REMARKS ON OCEANOGRAPHIC OBSERVATIONS OFF THE EAST COAST OF INDIA

KARL BANSE
School of Oceanography, WBIO,
University of Washington, Seattle, WA 98195, U.S.A.

ABSTRACT

This article translates a literature survey of oceanographic observations off the east coast of India, which was published in 1960. It is suggested that off Waltair/Visakhapatnam during the fall, the tendency for sinking is counterbalanced by the salinity stratification. Strong vertical mixing greatly depresses the surface concentration of oxygen. Nutrients are brought up at the same time as indicated by phytoplankton blooms. River discharge during the southwest monsoon does not contribute an important amount of phosphate-phosphorus to the sea. Off Madras, markedly seasonal blooms of phytoplankton are not observed as there is no marked seasonal upwelling. Conditions in other areas of the northern Bay of Bengal are mentioned.

Key-words: Oceanography, IIOE, east coast

INTRODUCTION

In view of the planned international investigation of the Indian Ocean (later called International Indian Ocean Expedition), it seems appropriate to review coastal oceanographic observations and to point out insufficiently investigated phenomena. For the east coast of India, multi-faceted time series and sections across the shelf near Waltair (17°44'N) will be discussed in detail. Nearshore planktonical-chemical studies, available for Madras (13°04'N), include observations of temperature, salinity, and oxygen, which suggest a lack of markedly seasonal plankton blooms. Finally, data from adjoining areas will be treated.

Hydrographic conditions near Waltair during autumn

For the waters off Waltair, LaFond (1954) concluded that pronounced upwelling occurs during March and April (May) and tentatively suggested upwelling for June to August (evidently a copying error of mine in 1960: should be July to August). Indeed, surface observations of temperature and salinity for 4½ years (Ganapati and Murthy, 1955; Satyanarayana Rao, 1958a) show falling temperatures between February and April and from June to August. Whereas upwelling during spring has been demonstrated by hydrographic sections (LaFond, 1955), detailed invest-

Note: This is a translation of a paper by the author, "Bemerkungen zumeeeskundlichen Beobachtungen vor der Ostkuste von Indien" (Kieler Meeres-forschungen 16: 214-220, 1960). Since the journal ceased publication in 1975, the paper might be difficult to obtain, as may be true for some of the cited references. The text has not been updated, but corrections clarifying the phrasing have been added in brackets.
tigations for the period of the southwest monsoon are wanting. The following may be stated: During the summer monsoon, the decline of surface temperature is largely caused by the decline of air temperature, wind, and cloud cover and, thus, is present over the entire Bay of Bengal. However, the following data suggest upwelling at least in some years (during this season): a) the wind direction is offshore; b) the map of monthly mean surface temperature for August (Anonymous, 1952) shows < 28°C along the Indian coast from 16° to somewhat beyond 18°N; the summer minimum of the above-cited time series, usually 27.7°C, occurs in this month; c) off Waltair, a particularly low monthly mean of 26.3°C in August 1955 co-occurred with an increase of salinity, whereas the August salinity of each of the other three years was lower than during June/July, d) rather high means of phosphate values have been reported for July and August 1954 (Ganapati and Venkata Rama Sarma, 1958).

Further, beginning in August, the coastal current off Orissa sets to the south (British Admiralty Chart, in Ganapati and Venkata Rama Sarma, 1958). For the subsequent period, LaFond (1954) has stated that sinking of surface water is present. I note however that according to the surface observations of Ganapati and Venkata Rama Sarma (for August 1953 to June 1955), the months with low means of oxygen concentrations were August to December 1953 and July to October 1954. In both years, the minimum monthly mean was observed in October (49% of saturation for 1953; 64% for 1954). Similarly low values also were found on the middle of the shelf (stations of Ganapati, LaFond and Bhavanarayana, 1956) for one station each in October, November, and December 1956, the oxygen surface concentrations correspond to approximately 72, 61, and 71% of the saturation values. The temperatures for this estimate were taken from Satyanarayana Rao (1958a) in conjunction with the results of Ganapati and Murthy (1954) on the temperature distribution across the shelf. The error of the estimate might be 2 - 3 % in terms of saturation.

