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A Simple Model for Predicting Upwelling Status along Visakhapatnam Coast

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The variations in water mass characteristics of temperature, salinity and density over 12 year period (1986-1997) from a near-shore station are presented to delineate the phenomenon of upwelling off Visakhapatnam. The spatial variation in the parameters during upwelling months for a limited period was examined to justify the selection of a near-shore station for predicting the status of upwelling. A simple model to predict upwelling status based on Knudsen's hydrographic calculations and La Fond's classification of water masses was constructed and the algorithm presented. The utility of the model is briefly mentioned.

Keywords : Upwelling, simple model, Visakhapatnam coast

Coastal upwelling is an interesting phenomenon observed in many parts of the world. The significance of upwelling is pertinent to the replenishment of nutrients and resultant increase in production at all levels. After the pioneering work of Sewell (1929) dealing with the temperature and salinity features of Bay of Bengal, studies on upwelling off East Coast of India gained attention only in the fifties (Ganapati & Murty, 1954; La Fond, 1954, 1955, 1957, 1958; Murty & Sastry, 1957; Varadachari, 1958). Later studies by Murty and Varadachari (1968), Bhavanarayana (1970), Rao *et al.* (1986), Shetye *et al.* (1991, 1993), Vijayakumaran *et al.* (1996) also dealt with various aspects of upwelling along the East Coast of India, especially off Visakhapatnam.

Long-term studies on the hydrography of near-shore waters off Visakhapatnam are very rare. Physicochemical and biological parameters of near-shore waters from fixed stations were studied by Vijayakumaran *et al.* (1996). Time-series data on temperature and salinity from a single station were examined to understand the seasonal changes in upwelling. A simple model to predict the status of upwelling along Visakhapatnam waters based on water mass characteristics such as surface salinity, temperature and sigma-t (σ_t) data is attempted here.

Material and Methods

Two sets of data on surface salinity, temperature and dissolved oxygen collected from off Visakhapatnam were used for this study. One set (st.1 and st.2) was collected from on board *RV Cadalmin-V* during 1987-88 (Vijayakumaran *et al.*, 1996) and another set collected from beyond the breakwaters of the outer harbour (st.3) during 1986-1997. The locations of the stations are depicted in Fig.1. In order to minimize the impact of diurnal variations in parameters, especially temperature, the collection of samples and recording of temperature was done between 0800 and 0900 hrs throughout the study period. The density parameters were worked out from temperature and salinity (chlorinity) data as per Knudsen's method. The classification of water masses given in La Fond (1958) was adopted for developing the model and algorithm for predicting upwelling status along Visakhapatnam, based on near-shore surface salinity and temperature data.

Table 1. Twelve-year (1986-1997) monthly averages and standard deviations of density, SST and salinity at the shallower station (st.3) off Visakhapatnam.

Date	Density (σ_t)		Surface Temp (°C)		Salinity (‰)	
	Average	Stdev	Average	Stdev	Average	Stdev
Jan	20.14	1.4864	25.07	1.7996	30.77	1.7317
Feb	21.67	0.6309	26.14	1.5780	33.23	0.4913
Mar	22.11	0.9150	26.67	1.8233	34.05	0.8214
Apr	22.45	0.9595	26.18	1.8545	34.30	0.6430
May	21.50	0.8383	28.25	1.2859	33.90	0.8263
Jun	21.80	0.9998	26.88	2.1063	33.72	0.5232
Jul	21.92	0.9035	26.95	1.4492	33.91	0.7815
Aug	20.75	1.0958	28.22	1.6228	32.88	1.0069
Sep	17.99	1.8305	28.68	1.0676	29.39	2.2846
Oct	13.84	1.6972	27.91	1.5072	22.95	2.0101
Nov	15.72	2.6469	26.34	1.5246	24.91	3.2122
Dec	18.25	2.1662	24.79	1.6310	28.13	2.7062

Results and Discussion

The sea surface temperature (SST) data at st. 3 showed definite seasonal pattern with some deviations in certain years (Table 1). The SST varied between 21°C (20-1-1995) and 31.1°C (29-6-1987) during the 12-year period. The average value worked out to be 26.79(± 2.0159) °C for the entire period. The surface salinity data at st. 3 showed definite seasonal trend with some fluctuations in certain years. The salinity varied between 17.2‰ and 36.85‰, with an average of 31.13 (± 4.0536) ‰ during the 12 year period. The density or sigma-t (s_t) of surface waters at st.3 also showed definite seasonal trend more or less in tune with salinity. The s_t varied between 8.84 and 24.82 with an average of 19.89 (±3.13) for the entire period. The twelve-year monthly averages and standard deviations of density, SST and salinity are given in Table-1 and the time series of monthly averages of these parameters during the 12 years is depicted in Fig. 2.

