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Surface Water Characteristics in the Bay of Bengal off Madras

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ABSTRACT. Two dimensional frequency distributions of temperature and salinity off Madras are presented from eight years' data of daily measurements of sea surface temperature and density. The distributions are highly concentrated around the mean during March to September. Maximum dilution occurs in October and the recovery of salinity to the normal takes place gradually during the next four or five months. The percentage frequency of occurrences of different characteristics is discussed. The mean annual variation of temperature is bimodal with maxima in May and October. The interaction of the surface water masses of the Bay of Bengal and the seasonal heating and dilution give rise to the observed annual cycles of temperature and salinity and hence of the surface water characteristics.

1. Introduction

Temperature and salinity are two conservative properties of sea water and are mostly used to study the characteristics of water masses. The T—S diagram as originally introduced by Helland-Hansen has been a widely used tool in Physical Oceanography. Its use is, however, restricted only to such layers of the sea where seasonal and local variations are negligible. In the case of surface layers, where these variations are considerable, it has become necessary to discuss only the mean values together with relevant measures of dispersion. For such cases Montgomery (1955) has employed the use of a scatter diagram on temperature salinity axes. Also this two dimensional frequency distribution can be put to different uses such as (1) for studying the sea surface characteristics (Cochrane 1956), (2) for making a descriptive inventory of the ocean waters (Cochrane 1958, Pollak 1958 and Montgomery 1958) and (3) for studying the water masses of the upper layers of the sea (Rama Sastry 1960) etc.

In the present investigation, it is proposed to give the two dimensional frequency distributions of the surface waters in the Bay of Bengal off Madras for different periods with a view to study the annual cycles of temperature, salinity and density. LaFond (1957) has plotted monthly mean values of temperature and salinity on the T—S grid and has shown the mean seasonal trend of the changes. He has pointed out that the observed changes are mostly due to the interaction of different water masses brought into the region by the coastal circulations and that upwelling also influences the seasonal cycle. The distributions presented here, clearly bring out these details and represent the entire data collected during a period of eight years, thus including all the climatic information of the waters off Madras.

2. Data and methods

The data utilised in this paper comprise of daily measurement of sea surface temperature and density from 1 July 1951 to 30 June 1959 at the Madras harbour. The density values are converted into salinities using Knudsen's Hydrographical Tables. Following the early investigations, mentioned above, a sea water characteristic is defined as a point on the T—S diagram. The characteristic class represents the area on the diagram between the class boundaries of the variates. The number of observations found in any characteristic class gives its frequency indicating the duration of occurrence of the particular characteristic during the period in question. Thus this definition does not eliminate any local diurnal fluctuations, amounting to the assumption that the characteristic classes are stationary at the station in any specific period. This assumption is valid only if the local diurnal range of the characteristic does not vary as greatly as that during the period. However, in the months of high dilution fluctuations of salinity are considerable, thus giving rise to a number of modal values of salinity.

Because of the limitations in the observational accuracy the ranges of temperature and salinity for the respective class intervals are chosen as 0·5°C and 0·5 $^0/_{00}$. The total frequency of each of the distributions is adjusted to be 1000, so that the frequencies of the individual characteristics of different periods, can directly be comparable. In each diagram of the distribution, the frequency curves of individual variates are shown on the appropriate axes.

The two dimensional frequency distributions of temperature and salinity were constructed for each month. A preliminary comparison has revealed high similarity during certain months, as far as the modal values of the distributions and the scatter of frequencies of other characteristics about the mode in general are concerned. Thus the distributions for March to June and July to September are nearly identical, and, therefore, for these periods the observations are combined and fresh distributions are constructed. For the remaining period of the year, except for October, monthly distributions are given. During October, because of very great dilution, diurnal local changes are very important as such the October distribution is not included here. However, in the annual distribution observations made during October were also included.

3. Discussion of results

The frequency distributions of temperature and salinity in any period results mostly from the different waters that are brought into the region by coastal circulations. In the Bay of Bengal there are two regions where water masses of the surface layers are formed. They are (1) at the head of the Bay where great dilution occurs because of large discharges from the rivers and (2) in the southern Bay of Bengal where clear oceanic waters of the equatorial origin are modified. From these regions the surface waters flow along the Indian coast. The coastal currents follow the prevailing winds of the monsoons. Thus from September to February the current is towards south along the coast with salinity ranging from 32·0 $^0/_{00}$ to 33·4 $^0/_{00}$ while in the remaining part of the year the current will be northerly. Also during this period salinity increases upto 34·5 $^0/_{00}$ (Sewell 1929). But very near the coast, though this circulation is in fairly good agreement, salinity values are much smaller often dropping to about 19·0 $^0/_{00}$ during the months of intense precipitation (Rama Sastry 1955). During winter, salinity gradually recovers to the normal oceanic value at a depth of about 10 m where the halocline forms (Balarama Murthy 1958). Also upwelling and sinking occur along the coast during February to April and from October to December respectively. These vertical circulations lead to mixing giving rise to an increase in the characteristic classes of the frequency distributions.