It is not likely that the low surface oxygen values resulted from oxygen consumption within the upper layers. If that had been the case, in view of the strong stratification (Rama Sastry, 1957,) the bottom (i.e., sub-thermocline) water could not have been as well-aerated, as observed (only) 5 - 20% lower saturation than at the surface). Rather one may surmise that the low surface saturation was caused by mixing with the bottom water.

Strong vertical mixing is indicated by the following: For October 1952, LaFond (1954) depicted the depth across the shelf of the 27.8°C isotherm, which on this occasion corresponded to the top of the thermocline. Like the thermocline, the isotherm sank toward the coast, from which fact LaFond deduced sinking. The original bathythermograph observations, however, show that at the same time, the vertical temperature gradient above this isotherm declined toward the coast, such that it had almost disappeared on stations 1 - 3 (≤ 10 nautical miles from the shore, ≤ 50 m depth). In addition, the surface temperature sank toward the coast, while
the bottom temperature rose. During the study, the air temperature did not deviate by more than 1°F (about 0.5°C) from the surface water value. Thus, the sinking of the isotherms toward the coast could be caused both by sinking of surface water and mixing of warm surface water with cool deep water on the inner shelf. The author believes that in this region the tendency to sinking, which is dynamically caused, is essentially overridden by the strong stratification that will be treated below; if that is so, the sinking of the (82°F) isotherm is the result of mixing.

During this season, the vertical stratification in the Bay of Bengal is principally caused by the rivers, which discharge the rains of the summer monsoon in the head of the bay. Off Waltair, the low-salinity water forms only a thin layer, as shown by the mentioned stations of 1955 by Ganapati, LaFond and Bhavanarayana (1956). On the middle of the shelf, the salinity increases in October from 15.6 (0 m) to 23.9 (9 m) and 31.1 ppt (16 m), in November from 23.2 (0m) to 29.9 ppt (20m), and in December from 28.5 (0m) to 31.2 ppt (20m). In spite of the tendency to sinking, high-salinity water is present very close to the shore, as shown by the data of Ganapati and Murthy (1954). On two occasions during October 1952, the surface salinity increased by 3 - 4 ppt (landward) within 10 nautical miles from the shore. (The enhanced mixing over shallow bottom depths was noted above in the review of the bathythermograph section of one of these cruises).

As a result of the strong vertical mixing in the area off Waltair, one should expect a very rapid increase of surface salinity downstream. In fact, the mean salinity distribution for the quarter September to November (Sewell, 1929) shows an increase of salinity from 22 to 29 ppt between 20 and 19°N. Admittedly, Waltair is situated at 17°44' N but, according to the observations of Satyanarayana Rao (1958), during October and November it is in the salinity range of 21 to 27 ppt (during September, the coastal salinity near Waltair is higher). Because checking of the data for Sewell's chart would be cumbersome and newer observations do not seem to have been published, one has to be satisfied by the fact that the available data are not contradictory. For investigating this question, sections along the east coast of India are much needed.

In summary, one can deduce from the hydrographic observations off Waltair that deep water may be brought to the surface both by upwelling (March to April, perhaps also May, and June to August) and by vertical mixing from August onward. The enhanced nutrient supply to the depleted surface waters of the tropics should result in an enhanced plankton content and one should expect three periods of phytoplankton blooms, of which the third follows the second immediately. Indeed, the available observations of diatoms (collected by nets) show maxima in March and April and from September to November; smaller outbursts occur in August (Ganapati and Murthy, 1955; Ganapati and Venkata Rama Sarma, 1958).
Phytoplankton distribution near Waltair and the role of rivers

In the preceding paragraph, it was pointed out that the (occurrence of) net-collected phytoplankton off Waltair depends on the addition of deep water to the surface layers. Also the study of the horizontal distribution of phytoplankton off Waltair by Ganapatil and Murthy (1957) supports the previously stated view of the author (Banse, 1959) that the addition of nutrients, especially of phosphate, by the rivers during the rainy season is of relatively small importance in these waters. The cited authors observed in the second half of 1952 that the large concentrations of net-collected phytoplankton were found first in water of high salinity, far away from the shore. Near the coast, large concentrations of phytoplankton appeared only after the annual salinity minimum.