The time series data on mean surface temperature showed marked fluctuations year to year, though a general seasonal trend could be delineated (Fig.2). The fluctuations are more common during the first half of the year than the later half. The major reason for this fluctuation was upwelling which varies in the time of onset, intensity and duration from year to year. During most of the years, the mean SST dropped to around 25°C during

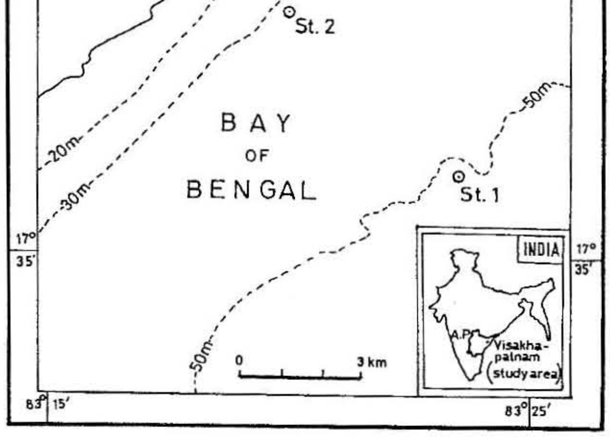

Fig. 1. Map showing location of stations

Table 2. The monthly averages of sea surface temperature, salinity, density and dissolved oxygen at three different stations during selected months of 1987 and 1988.

	Temperature (°C)			Salinity (‰)			Density (σ_t)			Dissolved O_2 (ml l^{-1})		
St. No.	# 1	# 2	# 3	# 1	# 2	# 3	# 1	# 2	# 3	# 1	# 2	# 3
Jan-87	24.97	24.67	25.28	30.3	29.15	27.73	19.83	19.06	17.81	7.33	7.67	7.4
Feb-87	26.3	26.3	26.4	31.53	31.88	31.63	20.35	20.61	20.4	7.3	6.8	6.07
Mar-87	27.4	26.87	26.17	33.6	33.92	34.22	21.56	21.97	22.41	6.6	6.43	4.11
Apr-87	27.9	25.0	24.9	34.07	34.8	34.9	21.75	23.21	23.32	7.0	5.27	3.9
May-87	28.1	27.75	27.9	33.78	33.87	33.98	21.47	21.65	21.68	6.4	5.95	5.7
Jan-88	25.75	25.55	25.8	29.02	28.78	28.74	18.64	18.52	18.41	7.9	7.3	6.9
Feb-88	26.6	26.63	27.1	30.53	30.21	30.59	19.51	19.26	19.4	7.53	7.0	5.98
Mar-88	28.14	28.26	28.1	32.68	32.97	33.29	20.63	20.81	21.1	6.85	6.9	6.0
Apr-88	27.85	27.63	27.0	33.61	33.62	33.68	21.42	21.5	21.75	6.27	5.53	5.45
May-88	30.48	29.94	29.03	33.01	33.2	33.45	20.09	20.42	20.91	6.15	6.6	5.3
Jun-88	28.3	27.8	28.03	32.79	33.99	33.32	20.66	21.72	21.14	6.6	5.0	6.13

December-January, fluctuated between 26-28°C during February-May and between 26-30°C during June-September to decline during November-December. Higher monthly mean SST was recorded during July-September period and lower mean SST during January-April. An overall fall in the monthly mean SST during 1992-1994 and subsequent revival could probably be an indication of a larger oscillation.

Unlike the mean SST, the mean monthly salinity showed a regular seasonal pattern without much fluctuation. The salinity showed steady increasing trend from around 30‰ during January to above 33‰ during March-April. The values fluctuated between 30 and 35‰ during May-August period. A steep fall during September-October brought the salinity down below 25‰. A revival was observed during November-December when the mean salinity again assumed values above 25‰. An exception to this pattern was observed during 1992 and 1994 when the annual salinity never came below 25‰, indicating unusual prevalence of high saline water instead of dilute Gangetic water. A change in the normal pattern of circulation caused by some larger oscillation could be the reason for this anomaly.

