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High saline waters in Bay of Bengal

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Abstract. Bay of Bengal is well known for less saline waters in the surface layer of northern Indian Ocean. High saline waters of the Bay are considered as an influx from the Arabian Sea within a depth range of 200 to 900 m. Some of the recent observations in the western Bay of Bengal have shown salinity values higher than those reported earlier ($35{\cdot}2 \times 10^{-3}$). Such values are explained on the basis of regional climatology suggesting their local formation on the shallow continental shelf during pre-monsoon months and their subsequent distribution along the coast.

Keywords. High saline water; western Bay of Bengal; monsoon climatology.

1. Introduction

Formation of high saline waters (HSW) is well known in the tropical oceans. In the northern Indian Ocean, the waters with high salinity values have been reported in the Arabian Sea (Rochford 1964). Although the Bay of Bengal occupies the same tropical belt, the region has been considered as a source of low saline waters in the surface layer. This impression is because of large volumes of freshwater discharge from the rivers of Indian subcontinent. However, the high salinity waters of Bay have been reported as a mixture of the Persian Gulf and the Red Sea watermasses extending to the south of 14°N within 200–900 m depth with a maximum salinity of $35{\cdot}2 \times 10^{-3}$ (Rochford 1964; Varadachari *et al* 1968). While analysing the IIOE data, Wyrtki (1971) also showed a similar layer of HSW within 250 to 750 m depth along 88°E being intercepted by a low salinity water around 14°N. Subsequently, Sastry *et al* (1985) reported two high saline pockets within 80 m and 120 m depth around 8°N and 14°N along 88°E as remnants of the Arabian Sea HSW (ASHSW). The northern pocket is seen to have a higher concentration and a larger volume than that of south. This looks contradictory, since ASHSW enters through the southern boundary of the Bay, a low saline region. Further, ASHSW is expected to move eastward under the influence of southwest wind and the Coriolis effect, whereas the recent observations of salinity values $> 35{\cdot}2 \times 10^{-3}$ are reported in the western Bay of Bengal. These values are considered erroneous. However, no effort has been made to study their possible formation in the Bay itself. The present study has been attempted to justify their local formation and distribution under the prevailing climate of the Bay.

2. Hydrographic observations

The sporadic observation of HSW in the northern part of western Bay of Bengal (figure 1) during the late northeast (NE) and southwest (SW) monsoon is presented below.

2.1 *Northeast monsoon*

During the 13th cruise of *ORV Sagar Sampada* from 20 February to 19 March 1986 in the western Bay, the waters of salinity $> 35 \times 10^{-3}$ have been observed along 19°30′N (figure 2a) on the shallow shelf extending offshore in the form of a tongue-like feature. The density on the shelf ($> 22{\cdot}5\,\sigma_t$) was found comparatively higher than those of the offshore region (figure 2b). Dissolved oxygen has also shown features similar to that of salinity and density in the surface layer (figure not shown here). Comparatively high salinity values at around 30 m depth being sandwiched within the low saline

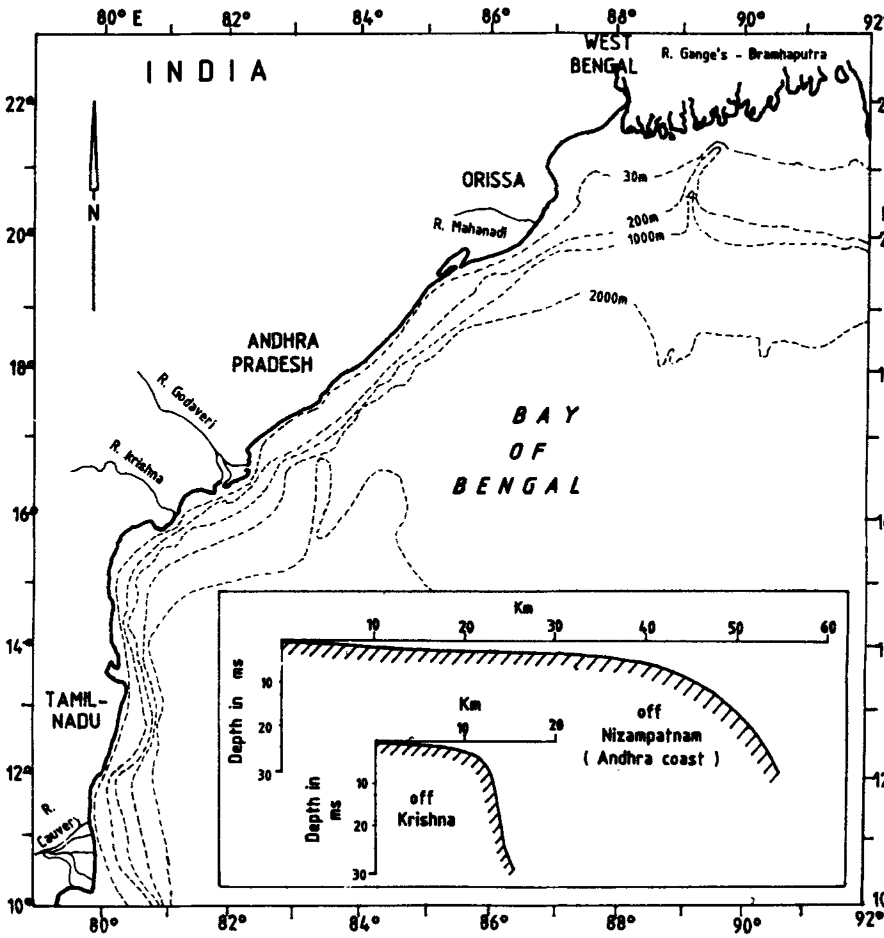

Figure 1. Map showing bathymetry of the western Bay of Bengal (inset: topography of the central region).

