective ecological model to predict primary production. Despite the complexity of the interactions between nutrient availability, phytoplankton biomass and an equally important zooplankton grazing (not included in the present study), the results showed that it is possible to disentangle environmental processes causing observed trends in standing stock using multivariate statistical analysis during non monsoon period and improves our understanding of the governing role of environmental variables upon phytoplankton variability in Indian coastal waters.

Author Keywords: Nutrient interactions, Phytoplankton, mudbanks, Cochin backwaters, multiple regression analysis.

1. Introduction

The availability of nutrients in the euphotic zone and the subsequent biological response is the basis of any biochemical model for a coastal marine system. It is recognized that the physico-chemical characteristics prevailing in the water column play an important role in selecting the size structure of the phytoplankton community (Malone, 1980; Platt, 1983; Chavez, 1989; Legendre and Le-Ferre, 1989). Biomass of phytoplankton in the seas in terms of chlorophyll *a* concentration is one of the most widely accepted methods in the study of primary production as it indicates total plant material available in the water at primary stages of food chain (Weyhenmeyer et al. 1999). The spatial and temporal gradients in environmental parameters offered by the coastal waters of Cochin make this ecosystem suitable for examining the relationship between physico-chemical parameters and phytoplankton, which forms the main objective of the present study. The coastal region of Cochin in an area of approx. 2500 km² is studied for changing seasons to derive the salient features that characterize its productivity in this coastal environment. The study aims to achieve a) controlling and interactive factors of abiotic nature governing changes in phytoplankton biomass and b) inter-relations between nutrient manipulation and phytoplankton dynamics of the coastal waters of Cochin with respect to seasonal periodicity permitted by more powerful multivariate statistical approach.

2. Material and methods:

2.1. Environmental setting of the study region

Cochin is the second largest city along the west coast of India situated at the tip of one of the largest wetlands of the country (Vembanad Lake). The lake was formed in the 14th century AD following a catastrophic deluge modifying the drainage area of the six rivers to the present state, retaining its pristine glory for rich biodiversity till the later part of 19th century (Gopalan et al., 1988). There has been a growing deterioration in the environmental condition of this lake since 1970s, particularly towards the lower reaches of the lake known as Cochin backwaters, due to increased human settlements and industrialization (Balachandran, 2001). Thus, the coastal waters of this region are significant in two ways, as the recipient of approximately 19,000 Mm³.y⁻¹ of waters from the Cochin backwaters (Srinivas, 2000) and as the unique region occupying the well-known *mudbanks*, which are store houses of primary nutrients, attracting immense

fishery during southwest monsoon (Varma, Kurup, 1969; Sylas, 1984; Joseph Mathew et al, 1995, Balachandran, 2004).

The present study is based on the environmental properties of coastal waters of Cochin, surveyed during 3 critical seasons viz; October (fall intermonsoon), November (wintermonsoon) and February (late wintermonsoon) between 1997 and 2000. The locations of stations were so selected that during October, as many as 56 stations of 7 transects were sampled from about 500 km² (between 9° 51' and 10° 09' N Lat., 76° and 76° 18' E Long.) area of coastal region (Figure 1). October is selected for sampling because it is during this short time that the coastal currents reverse their direction from south to north, with all possibility of developing a net resident and stratified water mass, and the presence of upwelled waters combined with fresh water discharge from the backwaters cause stratification. As the stratification is not felt once the monsoon withdraws, study area has been extended to the southern region, stretching to about 100 x 25 km² area during February and November (between 9° 12' and 10° 12' N Lat., 76° and 76° 24' E Long.) and 45 stations of 9 transects. The pace of each survey was such that 5 stations are sampled in a day, thus consuming about 9 to 10 days to cover the entire region.

2.2. Sampling and analytical procedures

Water samples from surface, mid and near-bottom were collected using all-plastic 5-litre Niskin samplers (Hydrobios-Kiel). Temperature and pH were recorded *in situ* and samples for dissolved oxygen were collected separately. Water samples for the analysis of salinity and nutrients were collected in pre-cleaned polythene bottles and kept in iceboxes till analysis at the shore laboratory, within hours of collection. One litre each of water samples collected from surface and bottom from all the stations were kept in iceboxes, filtered through Whatman GF/C filters and Chlorophyll *a* was extracted with cold 90% acetone and estimated spectrophotometrically (UNESCO 1966). The nutrients (nitrite, nitrate, phosphate, ammonia and silicate) were analyzed immediately after filtering through Whatman No.1 filter papers, following standard procedure (Grasshoff et al., 1983) using a double beam Spectrophotometer (*Hitachi U-2000*) after proper calibration.