The time series data on monthly mean density reflected the trends in both salinity and temperature to a great extent. The mean density showed steady increasing trend from below 20 during January to above 22 during March-April. The values fluctuated between 20 and 23 during May-August period. A steep fall during September-October brought

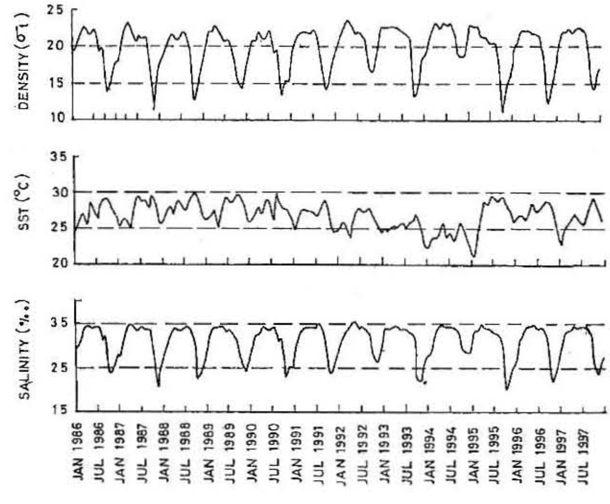

Fig. 2. Time series data of monthly average of density, temperature and salinity at st.3 during 1986 to 1997

the mean density down below 15. A revival was observed during November-December when the mean density shot up beyond 18. As in the case of salinity, during 1992 and 1994 the annual low density never came below 15, indicating the unusual presence of denser water instead of northern dilute water.

From the above results, it is clear that changes in surface temperature, salinity and density brought about by intense upwelling were observed during March- April, which extended up to August. Though the low surface temperature observed during January can be clearly attributed to the atmospheric cooling, the higher salinity and density observed in certain years could be due to early onset of upwelling. Similarly the upwelling conditions were observed during August in certain years. There was indirect evidence such as occurrence of deeper water fishes in the usual fishery (Vijayakumaran, unpublished data) to support this argument. It was also observed that intense upwelling occurs in spells of one or two weeks. A subsidence of upwelling invariably occurs during May-June and

Table 3. The classification of watermass based on characteristic density according to La Fond (1958) and the assigned status of upwelling for the water mass for the purpose of the predictive model.

Density Range	Characteristic Water Mass	Status of Upwelling
$\sigma_t \leq 19$	Northern Dilute Water (NDW)	*Nil*
$19>\sigma_t \leq 21$	Transition Water (TW)	*Not Significant*
$21>\sigma_t \leq 22$	Southern bay of Bengal water (SBW)	*Mild*
$22>\sigma_t \leq 23$	Upwelled Water (UW)	*Moderate*
$23>\sigma_t \leq 24$	Subsurface Shelf Water (SSW)	*Intense*
$\sigma_t>24$	Indian Equatorial Water (IEW)	*Very Intense*

revival during June-August, the timing and duration varying from year to year. Thus it could be concluded that upwelling off Visakhapatnam coast occurs during February-July with the onset, intensity and duration of spells varying from year to year. In certain years the onset of upwelling may be as early as in January and the revival may take place as late as in August.

The surface data on monthly mean temperature (SST), salinity, density and dissolved oxygen from three stations during January-May 1987 and January-June 1988 clearly showed some important spatial features (Table-2). The SST gradient during January- February was tilted up from deeper station (st.1) towards shallower station (st.3) during both the years. During March – May, the period of upwelling, there was reversal of the gradient. During June 1988, however, st.1 and st.3 recorded more or less similar mean SST while st.2 recorded lower value.

The mean surface salinity showed a decreasing trend from deeper to shallower station during January of both the years. During February 1987, both the shallower stations (st.2 and st.3) recorded higher salinity than deeper station (st.1), though in February 1988 only st.3 recorded higher value. During March-May of both the years, the mean salinity showed an increasing trend from deeper to shallower stations. During June 1988, st.2 recorded highest salinity followed by st.3. In1988, the mean density of surface waters showed similar trend as salinity during all the months, except in February.