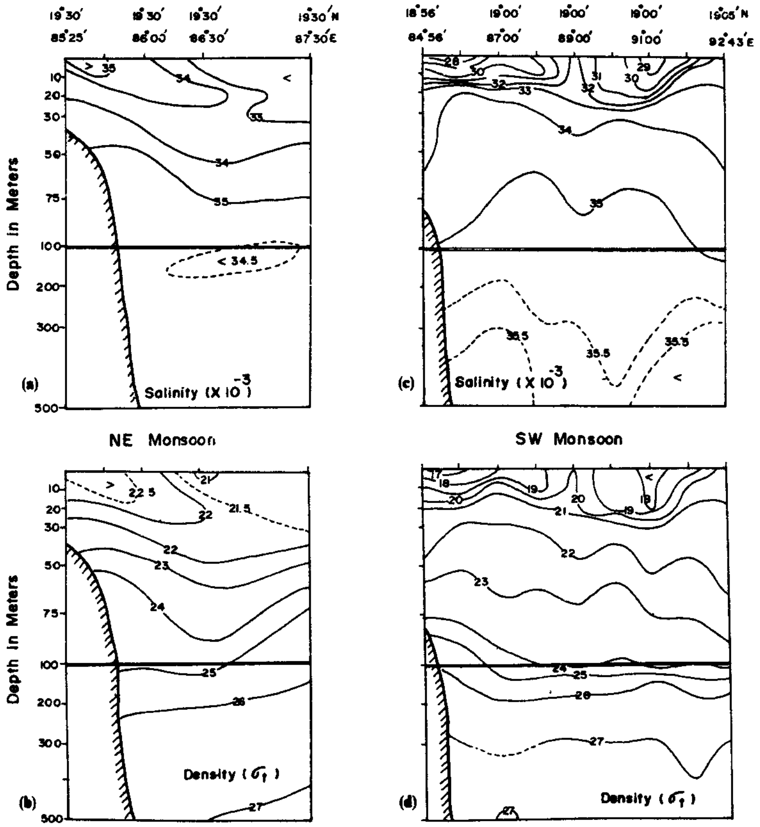

Figure 2. (**a**) Salinity and (**b**) density along 19°30′N during NE monsoon and (**c**) salinity and (**d**) density along 19°N during SW monsoon.

waters along 18°30′N (figure not shown here) indicate some local source of HSW along the coast.

2.2 *Southwest monsoon*

During the 7th cruise of *RV Gaveshani* from 26 August to 2 September, 1976, the waters of salinity $> 35 \times 10^{-3}$ have been encountered below 75 m depth along 19°N and 20°30′N of the northern Bay. Along 19°N (figure 2c), salinity $> 35{\cdot}5 \times 10^{-3}$ has been observed beyond 200 m depth with less saline waters (28×10^{-3}) in the surface layer. The high salinity waters associated with a density $> 23\,\sigma_t$ (figure 2) are found in the subsurface layer. The possible suppression of the high salinity waters under the buoyant low saline waters has been explained in the northwestern Bay of Bengal (Sasamal 1989).

2.3 *Annual mean salinity along the east coast*

The pockets of high salinity waters are seen in the atlas prepared on the basis of integrated annual average values from 1976 to 1980 (Sarupria *et al* 1988). The waters

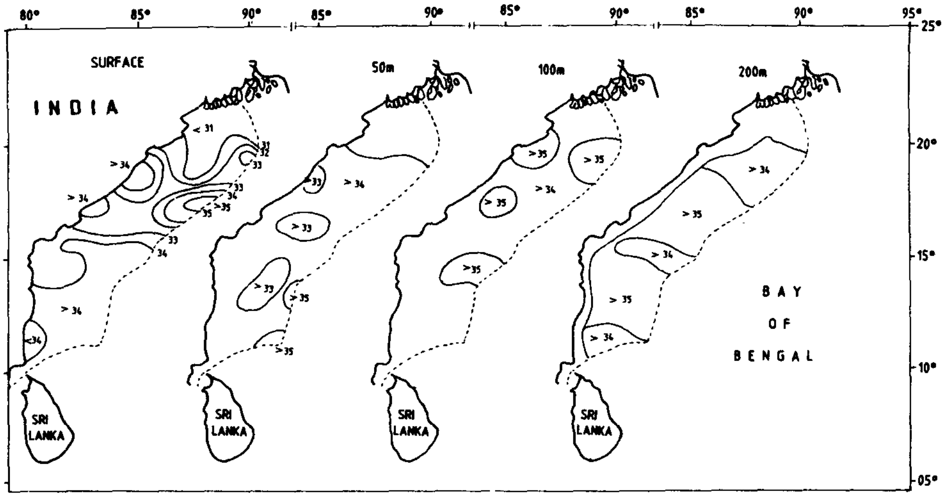

Figure 3. Salinity distribution at surface, 50 m, 100 m and 200 m level of EEZ along the east coast of India.

of salinity $> 35 \times 10^{-3}$ are seen in the surface layer around 18°N, 87°30'E and to the south of 14°N along 83°E (figure 3). At 100 m level, such waters are seen within 19°N and 21°N with a pocket along the coast extending 100–150 km offshore and another in the offshore region to the east of 88°E. At the 200 m level, the high saline features are encountered all along the coast with a low saline water extending from the offshore region along 15°N (figure 3).