Salinity, as such, is unlikely to have been the cause of this sequence, since Muthu (1955) observed plankton blooms with similar specific composition off Madras at both 22-23 ppt and higher salinities (see, however, Subrahmanyan, 1959, according to whom at 25 ppt off Calicut the phytoplankton does not look healthy). Also regarding the observations off Waltair, the distribution of turbidity does not appear to be responsible for the (bloom) preference for high-salinity water (based on transparency data in Satyanarayana Rao, 1958 b), but this will not be discussed here. The water off Waltair is always stratified i.e., the mixed layer is always shallow and, hence, its mean irradiance is high.

The following review of the phosphate content shows that the river runoff does not have the importance ascribed to it by some authors; instead, the nutrient content of the deep water must be the source driving the large phytoplankton blooms. For the southwest coast of India, Suryanarayana Rao (1957) through analyses of total phosphorus already suggested strongly that the short rivers of that region do not transport significant amounts of phosphorus to the sea. The same seems to hold also for the rivers of the north Indian plains, based on the data of Bose (1956) from the mouth of the Ganges (River Hooghly, station 2 near Diamond Harbour). The high phosphate values co-occur there with high salinity prior to the southwest monsoon. The mean content of the freshened water of the rainy season, with about 0.4 μg-at/1 P, is low, and the minima are not far from zero. The data by Dutta., Malhotra and Bose (1955) from the same site show that the phytoplankton is richest prior to the southwest monsoon and least during that season; thus, the phytoplankton is not the cause of the low phosphate values in the rainy period.

If one were to dilute oceanic water of 35 ppt lacking phosphate entirely, with Hooghly water of the rainy season, one would obtain a phosphate content of 0.2 μg-at/1 P at 17.5 ppt. In fact, however, the mean phosphate content of water of this salinity off Waltair is 0.5 - 0.8 μg-at/1 (Ganapati, La Fond and Bhavanarayana Rao, 1956; Ganapati and Venkata Rama Sarma, 1958). Thus, the phosphate content off Waltair has to be principally of marine origin (note though that investigations of
the total phosphorus content are lacking). The observations by Jayaraman (1951) of the phosphorus content off Madras support these arguments. Also the low-salinity water off Madras, which appears there somewhat later than off Waltair, has only a moderate phosphate content (see, however, data for September 1951 in Ramamurthy, 1953b. Local influence of the rivers in Madras?). In contrast, off Madras as off Waltair, the silicate maximum occurs in the low-salinity water (Jayaraman, 1951; Ganapati and Venkata Rama Sarma, 1958), as to be expected (where river silicate is high).

It must be granted that it is unknown how much bound nitrogen is brought to the sea by rivers. For the (offshore) Pacific and Indian Oceans, Steemann-Nielsen and Aabye Jensen (1957) strongly suggested that nitrate, as well as phosphate, can reach minimal values and impede organic production. Unpublished measurements off Cochin during 1958 to 1960 by the author show that phosphate never becomes very low, whereas nitrate does. The observations by Jayaraman (1951) and Ganapati and Venkata Rama Sarma (1958) likewise indicate that the times of low surface salinity off Madras and Waltair are not periods of especially high nitrate values. Prior to making definitive judgments about the role of river runoff for coastal plankton production, however, investigations of nitrogen compounds with reliable methods are desirable.

Observations off Madras

Marine-chemical observations off Madras have been mentioned above; here, the differences between the regions off Madras and Waltair will be described. As the crow flies, the sites are somewhat more than 300 nautical miles distant. Both are subject to the same systems of currents, even though the reversals of directions, approximately in January and August, are not exactly simultaneous, and the low-salinity water of the rainy season from the north of the Bay of Bengal reaches Madras somewhat later than Waltair (La Fond, 1958). In spite of this general agreement, however, the conditions of pelagic production differ appreciably, as far as it can be deduced from about 4½ years of discontinuous investigations off Madras. Whereas a periodicity of plankton development is distinct off Waltair, relative maxima of phytoplankton development have been observed off Madras, a few miles from the beach, during all months except January, March, and April (Aiyar, Menon and Menon, 1936; Ramamurthy, 1953 b; Muthu, 1956), without, however, a particular season being clearly distinguished. This previously was emphasized by Ramamurthy (1953 b); also it appears from his observations (Ramamurthy 1953 c) that plankton concentrations can change greatly from one sampling to the next, so that the consideration of monthly means may be some what misleading.