The mean surface dissolved oxygen was lower at st.1 only during January 1987. During February to May 1987 and January to April 1998, there was a clear decreasing trend of dissolved oxygen from deeper to

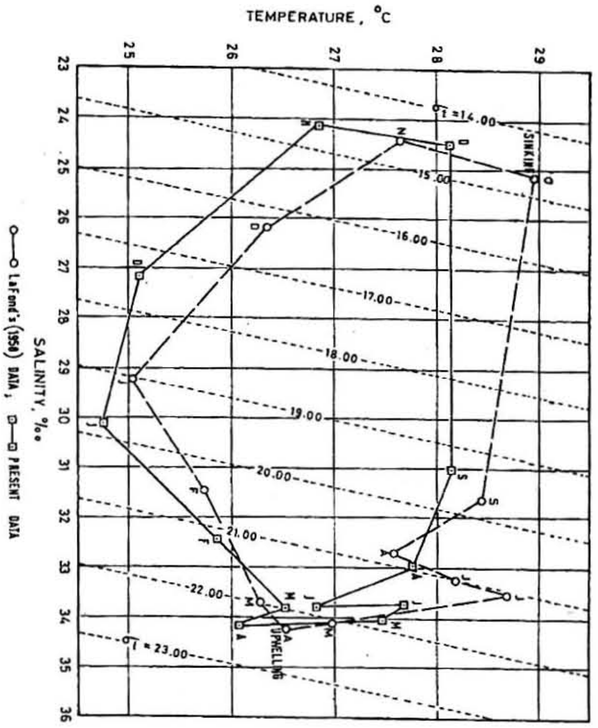

Fig. 3. T-S plot of twelve-year monthly means juxtaposed over the T-S plot of La Fond (1958).

shallower stations. During May and June 1988, though the trend was disturbed, the lower mean values were recorded at st.3 and st.2 respectively.

While discussing the hydrological features off Visakhapatnam, Vijayakumaran *et al.* (1996) mentioned that high surface salinity and low surface temperature could be considered as reliable indicators of upwelling and that the evidence of upwelling was more pronounced nearer to the coast than away from it. This is because of the offshore transport of surface waters and the replacement of the same with deeper denser waters close to the shore. Upwelled water, which appears as a narrow band off Visakhapatnam, becomes wider (spreads offshore) towards Orissa coast depending upon the intensity and duration of the wind (La Fond, 1958).

It could be noticed from the above results that during upwelling, the decrease in temperature as well as increase in salinity and density of the surface waters is more pronounced at the shallower station than at the deeper station. Being close to the surf zone of breakwaters, the dissolved oxygen values at st.3 would be expected to be higher. But surprisingly, the dissolved oxygen values were lower at the shallow station than at the deeper station during upwelling period. Thus it could be concluded that the evidence of upwelling as indicated by the temperature, salinity, density characteristics and dissolved oxygen of the surface water is more pronounced at the near-shore of Visakhapatnam than away from it. This conclusion justifies the selection of a near-shore surface station for understanding the upwelling status off Visakhapatnam.

The T-S plot constructed out of twelve-year monthly average of temperature, salinity and density data of the near-shore station (st.3) juxtaposed with the T-S plot given in La Fond (1958), showed some significant departure from the latter. During January, February and December, the T-S plot from the present study showed a shift towards bottom right side, indicating a general increase in salinity, density and decrease in temperature. During March an upward right shift of the point indicated slight increase in temperature and salinity, but density almost remained the same. During April, a marked shift of the point downward right indicated a significant increase in density and salinity as well as a decrease in temperature. During May the point shifted upwards left and during June and July again there was a shift downward to right. During August a slight upward right shift indicated increase in all the three parameters. During September, October and November the points shifted towards bottom left, indicating decrease in all the three parameters.