2.3. Statistical analysis (Step-up multiple regression analysis):

Chlorophyll *a* can be related to the environmental parameters by means of linear regressions, though it provides only the prediction efficiency of a single factor at a

time. The interaction effects of a number of abiotic factors on planktons are very important in an ecosystem. Method of choosing the minimal set of environmental variables that can explain the variation in the affected parameter (Pedersen et al., 1995), and the Monte Carlo permutation test that replaces the F test or the test in forward selection in univariate multiple regressions were adopted earlier (Ter Braak, 1990). It has been stated that modeling the dependent variable on the individual effects of the environmental parameters alone would become an artifact on the production relation (Evonne et al., 1995). A modern approach to explore the possible influence of various environmental variables on phytoplankton dynamics is the application of a multivariate statistical analysis (Lau; Lane, 2002). These methods are widely used in ecological studies and have proved to be useful for understanding interactions between ecological factors that influence plankton communities in highly complex systems. Here, an attempt is made to include the individual factors and first order interaction effects of the environmental parameters viz; temperature, salinity, dissolved oxygen, nitrite, nitrate, ammonia, phosphate, silicate and pH to relate chlorophyll *a* concentration in the predictive model. A step-up multiple regression analysis is applied using phytoplankton (chl. *a*) as the dependent variable and direct and first order interaction effects of the above listed environmental parameters as the independent variables, to examine the controlling role of any particular parameter or group of parameters on phytoplankton biomass. The multiple regression model fitted is of the form

$$Y = a_0 + \sum_{i=1}^k a_i X_i + \sum_{i=1}^k \sum_{j=1}^k (X_i * X_j) b_{ij} \dots\dots\dots (1)$$

Where a_i and b_{ij} , $i, j = 1, 2, \dots\dots\dots k$, $i < j$ are the regression coefficients. Independent variables as well as dependent variables are standardized using the transformation,

$$Z_i = (X_i - \mu_i) / \sigma_i \quad \text{for independent variables and } \dots\dots\dots (2a)$$

$$Z = (Y - \mu) / \sigma \quad \text{for dependent variable } \dots\dots\dots (2b)$$

where μ_i (μ) = arithmetic mean (mean of X_i (Y)) and σ_i (σ) is the standard deviation of X_i (Y). The regression coefficients are called standard partial regression coefficients or the relative importance of the independent parameters. The model has been fitted by least square method considering the parameters and also their interaction effects of first order as the independent variables. The significance of the regression coefficients are tested using the Students' 't' statistic

$$t_i = a'_i / S_{ei} \text{ and } t_{ij} = b'_{ij} / S_{eij} \text{-----(3)}$$

where a'_i is the estimated value of the i^{th} regression coefficient and b'_{ij} is the estimated value of the $(ij)^{\text{th}}$ interaction effect, S_{ei} and S_{eij} are the standard errors of the regression coefficients.

$$S_{ei} = S (C_{ii})^{1/2} \text{-----(4)}$$

where S^2 is the deviation mean square and C_{ii} is the i^{th} diagonal element in the inverse of the matrix of sum of squares and products (Snedecor and Cochran, 1967).

When k parameters are considered there will be $k(k-1)/2$ interaction effects and total number of parameters for the model will be $k + k(k-1)/2$, ie; $k(k+1)/2$ and total number of regression models fitted is (2^k-1) . The regression model of Y (dependent variable) on all the parameters (individual effects only) is also determined. From these 2^k predictive models (2^k-1+1) , that model with highest value for the explained variability (V.E) is calculated as,

$$V.E = [1 - MDSS / MTSS] * 100 \text{-----(5)}$$

where MDSS = Mean deviation sum of squares and MTSS = Mean total sum of squares, is considered. Further, the above analysis is repeated with different transformations for Y and X_i^s as

$Y \text{ on } X_i^s$	$\log Y \text{ on } X_i^s$	$\log Y \text{ on } \log X_i^s$
$\sqrt{Y} \text{ on } X_i^s$	$\sqrt{Y} \text{ on } \sqrt{X_i^s}$	$Y \text{ on } \sqrt{X_i^s}$

Thus, a variety of $2^9 \times 6 = 3060$ models are altogether fitted to choose the best predictive model for each case. Among these that model which explains the maximum variability is considered as the best predictive multiple regression model where the insignificant regression coefficients (parameters) get deleted based on the t statistic.

Lohrenz et al (1990) has observed that the transit time for the entrainment of fresh nutrient-rich water to the salinity range where biomass and productivity peak is very short relative to the nutrient uptake. It has been argued that even time-series data, collected through monitoring programs, inherently have characteristics that violate basic assumptions of parametric procedures, and necessitate the use of non-parametric procedures (Momen et al., 1996). Our sampling procedure also has some reservations in that; each survey is spanning about 9-10 days (approx. 5 stations in one day). Thus, the inconsistency in measuring the real impact of nutrient-chlorophyll transformation is compensated by the fact that life cycle of phytoplankton is a matter of a few days (less than a week; Reynolds, 1984) leading to minimal collinearity. Preliminary data manipulations including separate analysis of seasonal data, utilization of mean seasonal values to standardize the data and minimize serial dependence, and standardization to mean zero and variance one, precluded the need for non-parametric procedures. Further, the step-up multiple regression analysis is an exploratory procedure that is sufficiently powerful to detect both abrupt and gradual patterns, though it may not necessarily signify cause and effect that actually occur (Ludwig, Reynolds, 1988).