To understand the lack of a preferred season of phytoplankton development off Madras, one has to look at the hydrographic situation. Regular occurrences of
pronounced upwelling seem to be lacking, as far as one can determine this from surface data for oxygen. According to LaFond (1958) and Ramakrishna (1953a) recent data indicated upwelling in May. However, lacking off Madras is the regular decline of oxygen at the surface that is typical for the southwest coast of India and also the region off Waltair; therefore, regular sudden injection of large amounts of nutrients to the surface layers also must be absent near Madras. Instead, considering the shallow depth at the sampling station (15 - 25 m; only Aiyar, Menon and Menon (1936) collected occasionally to 35 m depth), it is likely that bottom water will be mixed locally into the upper layers and cause limited growth of phytoplankton. Clear examples for this process can be found in the data of Jaya Ratnam (1951), when on four dates, from June to August 1948, the oxygen saturation of the surface water sank from the usual 85 - 90% to 55 - 60%. Anomalously high phosphate values (1.5 and 3 µg-at/l) occurred at this time.

Entirely unknown is the extent of the phytoplankton maxima off Madras and Waltair relative to each other (and to other places in India) and whether, over the entire year, the continuous remineralization of nutrients on the sea bed can effect as much organic production as temporally limited upwelling elsewhere. In this context, knowledge about vertical stability and eddy diffusivity is lacking, except a paper by Rama Sastry (1957). The fact that India's principal concentrations of fish are found along the Malabar coast and off Saurashtra, where upwelling is present on a large scale, points to the great effectiveness of vertical advection of truly deep water relative to the mere upward-mixing of near-bottom water into the surface layer nearshore. For a profitable comparison of phytoplankton blooms, it will be necessary to discontinue using plankton nets, which have been employed almost exclusively so far off these coasts, and substitute counts from water bottle samples.

The western half of the Bay of Bengal

One would expect that the Bay of Bengal offshore, because of being under the influence of the monsoons and in view of the peculiarities of its current system, would exhibit areas with enhanced vertical eddy diffusivity and subsequent plankton development. The monthly current charts of the British Admiralty, which Ganapati and Venkata Rama Sarma (1958) reproduced, show at least two cyclonic gyres in the centers of which deep water must raise. One is present from July to September in the northern part of the bay, with the center at about 20°N, 90°E. The other appears in October off the coast of Madras at about 85°E, moves subsequently in a southerly direction, and disappears in December northeast of Ceylon. A third cyclonic gyre exists during October off Waltair, but it might be identical with the first-mentioned one. The paper by Prasad (1952) conveys an idea about the regionally very variable depth of the thermocline along the east coast of India. Perhaps his stations 811 and 1720 were within the reach of the first-mentioned gyre.
Further, it may be pointed out that LaFond (1958) observed surface water of very high salinity in June 1953 off the mouth of the Ganges. The above-mentioned first gyre does not appear until July, and also farther to the east. Similarly, the time series from Sagar Island in the mouth of the River Hooghly (LaFond, 1958) suggests a regular occurrence of surface water with very high salinity around 37 ppt from April to June, which deserves a closer investigation. It was noted earlier that the phosphate maximum in the Hooghly also occurs during this time, prior to the southwest monsoon. For the time being, it cannot be decided whether the data indicate upwelling off the mouth of the Ganges or advection from the area off Waltair (the latter believed to be the case by LaFond, 1958).

The decline of temperature in the northernmost part of the Bay of Bengal during autumn, which lasts until January (Anonymous, 1952), is apt to be caused exclusively by surface cooling from the low air temperature over the continent (Anonymous, 1955) brought by the northeast monsoon rather than upwelling. This view is based on the vertical distribution of temperature provided by LaFond and Borreswara Rao (1954) for December 1952 from this area. The same process seems to be at work off the northwest coast of India, in the sea off Saurashtra, where starting in October, temperatures decline strongly 22°C off Karachi in January, (Anonymous, 1952). The not yet completed study of about 1500 bottom water temperatures, on which the mean values of Jayaraman, Seshappa, Mohamed, and Bapat (1951) are based, indicates an increase of temperatures toward the bottom during two years of observations south of the Gulf of Kutch, beginning in January which would not be the case during upwelling. Starting with this month, the distribution of surface temperature seems mainly to be determined by surface cooling, not by upwelling (Banse, 1968).

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