It could be noticed that there is an overall shift of mean values towards bottom

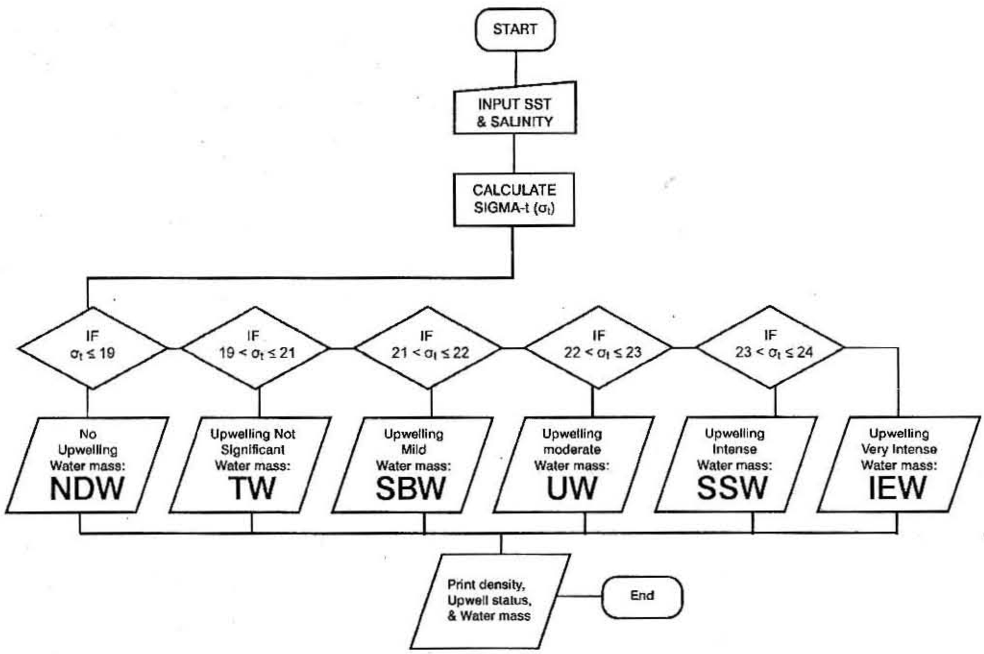

Fig. 4. Algorithm depicting the model for predicting the upwelling status off Visakhapatnam.

right during the upwelling months. This is clear indication that the signs of upwelling are more prominent at near-shore surface waters. From the pattern of shift of the plot during July, a revival of upwelling condition is also indicated. The downward left shift during September, October and November is again an indication that the influx of northern dilute water, induced by sinking, is quite prominent at the near-shore surface waters. From the above facts, it is quite reasonable to consider the near-shore surface parameters as sufficient indicators of upwelling status off Visakhapatnam.

Based on the T-S plot for surface waters off Waltair, La Fond (1958) named water masses according to their density (s_t) as given in Table-3. The low density northern dilute water ($\sigma_t < 19$) predominate during September to December, though peak sinking process is assumed to occur during September-October. The transition water generally predominates during January-February and may also prevail during May-August. The characteristic high-density ($\sigma_t > 21$) southern Bay of Bengal water (SBW) upwelled water (UW), subsurface shelf water (SSW) and Indian equatorial water (IEW) predominate during March-April, but may appear as early as in January and also prevail/ recur at intervals up to August.

The coastal upwelling off Visakhapatnam being influenced by both the western boundary current (WBC) of the subtropical gyre (STG) and prevailing winds (Shetye *et al*, 1991 and 1993), variability in the intensity and duration of upwelling is quite usual. However, the density (s_t) derived from temperature and salinity of the near-shore waters would definitely indicate the characteristic water mass. Murty (1999) mentioned that 'intensive upwelling' takes place in areas where wind and current are favourable to cause upwelling. Therefore, the status of upwelling ranging from 'mild' to 'very intense' was assigned to the different water masses for the purpose of the model (Table-3).

The model incorporates Knudsen's formulae for deriving the density from temperature and salinity and successive decision loops checking the agreement of density with that of characteristic water masses (Fig.4). It is assumed that 'mild upwelling' brings water mass of density about 21-22, 'moderate upwelling' that of σ_t 22-23, 'intense upwelling' that of σ_t 23-24 and 'very intense upwelling' water masses of density > 24. The algorithm can be translated into a simple computer program and conveniently used for predicting the status of upwelling off Visakhapatnam.

This predictive model will be useful for understanding the status and intensity of upwelling process with a simple estimation of temperature and salinity (estimated either by titrimetry or with a refractometer). This information can provide an immediate explanation to the changes in the fish landings (presence, disappearance and abundance of species) as well as unusual plankton blooms. However, it must be remembered that this model has spatial restriction in application, being suitable particularly off Visakhapatnam, and may not work true for other areas.

The significance of the outcome of the present study is in the initiation of continuous monitoring programme deploying moored buoys. A single buoy installed within an easily accessible distance off the outer harbour would be sufficient to monitor all relevant parameters off Visakhaptanam. Telemetric recording of key parameters on a continuous basis would provide a wealth of information on the coastal phenomena of upwelling and sinking.

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