3. Results : The step-up multiple regression model

The predicted chlorophyll *a* values based on equations 8 to 11 (Table.1) respectively are superimposed as filled contours for respective layers in figure 2, along with the observed chlorophyll *a* (lines). There is remarkable agreement between the observed and predicted values especially during February (bottom) and November (surface and bottom), with the explained variability as 69.21, 77 and 77.42 % respectively, while February surface chlorophyll showed the least explained variability (37 %). A predictive phytoplankton model for these coastal waters for all season emerged insignificant, as the combined analysis of environmental data for the three seasons ($n = 300$) gave only 13 % explained variability ($F_{(15,284)}=2.885$, $P<0.05$). The main reason for this may be due to an upset by seasonality, where the west coast of India experiences upwelling during June to October inducing strong stratification (Naqvi et al., 2000). A generalization pursued by leaving out the monsoonal data and treating February and November as combined ($n=188$) non-monsoon also could explain only 19 % of the variability, possibly indicating that the

nutrient availability and their interactions are too sensitive between winter and late winter.

Alternatively, pooling all the surface and bottom water quality during each period evolved an empirical model given by equations 12 and 13 (Figure 3), predicting the observed chlorophyll *a* values during both November (VE= 31.27 %, *r* = 0.49) and February (VE= 30.95 %, *r* = 0.48). The equation for February (12) is based on standardized values of square root transformed values of Chlorophyll *a* on standardized values of square root transformed values of parameters ($F_{(28,65)} = 2.5111$, $P < 0.05$, $n=94$) and for November (13) based on standardized values of log-transformed values of chlorophyll *a* on standardized values of log-transformed values of parameters ($F_{(21,72)} = 2.9803$, $P < 0.05$, $n=94$).

$$\begin{aligned} \text{Chl.}a = & \{0.6597 \text{ pH} + 0.4637 \text{ NO}_2 + 0.2121 \text{ NO}_3 + 0.2388 \text{ S} \cdot \text{NH}_4 + 0.2926 \text{ PO}_4 + \\ & 0.6050 \text{ pH} \cdot \text{S} + 0.8282 \text{ pH} \cdot \text{DO} + 0.5975 \text{ pH} \cdot \text{NO}_2 + 0.3575 \text{ pH} \cdot \text{NO}_3 + 0.1133 \\ & \text{NO}_3 \cdot \text{NH}_4\} \\ - & \{1.3618 \text{ pH} \cdot \text{NH}_4 + 0.3858 \text{ pH} \cdot \text{PO}_4 + 0.4473 \text{ S} \cdot \text{DO} + 0.2755 \text{ S} \cdot \text{NO}_2 + 0.2156 \\ & \text{S} \cdot \text{NO}_3 + 0.1939 \text{ DO} \cdot \text{NO}_2 + 0.4881 \text{ DO} \cdot \text{NO}_3 + 0.4667 \text{ S} + 0.2253 \text{ DO} + \\ & 0.2821\} \text{ --- (12)} \end{aligned}$$

$$\begin{aligned} \text{Chl } a = & \{0.08513 + 0.2287 \text{ NH}_4 + 0.2391 \text{ T} \cdot \text{pH} + 0.1174 \text{ T} \cdot \text{NH}_4 + 0.3586 \text{ pH} \cdot \text{SiO}_4 \\ & + 0.1492 \text{ PO}_4 \cdot \text{SiO}_4\} \\ - & \{0.3855 \text{ NO}_3 \cdot \text{PO}_4 + 0.1410 \text{ T} + 0.1782 \text{ pH} + 0.3179 \text{ NO}_3 + 0.5593 \text{ SiO}_4 + \\ & 0.1337 \text{ pH} \cdot \text{NO}_3\} \text{ -----(13)} \end{aligned}$$

The low variability explained also cautions that apart from seasonal changes, vertical gradients are to be considered for attaining perfection in coastal ecosystem modeling.

4. Discussion: control of abiotic processes on phytoplankton variability

The predictive models of multiple regression analysis using equation (1) are formulated to show the significant relation between the environmental variables, their interaction effects and Chlorophyll *a*. For interpretation purposes, the model parameters are arranged in descending and clockwise manner based on their relative importance (> 20%) for surface and bottom during different seasons (Figure 4). It summarizes the intensity of particular environmental (abiotic) variables upon chlorophyll *a* and suggests that there is a strong temporal heterogeneity in controls upon phytoplankton

biomass. Regarding the Chlorophyll *a* distribution, the 9 environmental factors play selective roles, either as controlling or limiting factors, while their interaction (*) effects are more decisive. The overall results show that more variables fall in a relation with phytoplankton in winter (November) and late winter (February), possibly indicating their reflex to environmental variability as compared to monsoon season. The interaction effect of PO₄ with NO₃ determines the outcome of interspecific competition at different nutrient concentrations, because the intakes of these parameters are species specific to a great extent (Kautsky, 1981). As the present study does not reflect this interaction effect, it could be assumed that the pigment production in these coastal waters is not controlled by this interaction: i.e. availability of these nutrients is not restricted. Temperature is obtained as an important factor for this model during February (Figure 4.d) and November (Figure 4.e,f), suggesting that temperature sets the condition for optimal metabolic activity, proportional to the abundance of flagellates and succession of diatom species (Fisher and Gray, 1983). This also underlines the fact that primary productivity is a function of surface irradiance (Platt, 1986). With an unexplained variability of < 25% observed during November, it can also accommodate the view that the physiological variability like responses to variations in nutrient availability, temperature and salinity, has primary control while photoperiod has a secondary control on phytoplankton production (Brian Ecole and James E.Cloeran, 1987). In some cases, as inferred in Table.1, limiting factors are found to be more important than controlling factors. Surface salinity during fall Intermonsoon (October), thus form the dominant factor limiting the production of phytoplankton, as evident from the increased estuarine input freshening the surface layers to < 25 psu (Balachandran, 2001). Similarly, the same study observed persistent upwelling in the sub surface layers characterized by oxygen-deficient (< 1.4 ml/l) and nitrite-replete (> 1.2 µM) waters. These features possibly infer the limiting role played by DO and NO₂ in the bottom waters during October (Table.1). Since (NO₂*NO₃) interaction is obtained as one of the limiting factors during November (Figure 4.f), it follows that the growth of phytoplankton is often controlled to a certain extent, by the supply of ammonium excreted by zooplankton and members of higher trophic levels (Kiefer and Atkinson, 1984). Since nitrogen compounds and DO are obtained as important factors (Figure 4), it means that they are also brought into the medium by decomposition of particulate organic