2.4 *Surface hydrography along the east coast*

At four different stations along the east coast of India (La Fond 1957) high values of salinity are seen during dry months of the year (figure 4). The maximum salinities of $37{\cdot}54 \times 10^{-3}$ corresponding to a temperature of 23·78°C at the northern station (Saugor Island) and $36{\cdot}22 \times 10^{-3}$ with a temperature of 27·83°C at the southern station (Mandapam) have been observed. Some of the high salinity situations are presented in table 1.

3. Possible formation and distribution of HSW

3.1 *Climatic impact*

The high salinity situation observed above can be explained on the basis of climatic conditions prevailing along the coast. These waters possibly form on the shallow continental shelf under a dry climate with evaporation predominating precipitation. The region experiences two significantly different periods in terms of precipitation. The wet phase of an year covering the SW monsoon from June to October and the remaining months covering the NE monsoon are considered as wet period and dry period, respectively. The wet period receives about 90% of annual rainfall. While discussing the climatology of the area, Landsberg *et al* (1965) reported 5 to 7·5 months

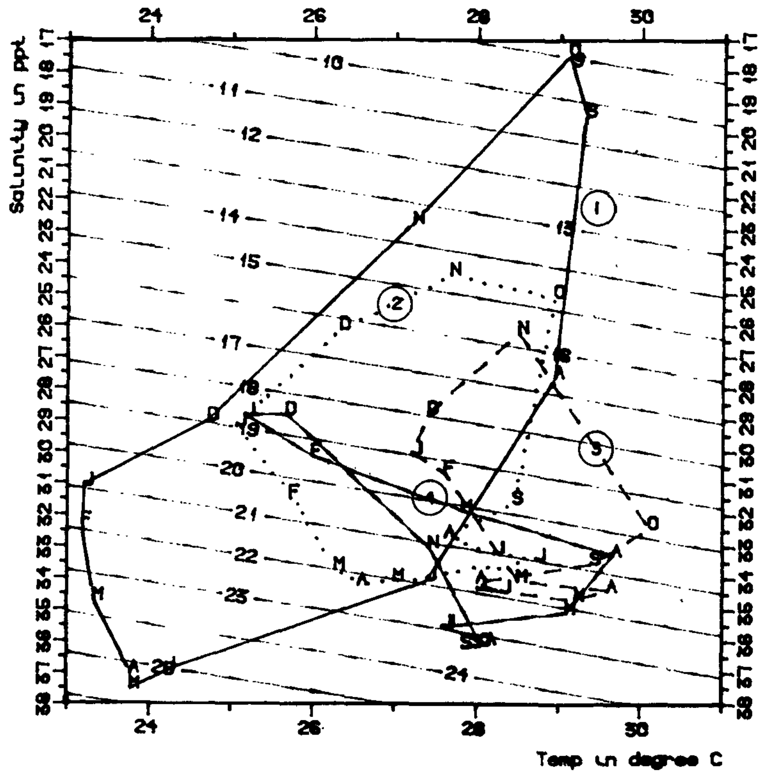

Figure 4. Hydrography of four coastal stations in the western Bay of Bengal. (1) Saugor Is, (2) Waltain, (3) Madras, (4) Mandapam.

Table 1. Surface high saline waters along the east coast of India.

Coastal station	Salinity ($\times 10^{-3}$)	Temperature (in °C)	Density (in σ_t)	Period (months)
Saugor Is.	> 37	< 24	25–26	Apr–June
Waltair	34	26–27	22	Mar–May
Madras	34	28–29	22	Mar–Sept
Mandapam	36	28	23	June–Oct

as the dry period. Rao *et al* (1971) have also shown a gradual change in climate along the coast from humid in the north to semi-arid in the south. Rao (1981) reported about 78% percent of annual rainfall during June to September in 50 to 75 rainy days. So, an effective dry spell of around 200 days is experienced during November-May with negligible rainfall along the coast. This is further confirmed from the percentage of rainfall frequency (figure 5a) reported over the Bay (Hastenrath and Lamb 1979a; Ramage *et al* 1972). Since the quantitative information on rainfall over the shelf is meagre, 75% of the values of adjacent coastal weather stations (figure 5b) can be considered (Jacobs 1968). Recent estimations of INSAT-1B-derived quantitative precipitation over the Bay (Anon 1988) also support the idea of a long spell of dry