While these are the general conditions along the east coast of India, we shall examine the mean annual variation of temperature and salinity off Madras before discussing the frequency distributions. Mean monthly values of these parameters are presented in Fig. 1, together with the mean monthly precipitation for Madras. The variation of temperature is bimodal with maxima in May and October. But the mean annual variation of air temperature for Madras is unimodal with a maximum in May. Thus the first maximum of water temperature corresponds to that of the air temperature. The latter must be related to the change in circulation and to the fall of temperature of sea water immediately after the first maximum accompanying

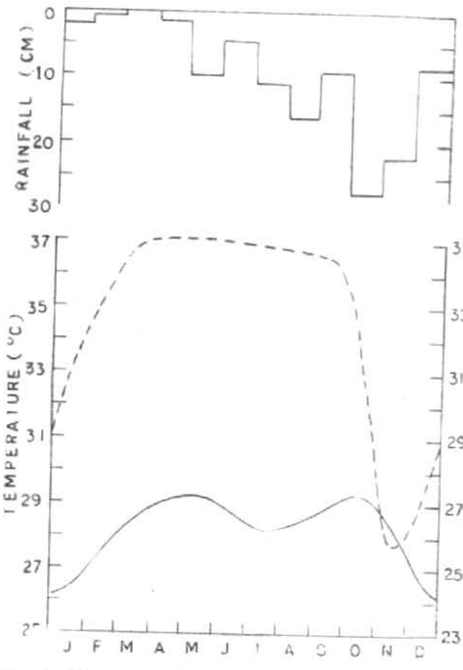

Fig. 1. Mean annual variation of temperature (solid curve) and salinity (dotted curve) together with mean monthly precipitation

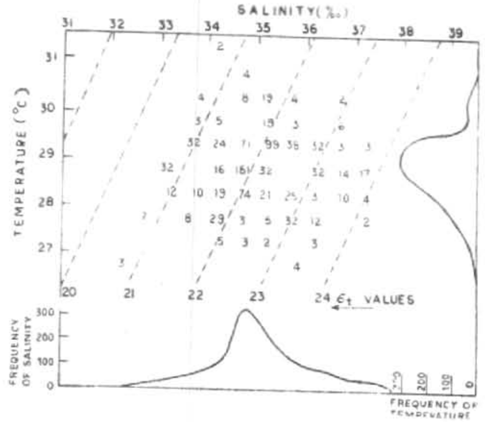

Fig. 2. Frequency distribution of temperature and salinity during March to June

upwelling along the coast. Mean salinity of Madras varies very little from April to September. Here it should be pointed out that the mean salinity ($S=35\cdot0\ ^0/_{00}$) during this period is too high compared to the open Bay conditions. This high value results from shallow water sampling in the harbour and also it might be partly due to the method of measuring it. However, the seasonal trend of salinity may not vary very much from the actual sea conditions off Madras. Salinity decreases very rapidly to $S=27\cdot0\ ^0/_{00}$ during the next two months and recovery to the normal takes place gradually in the remaining part of the year. The type of salinity variation is evident from the precipitation data (Fig. 1) and the southerly flow along the coast which brings in highly diluted waters from the head of the Bay. The minimum salinity occurs one month after the maximum precipitation. Reliable evaporation measurements are not available, but from the computational values of Venkateswaran (1956), it is seen that evaporation *minus* precipitation is maximum during December to February and minimum during September to November. Though this should be partly responsible for the observed time lag, local factors such as run-off etc should be of importance. These mean features together with temperature and salinity ranges are evident from the two dimensional frequency distributions.