carbon (Robinson et al., 1982). The controlling effects of pH and the interaction effects of pH with NH_4^+ , NO_2 , DO, T and NO_3 are also found to be vital factors in primary production. Similarly, pH and salinity are found to be a dominant and interaction factors in the present study region (Figure 4.f), a feature that was not reported for the Arabian Sea (Jayalakshmy, 1998). This may probably be associated with the greater land-sea interaction and also due to the fact that the biological production induced by chemical changes in coastal zones far exceed that of the oceanic region.

It is worth mentioning here that while this predictive model for the Arabian Sea could explain only less than half the variability in primary production (for 21 parameters and excluding pH), the same analysis in the present study (especially during November and February) could explain more than 70 % of the variability (Figure 2). Higher variability explained implies a more stable environment. This also consolidates the view that, in spite of seasonal fluctuations associated with monsoon, these coastal waters are more stable and pre-conditioned for the primary production during most of the time as compared to oceanic region.

5. Conclusions

Considering the uncertainties in the computational setting of prescribed (forcing) functions and biological parameters, the model results generally agree with the observed values. The process equations currently used in these studies are partly successful in predicting phytoplankton biomass using environmental variables. The unexplained variability for the model may be due to non inclusion of other biotic factors like grazing by zooplankton, mineralisation processes, rates of growth and mortality of phytoplankton etc. (Janse and Aldenberg, 1990). A more precise prediction of ecological processes necessitates the need of continuous monitoring data on a long-term basis. Albeit, the results invokes the existence of a strong seasonal control on trophic inter-relationships and cautions the need of inclusion of biotic components along with abiotic processes to address the complexity of triggering and blooming mechanism of standing stock.

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Table.1. Best fitted model equation explaining different parameters in terms of the nine environmental variables and the significant interaction effects.