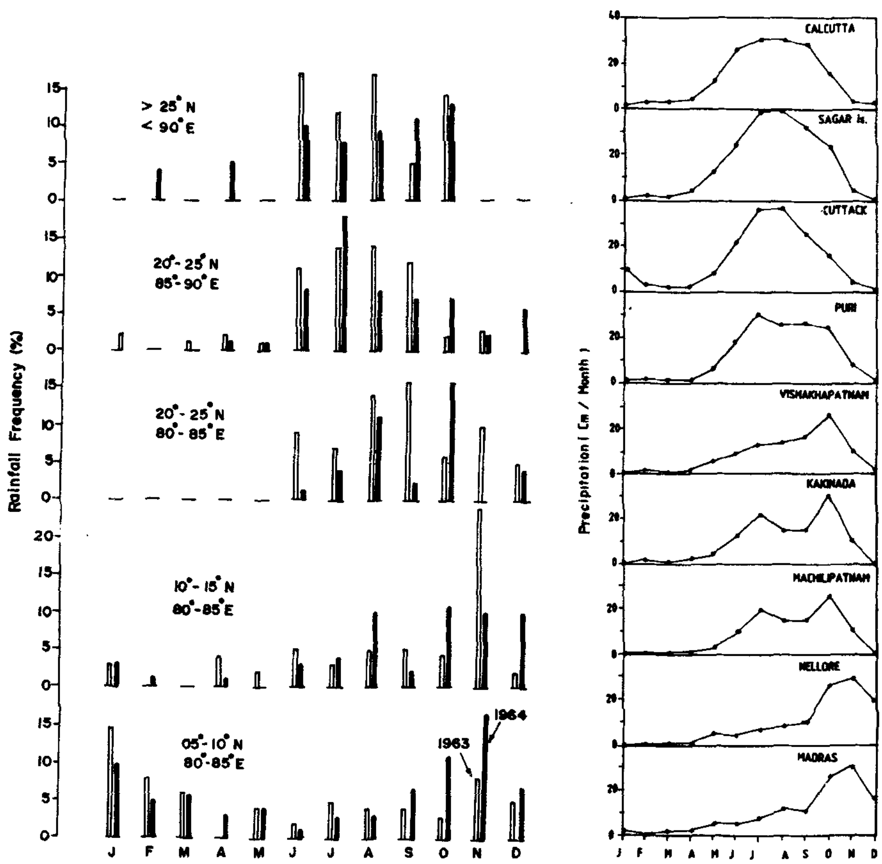

Figure 5. (a) Rainfall frequency in the western Bay of Bengal and (b) quantitative precipitation at the meterological stations along the east coast of India.

weather over six months. Further, the spatial and temporal variability of rainfall can also be followed from the trend of river run-off along the coast (figure 6). In addition, climatic variability with extreme situations is not uncommon to this region (Parthasarathy 1984; Mooley and Parthasarathy 1984). Quasi-biennial failure of monsoon further reduces the freshwater run-off over the shelf and increases the spell of dry period.

In addition to the reduced precipitation, an increased rate of evaporation over the shelf will have a considerable influence on the surface waters. Hastenrath and Lamb (1979b) reported about 3 to 6 mm/day of evaporation during pre-monsoon months. The rate of evaporation computed (Appendix A) on the basis of IIOE data (Ramage *et al* 1971) also shows > 5 mm/day during pre-monsoon months (figure 7). While discussing the seasonal water balance over the Bay, Varkey (1986) reported a net loss of water about 297·1, 292·2 and 266·8 mm during June-August over the areas within > 20°N, < 90°E, 15°–20°N, 80°E–85°E and 10°–15°N, 80°–85°, respectively and 213·8 mm during December-February in the south (5°–10°N, 80°–85°E). Subbaramayya and Rao (1984) reported a rather high value of evaporation with a mass flux of $19{\cdot}10 \times 10^{10}$ ton/day during June over the entire Bay. Harenduprakash and Mitra (1988) reported an annual mean turbulent masss flux of about -2 to -3×10^{-6} Kg·m^{-2}

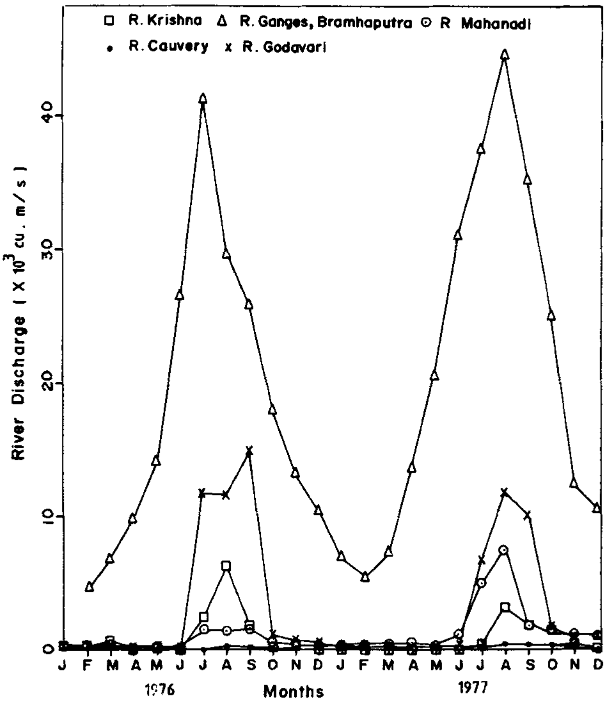

Figure 6. Major river discharges along the east coast of India.

s^{-1} of which the freshwater flux is about 75% during December to February in the northern Bay.