Pollak (1958) finds the Andaman Sea and the Bay of Bengal surface water (far removed from coasts) as more diluted and distinct from that of the remaining Indian Ocean. This water lies within $T=25°$ to 30°C and $S=32\cdot0$ to $34\cdot0\ ^0/_{00}$. The central tendencies of the two dimensional distributions generally agree with the above, but the extreme values are related to the shallow water sampling and to the coastal influences. From March to September the surface current is northerly bringing high saline southern Bay of Bengal waters along the Indian coast. Thus during March to June (Fig. 2) high salinities are

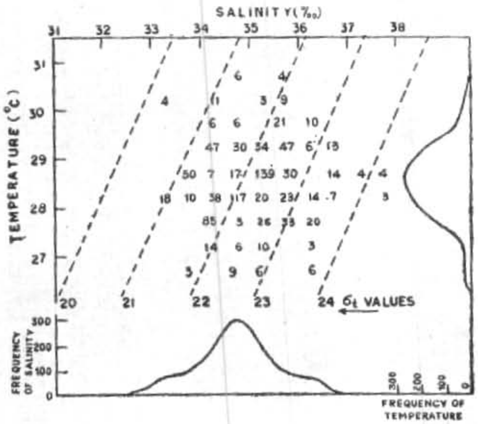

Fig. 3. Frequency distribution of temperature and salinity during July to September