Month (Eq.No.)	Best fitted model equations.
October-Surface (6)	$\log \text{Chl.}a = \{ 0.3636 + 0.3843 \text{ PO}_4 + 0.3526 \text{ pH}*\text{DO} + 0.5198 \text{ pH}*\text{NO}_3 + 0.3180 \text{ pH}*\text{SiO}_4 + 0.3536 \text{ S}*\text{DO} + 0.3827 \text{ S}*\text{SiO}_4 + 0.4208 \text{ DO}*\text{NO}_3 + 0.514 \text{ NO}_3*\text{SiO}_4 \} - \{ 0.2903 \text{ pH} + 0.5884 \text{ S} \}$
October-Bottom (7)	$\log \text{Chl } a = \{ 0.006640 + 0.0583 \text{ DO}*\text{NO}_2 \} - \{ 0.3473 \text{ DO} + 0.3824 \text{ NO}_2 \}$
February-Surface (8)	$\text{Chl } a = \{ 1.2242\text{pH} + 0.8075 \text{ NH}_4 + 1.099 \text{ pH}*\text{NO}_2 + 0.7508 \text{ pH}*\text{NH}_4 + 0.2038 \text{ DO}*\text{NO}_2 \} - \{ 0.8147 \text{ S}*\text{DO} + 0.3403 \text{ S}*\text{NO}_2 + 0.2897 \text{ DO}*\text{NH}_4 + 0.4651 \text{ NO}_2*\text{NH}_4 + 0.4157 \}$
February-Bottom (9)	$\sqrt{\text{Chl.}a} = \{ 2.3212 \text{ T} + 6.6292 \text{ pH} + 3.0092 \text{ PO}_4 + 13.4478 \text{ T}*\text{pH} + 3.9031 \text{ T}*\text{S} + 2.8590 \text{ T}*\text{DO} + 5.2124 \text{ T}*\text{PO}_4 + 2.3449 \text{ T}*\text{SiO}_4 + 5.8553 \text{ pH}*\text{NO}_3 + 4.5061 \text{ DO}*\text{NO}_3 + 2.6338 \text{ DO}*\text{PO}_4 + 3.8425 \text{ NO}_2*\text{NH}_4 \} - \{ 4.1846 \text{ T}*\text{NH}_4 + 3.6216 \text{ NO}_2 + 9.9409 \text{ pH}*\text{DO} + 3.3192 \text{ pH}*\text{NO}_2 + 5.2351 \text{ pH}*\text{SiO}_4 + 2.3441 \text{ DO}*\text{SiO}_4 + 3.0929 \text{ NO}_2*\text{PO}_4 + 0.3828 \}$
November-Surface (10)	$\log \text{Chl.}a = \{ 0.6120 + 5.0905 \text{ NO}_3 + 3.8983 \text{ PO}_4 + 9.2291 \text{ T}*\text{S} + 5.9416 \text{ T}*\text{DO} + 4.5114 \text{ T}*\text{NO}_2 + 7.6911 \text{ T}*\text{SiO}_4 + 10.6338 \text{ pH}*\text{DO} + 6.0322 \text{ pH}*\text{NH}_4 + 8.2181 \text{ S}*\text{DO} + 6.6513 \text{ S}*\text{NO}_2 + 11.5450 \text{ S}*\text{NO}_3 + 6.1475 \text{ DO}*\text{NO}_2 + 6.8465 \text{ DO}*\text{PO}_4 + 8.8471 \text{ NO}_2*\text{NH}_4 + 5.0991 \text{ NO}_2*\text{PO}_4 + 4.7485 \text{ NO}_3*\text{NH}_4 \} - \{ 7.4330 \text{ T} + 5.8609 \text{ pH} + 9.6135 \text{ NO}_2 + 3.6969 \text{ SiO}_4 + 17.2511 \text{ T}*\text{pH} + 4.5618 \text{ pH}*\text{NO}_3 + 8.5672 \text{ pH}*\text{SiO}_4 + 6.0193 \text{ S}*\text{NH}_4 + 8.8638 \text{ S}*\text{SiO}_4 + 1.9786 \text{ DO}*\text{NO}_3 + 7.2562 \text{ NO}_2*\text{SiO}_4 + 4.3571 \text{ NO}_3*\text{SiO}_4 \}$
November-Bottom (11)	$\sqrt{\text{Chl.}a} = \{ 0.7539 \text{ pH} + 0.7233 \text{ NO}_3 + 0.7034 \text{ T}*\text{NH}_4 + 0.8164 \text{ pH}*\text{S} + 0.5079 \text{ pH}*\text{DO} + 0.7146 \text{ S}*\text{DO} + 0.8261 \text{ S}*\text{NO}_3 + 0.7372 \text{ DO}*\text{NO}_2 + 0.5781 \text{ DO}*\text{NO}_3 + 0.9617 \text{ DO}*\text{NH}_4 + 0.6222 \text{ NO}_3*\text{PO}_4 + 0.5984 \text{ pH}*\text{NH}_4 \} - \{ 1.3286 \text{ T}*\text{PO}_4 + 0.7240 \text{ pH}*\text{PO}_4 + 0.6526 \text{ S}*\text{NO}_2 + 0.8482 \text{ DO}*\text{PO}_4 + 0.8774 \text{ NO}_2*\text{NO}_3 + 4.7574 \}$

Table.2. Variance explained (%) and relative importance of the first ten model parameters on Chlorophyll *a*. (Limiting parameters are typed bold)

Month	Relative importance (controlling/limiting parameters)	F ratio	% variance explained *	% variance explaine@
October (Surface)	S > pH*NO₃ > NO₃*SiO₄ > DO*NO₃ > PO₄ > S*SiO₄ > S*DO > pH*DO > pH*SiO₄ > pH.	$F_{(21,34)} = 3.4854,$ $P \leq 0.05$	28.52	48.69
October (Bottom)	NO₂ > DO > DO*NO₂	$F_{(3,52)} = 5.5877,$ $P \leq 0.05$	17.54	20.00
February. (Surface)	pH > pH*NO₂ > S*DO > NH₄ > pH*NH₄ > NO₂*NH₄ > S*NO₂ > DO*NH₄ > DO*NO₂ > S.	$F_{(15,31)} = 2.8098,$ $P \leq 0.05$	12.63	37.11
February (Bottom)	T*pH > pH*DO > pH > pH*NO₃ > pH*SiO₄ > T*PO₄ > DO*NO₃ > T*NH₄ > T*S > NO₂*NH₄	$F_{(45,1)} = 3.298,$ $P \leq 0.05$	31.24	69.21
November (Surface)	T*pH > S*NO₃ > pH*DO > NO₂ > T*S > S*SiO₄ > NO₂*NH₄ > pH*SiO₄ > S*DO > T*SiO₄	$F_{(45,1)} = 4.4221,$ $P \leq 0.05$	9.66	77.00
November (Bottom)	T*PO₄ > DO*NH₄ > NO₂*NO₃ > DO*PO₄ > pH*S > pH > DO*NO₂ > pH*PO₄ > NO₃ > S*DO	$F_{(36,10)} = 5.3807,$ $P \leq 0.05$	14.89	77.42

* For only the 9 environmental parameters

@ For the 9 environmental parameters and their interaction effects

Chl. *a* and the independent parameters are values calculated based on equation (2a, 2b)

Legends to Tables

- Table.1. Best fitted model equation explaining different parameters in terms of the nine environmental variables and the significant interaction effects.
- Table.2. Variance explained (%) and relative importance of the first ten model parameters on chlorophyll *a*.