Further, the ocean dynamics of this area also plays a significant role in the formation of HSW. The flow is northward along the coast before the onset of monsoon rainfall, which transports warm and high saline equatorial water into the Bay (Varadachari and Sharma 1967). This turns southward with the change in season (La Fond 1958). The wind stress curl and circulation dynamics during February to June supports the coastal upwelling (La Fond 1954; Shetye *et al* 1985), which lifts the subsurface high salinity water on to the shelf. The salinity of the water is further enhanced during the dry months over the broad shallow continental shelf along the coast. The shelf is broader in the northern part covering 15% of the area within 10 m depth and 80% within 20 m depth. Therefore, the chances of HSW formation are more favourable on the northern shelf.

3.2 *Schematic representation*

Since the salinity is a conservative property of the sea water, the change in salinity over the shelf during the dry monsoon months can be represented by mass conservation equation as,

$$S(1)\,V(1) = S(2)\,V(2),$$

where S is the salinity and V, the volume with bracketed numbers representing two different states of waters over the shelf area of A and depth H. For a certain area over

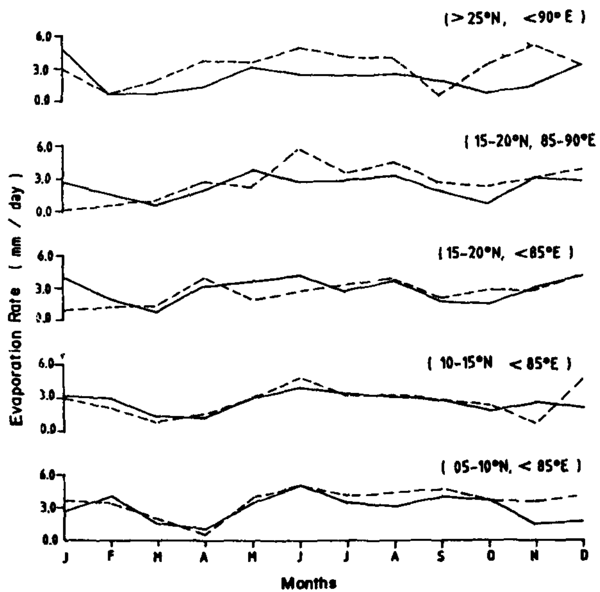

Figure 7. Evaporation rates based on IIOE meteorological data during 1963 and 1964 in the western Bay of Bengal.

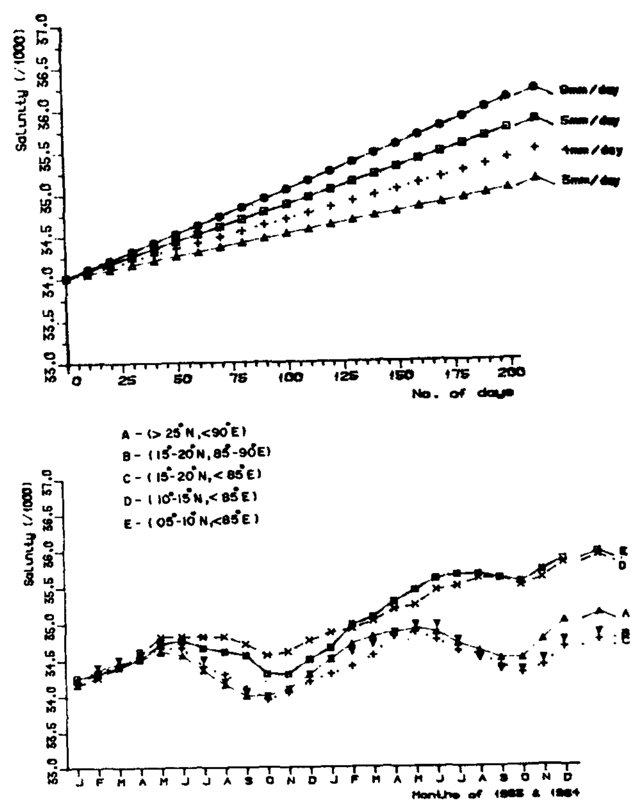

Figure 8. (a) Salinity computed for 200 days over the shelf area of an average depth of 20 m at the evaporation rates of 3 to 6 mm/day with an initial salinity of 34×10^{-3} (b) the monthly march of salinity computted over an shelf area of 20 m average depth with an initial salinity of 34×10^{-3} in January considering the climatic conditions of the western Bay of Bengal.