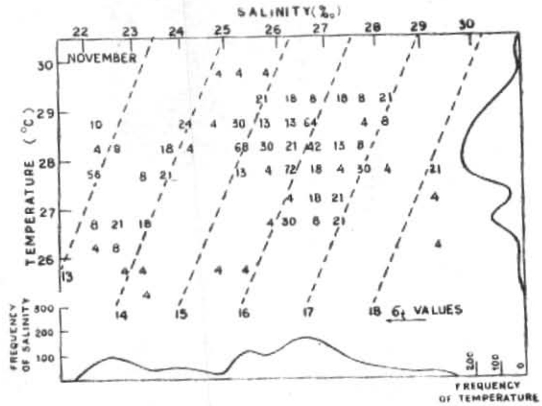

Fig. 4. Frequency distribution of temperature and salinity during November

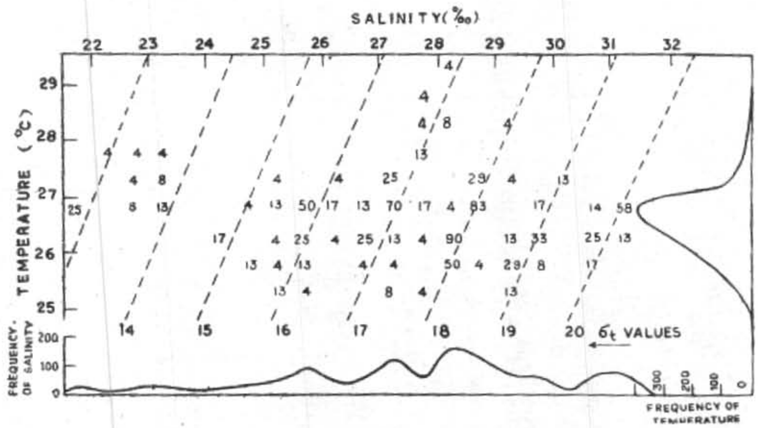

Fig. 5. Frequency distribution of temperatuie and salinity during December

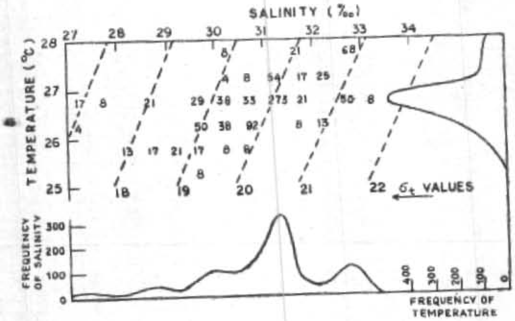

Fig. 6. Frequency distribution of temperature and salinity during January

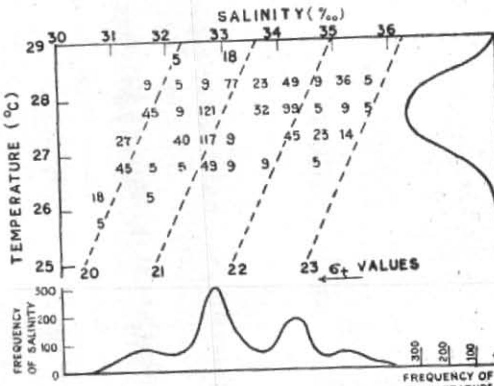

Fig. 7. Frequency distribution of temperature and salinity during February

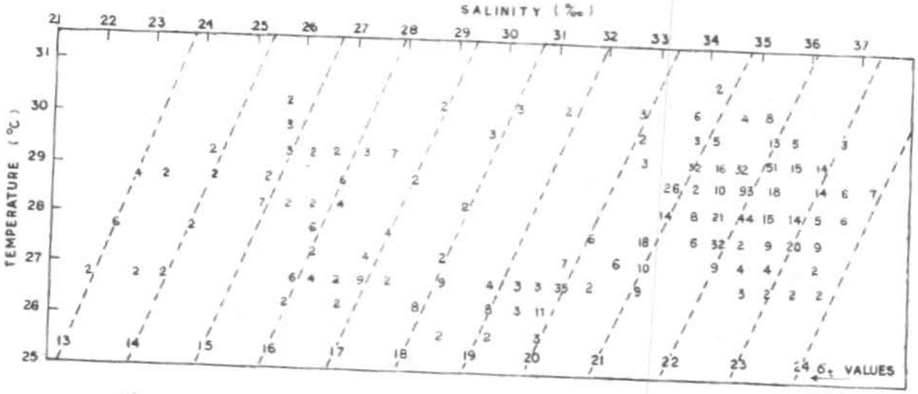

Fig. 8. Frequency distribution of temperature and salinity during the year

recorded. A major concentration of the frequencies occurs at $\sigma_t = 22 \cdot 0$ where about 40% of the observations are found. On either side of this modal value two peaks, at $\sigma_t = 21 \cdot 0$ and $23 \cdot 0$ are respectively related to the gradual recovery to maximum salinity and coastal secondary circulations. Though upwelling is more pronounced towards north of Madras (Rama Sastry 1955) from February to April, its influence is observable at Madras during the same period as the coastal circulation is in transition. The frequency curves of temperature and salinity are essentially unimodal corresponding to $T = 29°C$ and $S = 34 \cdot 75$ ‰.

During the next three months, *i.e.*, from July to September (Fig. 3) with the onset of monsoon surface salinity is decreasing though the southern Bay of Bengal water is still present. Distribution of temperature is more uniform during this period than in the earlier one. Thus 40% of the characteristics refer to the southern Bay of Bengal water, with σ_t between $22 \cdot 0$ and $22 \cdot 5$, and about 10% indicates local dilution. During the next month, dilution is very marked and traces of southern Bay water are still noticeable.

As a result of intense dilution, and transitary changes in the direction of coastal circulation during November (Fig. 4) salinity is multimodal, the chief one being between $S = 26 \cdot 0$ and $27 \cdot 0$ ‰ corresponding to $\sigma_t = 16 \cdot 0$. This water is mostly from the northern regions of the Bay. Thus the peak of the characteristics between $S = 25 \cdot 0$ to $27 \cdot 0$ ‰ and $T = 27 \cdot 5$ to $29 \cdot 0°C$ is the northern dilute water. The distribution of characteristics suggests non-uniform nature of dilution from year to year. Also the temperature distribution is bimodal, which could be attributed to the eddy processes off Madras observed in this part of the year by Rama Sastry and Balarama Murthy (1958).

In December (Fig. 5) the characteristics are more uniformly distributed and the northern dilute water is more prominent. The temperature shows a single mode at $26 \cdot 7°C$. By January (Fig. 6) with a further decrease in rainfall salinity is increasing gradually and still the northern dilute water is important. Nearly 30% of the characteristics fall only in two characteristic classes between $T = 26 \cdot 5°$ to $27 \cdot 5°C$ and $S = 31 \cdot 0$ to $31 \cdot 5$ ‰. In February (Fig. 7) the characteristics appear in three concentrations. While this is mainly due to the recovery of salinity to the normal, partly it might be due to the presence of off-shore waters.

The frequency distribution of the characteristics for the year (Fig. 8) shows three concentrations corresponding to the σ_t values $22 \cdot 0$, $21 \cdot 0$ and $20 \cdot 0$. In this diagram all frequencies less than $0 \cdot 1$% of the total frequency are not included. Then we obtain only about 90% of the characteristics included in the figure. About 30% of the water off Madras corresponds to $\sigma_t = 22\cdot0$ most of which is drawn from the southern Bay of Bengal. About 10% of the observations show high salinities because of sampling in shallow waters where evaporation would be considerable. It is to be expected that the northern dilute water would be about 30% though it is not possible to see any corresponding peak because of local dilution. The remaining part should be in transition influenced by mixing processes.

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