Legends to Figures

- Figure 1. Study area showing station locations in Arabian sea.
- Figure 2. Chlorophyll *a* (mg/m^3) distribution for February and November (observed value as contour line and predicted value as filled contours, based on eq. 8,9 (February) and 10,11 (November) respectively).
- Figure 3. Chlorophyll 'a' distribution (average of surface and bottom) of observed (line) and predicted (shaded) value during February and November (mg/m^3). Predicted values are based on equation 12 and 13 respectively.
- Figure 4. Relative importance ($>20\%$) of the model parameters predicting chlorophyll *a* during October (a) surface (variability explained, $\text{VE}=49\%$), (b) bottom ($\text{VE}=22\%$), February (c) surface ($\text{VE}=37\%$), (d) bottom (69%) and November (e) surface ($\text{VE}=77\%$), (f) bottom ($\text{VE}=77.4\%$).

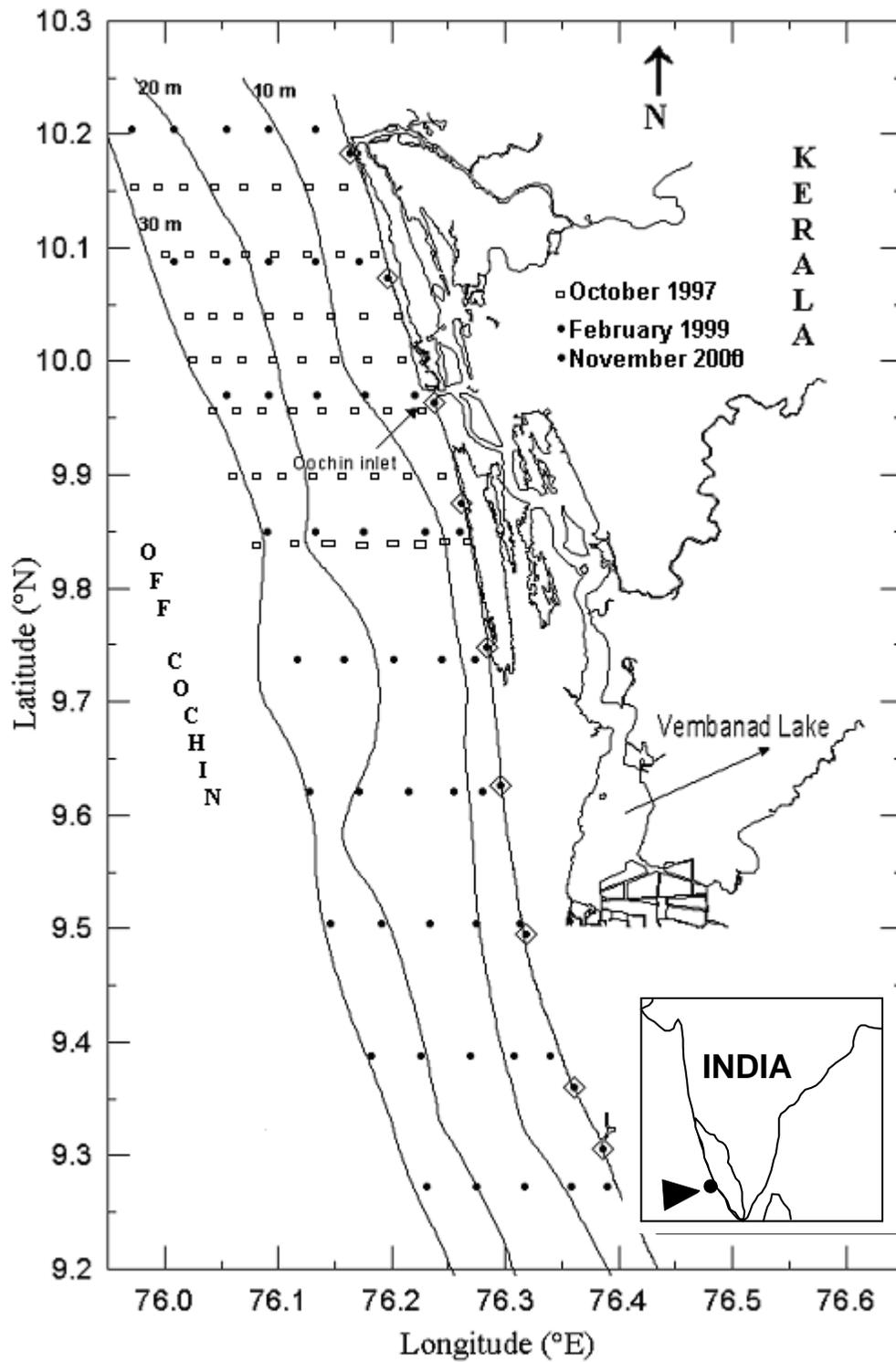


Figure 1. Study region showing station locations in Arabian Sea.