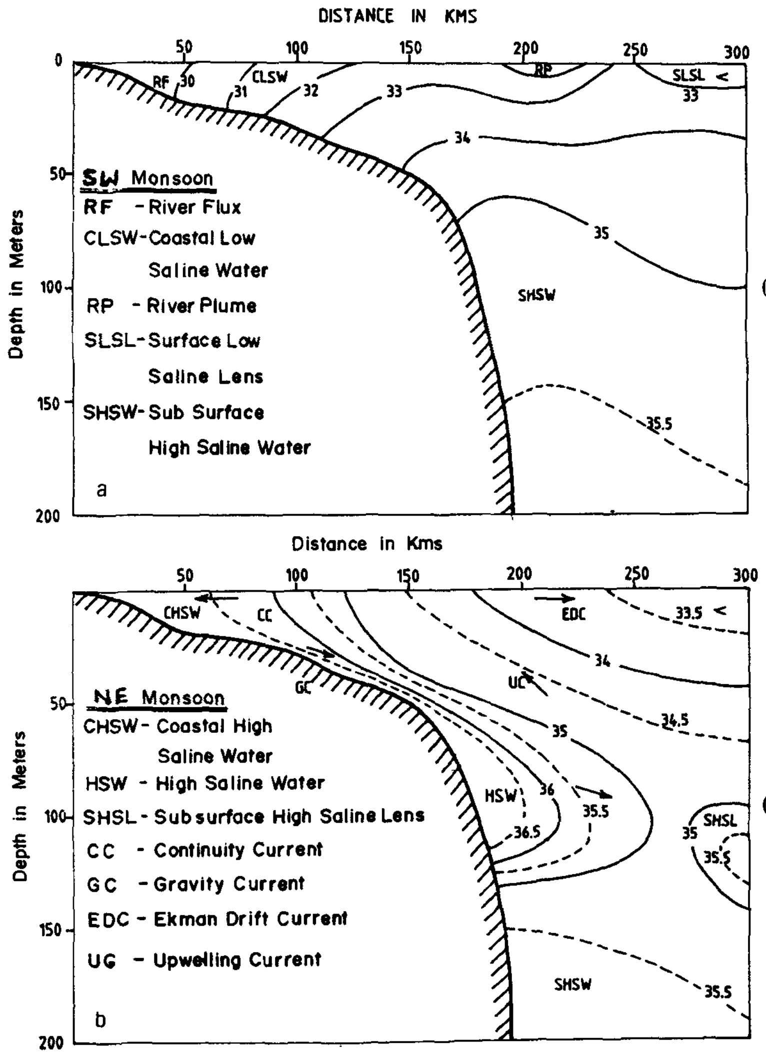

Figure 9. Schematic picture showing salinity distribution during (**a**) NE monsoon and (**b**) SW monsoon.

the shelf, the salt content depends on the depth of water column. In the western Bay, salinity in the surface layer varies within 32–35 $\times 10^{-3}$ annually (Wyrtki 1971; Sarupria *et al* 1988) except in the regions close to the river mouth. So, the waters of salinity 34 $\times 10^{-3}$ on the continental shelf with an average depth of 10 m evaporating at 4 mm/day is adequate to enhance the salinity by 8% over 200 days, which amounts to 36·67 $\times 10^{-3}$. Figure 8a shows the increment in salinity at different evaporation rates (3 to 6 mm/day) over an average depth of 20 m with an initial salinity of 34 $\times 10^{-3}$ over 200 days of dry period. Even the salinity computed considering the climatic conditions along the east coast of India shows values $> 35 \times 10^{-3}$ during the pre-monsoon months in the north and during post-monsoon months in the south (figure 8b).

HSW thus formed during the dry months on the shelf (figure 9a) as the coastal

HSW (CHSW) cascade at the shelf break due to high density and distributed as the pockets of HSW in the subsurface layer of offshore region at their isopycnal depth, termed as the subsurface high saline lenses (SHSL). During the subsequent period in the SW monsoon, a large volume of freshwater run-off (RF) over the shelf forms the coastal low saline waters (CLSW), which spreads as the low salinity plume (RP) close to the coast and as the low saline lens (SLSL) further offshore (figure 9b). Beyond the shelf break, these SLSL remain on the surface due to their high buoyancy, which have little influence on the subsurface HSW. However, HSW and SHSL lose their indentity in course of time either by merging with the subsurface HSW or due to intense mixing with the surrounding waters of comparatively low salinity.

4. Discussion

The situation as hypothesized above on the basis of local climatology (figures 8a, 8b) supports the high salinity values observed in the western Bay of Bengal (figures 2–5). It is interesting to note that this situation is observed more frequently in the northern Bay than in the southern part. The maximum salinities reported at the northern station at Saugor Island during March–July are higher than those of the southern station at Mandapam during November–January with comparatively low values at the central stations (table 1). The range of temperature and salinity values at these stations reflect the climatic conditions prevailing along the coast. The change in the periods attaining peak salinity can be explained in terms of temporal and spatial variation in rainfall along the coast, which shows a time lag of four to five months from north to south. It is well known that the northern India experiences peak rainfall during summer monsoon from July to September and the southern peninsula during winter monsoon from November to January (Das 1984).

Low values of high salinity in the central region is possibly due to the narrow shelf producing a small volume of HSW which loses their significance in a short period under the influence of alongshore dynamics. A multi-gyral system with anti-cyclonic gyres in the north and the south during the pre-monsoon months (Rao and Sastry 1981; Legeckis 1987; Rao *et al* 1987) is expected to converge the low salinity waters in the central region along with river run-off from the Krishna and the Godavari. In addition, a convergence zone of low saline waters at the central region as reported by Gangadhara Rao and Jayaraman (1968) and Wyrtki (1971) along 14°N intercepting the HSW of the Bay along 88°E also supports the reduction in maximum salinity. Further, the western boundary current as observed by Legeckis (1987) during the late February is also expected to carry low saline waters of the south to the central region.

The persistence of HSW in the north compared to that of the southern part can be explained on the basis of density during their formation. The density of the northern HSW is high due to low surface temperature attained either due to winter cooling (as seen in the GOSSTCOMP SST charts), upwelling during the pre-monsoon months (La Fond 1954; Murty and Varadachari 1968) and heat loss due to evaporation. This is further evident from the monthly hydrography along the east coast (figure 4) showing a low temperature of about 24°C during April–June with a salinity $> 37 \times 10^{-3}$ which results in a density of 25–26 σ_t at the northern station (Saugor Island) and a maximum salinity of $> 36 \times 10^{-3}$ at Mandapam in the south during June to October with high temperature of 28°C which attains a density of 23 σ_t (table 1). The HSW on the shelf after attaining density higher than that of surrounding waters sink to its corresponding isopycnal depth of around 200 m in the north and around 50 m in the south. So, the high salinity characterstics of the north is protected from early degeneration due to its sinking beyond the mixed layer depth of about 60 m (Colborn 1975). However, the increment in density of the HSW formed in the south being low due to thier formation in the late summer monsoon months remains in the surface layer. Therefore, these waters are possibly degenerated at an early period due to strong dynamical mixing under strong winds (see Hastenrath and Lamb 1979a). Further, the strong stratification of the northern waters than that of the south (Sastry and Rao 1981) supports the stability of the northern HSW in the subsurface layer for a longer period than that of the southern counterpart in the surface layer.

As the river run-off and precipitation in period subsequent to the formation of HSW are quite large, their mixing with the HSW needs further discussion. In the absence of proper studies on the influence of rivers on shelf waters of the Bay, the situation can be followed with an analogy to the South American river, the Amazon, which forms a plume spreading over 100 km from the coast extending to a depth of 10 m at the surface (Curtin 1986). In the context of Indian rivers, the maximum run-off of the Ganges and the Bramhaputra amounts about 11 times lower than that of River Amazon. So, the influence of Indian rivers flowing into the Bay will restrict to an area smaller than that of Amazon plume with a depth of about 10 m on the surface layer. The HSW in the subsurface layer remains undisturbed, unless the dynamics of the area is sufficient to mix the water column to the depth of HSW penetration. The energy required to mix waters across the pycnocline front separating the river run-off of the Ganges and the HSW formed on the northwestern Bay (Blanton and Atkinson 1983) is about 145 Wm^{-2} (Appendix A) during the early monsoon days, whereas the energy available for mixing is about 6 to 8 Wm^{-2} corresponding to the maximum current reported by Bhattacharya and Gotenkar (1968) and Rao *et al* (1987). So, the large deficit in energy across the front possibly restricts their immediate mixing, thus maintaining the characterstics of HSW for a considerable length of time.

Further, the sporadic observation of the high salinity values can be explained estimating the volume HSW on the shelf. Over a shelf area of 100 km along the coast extending 50 km offshore of an average depth of 20 m with waters of salinity 33×10^{-3} evaporating at a rate of 5 mm/day over a dry period of 200 days will form 55 km^3 of HSW with salinity of 36×10^{-3} Appendix. This water attaining an increment of density (10^{-2}) will flow at a speed of 0·18 m/s Appendix which takes about 3·22 days to reach a distance of 50 km from the coast. This water as it sinks at the shelf break possibly spreads over an area of about 26·46 km in diameter within a isopycnal layer of 100 m in the offshore region. The pockets of HSW thus formed are therefore too short in the area to be covered under the presently planned station locations at a separating distance of 1° lat./long. in the Bay of Bengal.

5. Conclusion

The formation and distribution of HSW in western Bay appear to be controlled by the duration of dry period, intensity of freshwater run-off and dynamical mixing along the coast. The northern Bay seems to be a favourable region for sporadic observation of high salinity values than that of the south. The waters of high salinity form in the north during pre-monsoon months (April–June) and in the south during monsoon months (June–October). Although the observational evidences are few, these support the idea of local formation of HSW. A sufficiently good quality hydrographic data are essential with better temporal and spatial resolution for a longer period. This will certainly be much useful for discussing the detail of HSW formation and distribution in the Bay in addition to their further confirmation.

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Appendix A

1. The rate of evaporation is estimated using IIOE meteorological data (Ramage *et al* 1982) as

$$E = 4{\cdot}6045 \times 10^{-2}(P_s - P_a)U_a \,\text{mm/day} \tag{1}$$

where P_s, P_a and U_a are the saturated vapour pressure and atmospheric vapour pressure in mb and wind speed in m/s.

2. The increment in salinity (dS/dt) is computed with an initial salinity (S) of 34×10^{-3} as

$$dS/dt = (Q_e/L - P)S/D \tag{2}$$

where Q_e the evaporative heat loss during IIOE (Ramage *et al* 1972), L the latent heat of evaporation, p the rate of precipitation at the coastal weather stations along east coast of India as specified in the (Anon 1978) and D the depth in meters.