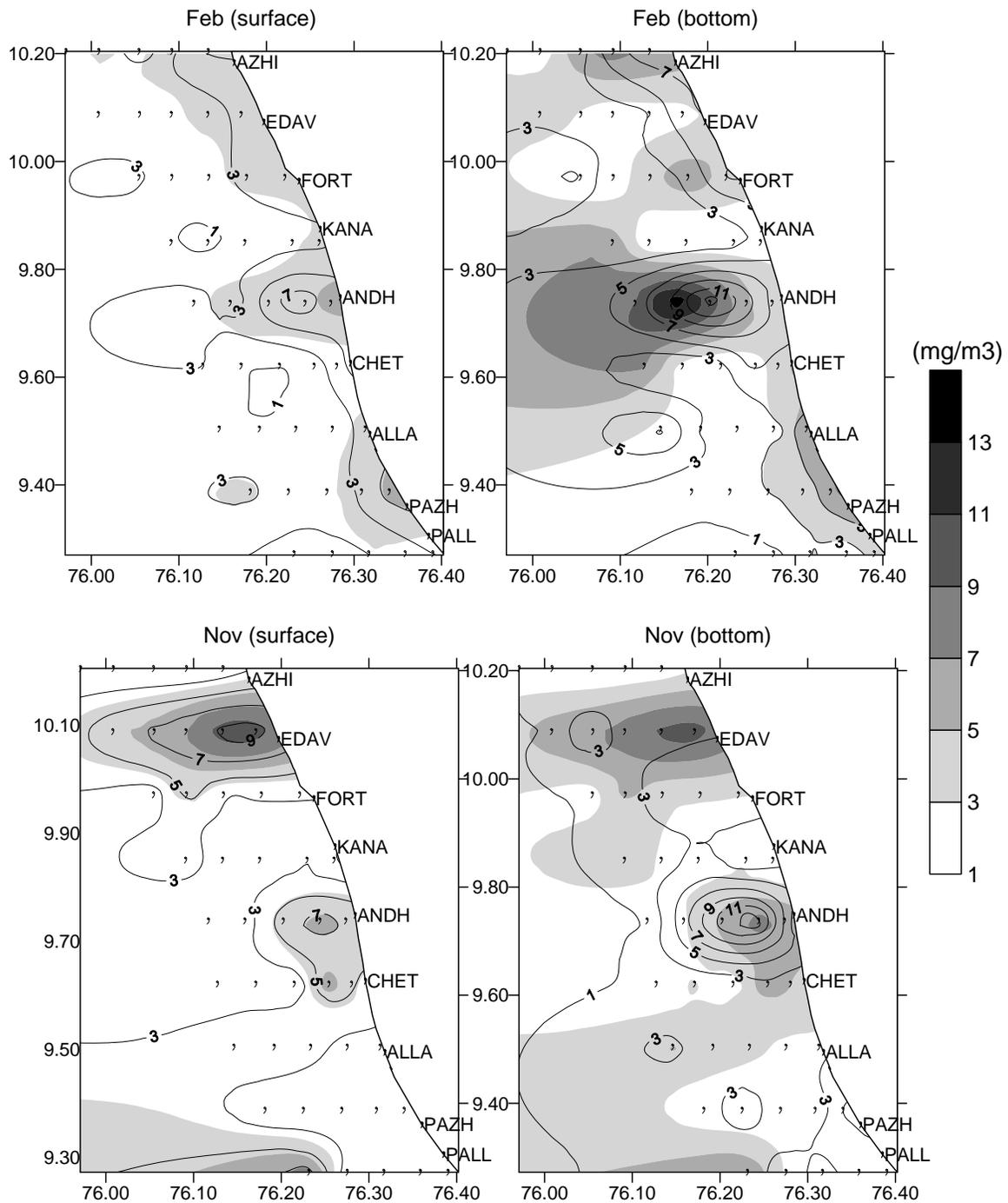


Figure 2. Chlorophyll a (mg/m^3) distribution for February and November (observed value as contour line and predicted value as filled contours, based on eq. 8,9 (February) and 10, 11 (November) respectively).

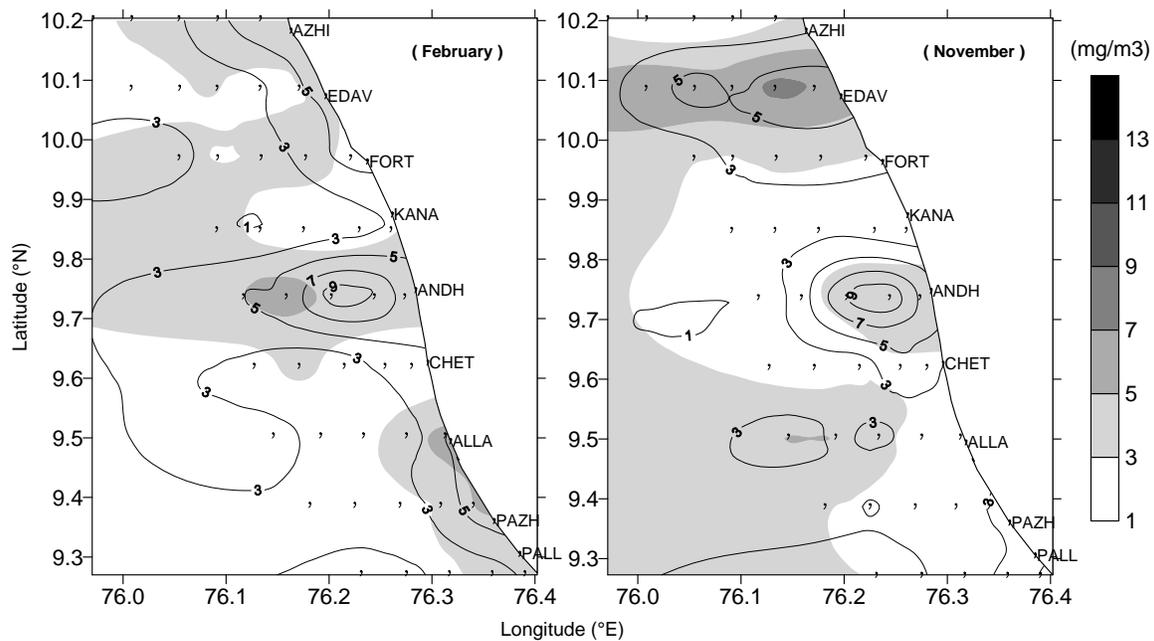


Figure 3. Chlorophyll 'a' distribution (average of surface and bottom) of observed (line) and predicted (shaded) value during February and November (mg/m³)
 Predicted values are based on equation 12 and 13 respectively.

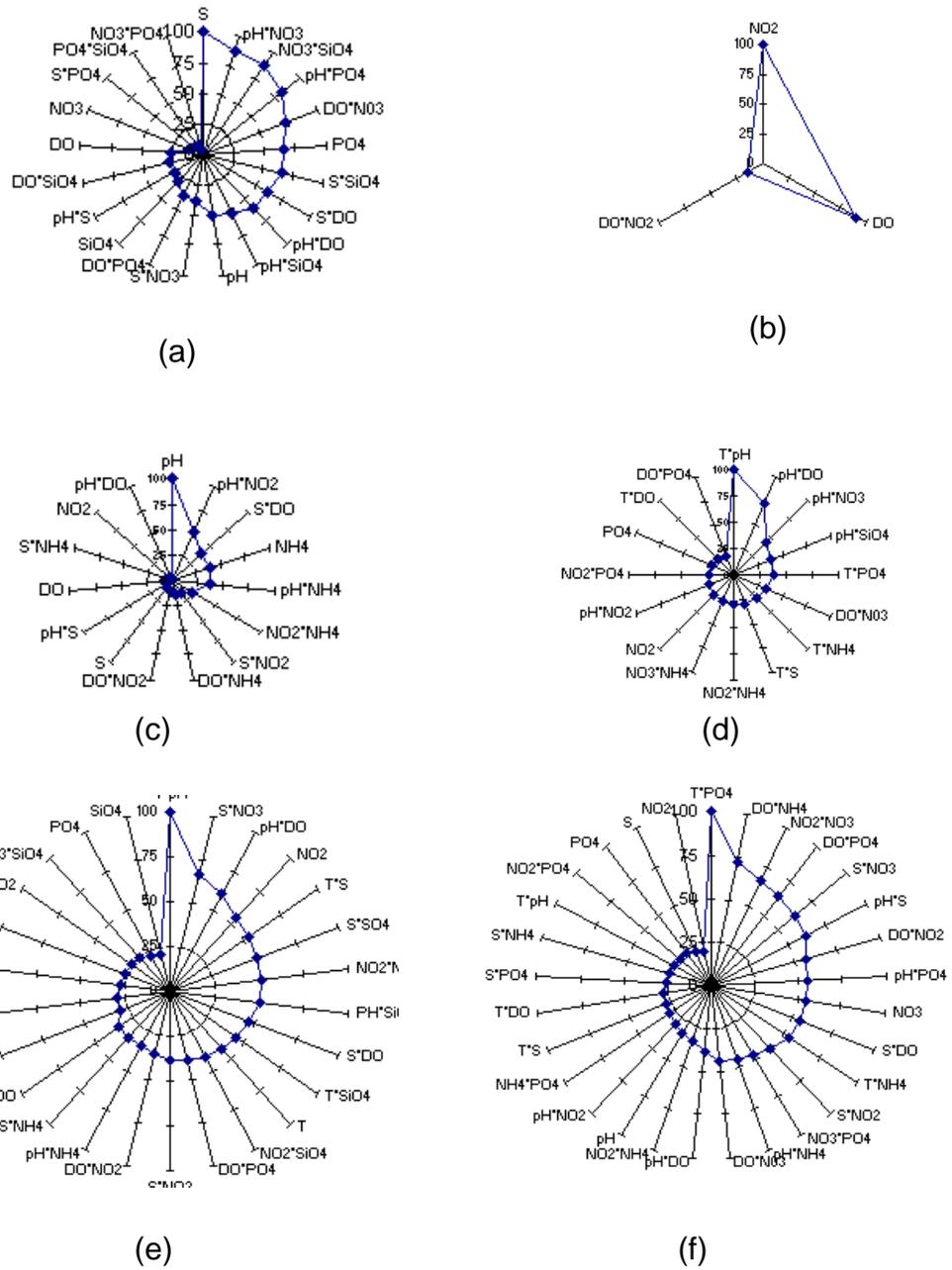


Figure 4. Relative importance (>20%) of the model parameters predicting chlorophyll a during October (a) surface (variability explained, VE=49%), (b) bottom (VE=22%), February (c) surface (VE=37%), (d) bottom (69%) and November (e) surface (VE=77%), (f) bottom (VE=77.4%).