3. The energy required for mixing can be obtained as,

$$dv/dt = ((H - h)/2)dB/dt - (B/2)(dh/dt) \tag{3}$$

where B ($= \rho' gh$) the buoyancy flux and ρ' the density deficit in the surface layer of thickness h, over a water column of depth H in meters. Neglecting the second term of R H S representing the initial energy required for mixing (Fearnhead 1975) is

$$dv/dt = ((H - h)/2)\rho' N_0. \tag{4}$$

The rate of change in buoyancy flux is,

$$dB/dt = \rho' N_0 \tag{5}$$

and the net buoyancy flux across the air-sea interface is given as,

$$N_0 = g/\rho_0((Q_s - LE)\alpha_v/C_p - ES)$$

where Q_s is the sensible heat flux, L the latent heat, α_v the volumetric coefficient of thermal expansion and E the rate of evaporation and S the increment in salinity (Phillips 1966).

Considering a thin layer of buoyant fluid at the surface ($H \gg h$)

$$dv/dt = (H/2)\rho' N_0 \text{ in Wm}^{-2}. \tag{6}$$

If precipitation exceeds evaporation, then the buoyancy flux becomes

$$N_0 = g/\rho_0(Q_s(\alpha_v/C_p) + F) \tag{7}$$

where F is the freshwater flux in $\text{kg} \cdot \text{m}^{-2}\,\text{s}^{-1}$.

The energy available for mixing across the pycnocline front is given as,

$$dE/dt = B\rho_0 C_d U_b^3 \tag{8}$$

where E the tidal energy, B the efficiency factor (0·01–0·02), C_d the drag coefficient (2–6×10^{-3}) and U_b the tidal current. For a current amplitude varying sinusoidally, the value is multiplied by $4/3\pi$ (Blanton and Atkinson 1983).

4. The amount of HSW formed on the shelf is calculated following Lennon *et al* (1987) as,

$$0 = A \cdot E \cdot S/DS \tag{9}$$

where E the evaporation rate of 5 mm/day over 200 days, S the initial salinity of 33×10^{-3} and DS the increment in salinity expecting 3×10^{-3} over a shelf area of 100 km alongshore and 50 km cross-shore.

5. The rate of flow of the HSW (Komar 1977) is given as

$$u = (g' h \sin\theta/k)^{1/2} \tag{10}$$

where $g'(= g\rho'/\rho)$ the reduced gravity of order 10^{-2}, θ the slope angle (10^{-3}) for a shelf area of 20 m average depth and k the combined coefficient of bottom and inter-facial friction of about 6×10^{-3}.

References

Anon 1978 *Bay of Bengal Pilot* published by Hydrographers of the Navy, England

Anon 1988 *Satellite derived monthly mean precipitation and outgoing longwave radiation maps over India and neighbourhood for the period June 1986 to December 1987*, Meteorological Monograph, Sat. Met/No.3/1988, India Meteorological Department, New Delhi

Bhattacharya S K and Gotenkar S T 1968 The estuary of the Hooghly; *Bull. Natl. Inst. Sci. India*, **38** 26–32

Blanton J O and Atkinson L P 1983 Transport and fate of river discharge on the continental shelf of the south-eastern United States; *J. Geophys Res.* **88** 4730–4738

Colborn J G 1975 *The thermal structure of the Indian Ocean* (Honolulu: East-West Center Press) p. 173

Curtin T B 1986 Physical observation of the plume region of the Amazon river during peak discharge – II. Watermasses; *Cont Shelf Res.* **6** 73–86

Das P K 1984 *Monsoon – A prospective* (New Delhi: Indian National Science Academy) pp 52

Fearnhead P G 1975 On the formation of fronts by tidal mixing around the British Isles; *Deep-Sea Res.* **22** 311–321

Gangadhara Rao L V and Jayaraman R 1968 Hydrographical features of the southern and central Bay of Bengal during the transition period between winter and summer; *Bull. Natl. Inst. Sci. India* **38** 184–205

Gopalkrishna V V and Sastry J S 1985 Hydrography of the western Bay of Bengal during SW monsoon; *Indian. J. Mar. Sci.* **14** 62

Harenduprakash L and Mitra A K 1988 Vertical turbulent mass flux below the sea surface and air-sea interaction—monsoon region of Indian Ocean; *Deep Sea Res.* **35** 333–346

Hastenrath S and Lamb P J 1979a *Climatic Atlas of the Indian Ocean, Part I: Surface Climate and Atmospheric Circulation.* The University of Wisconsin Press, 20pp + 97 charts

Hastenrath S and Lamb P J 1979b *Climatic Atlas of the Indian Ocean, Part II: Radiation and Heat Budget of the Ocean.* The University of Wisconsin Press, pp 104

Jacobs W C 1968 The seasonal apportionment of precipitation over the ocean; in *Electic climatology*, (ed) Court A (Corvallis: Oregon State University Press) 63–78

Komar P D 1977 Modelling of sand transport on beaches and the resulting shore line evolution; in *The Sea* Vol. 6 (New York: Wiley Interscience)

La Fond E C 1954 On the upwelling and sinking off the east coast of India; *Andhra Univ Memoirs Oceanogr.* **1** 171–121

La Fond E C 1957 Sea water density at four different stations along the east coast of India; *Indian J. Met. Geophys* **8** 1–5

La Fond E C 1958 Seasonal cycle of sea surface temperatures and salinities along the east coast of India; *Andhra Univ Memoirs Oceanogr* **2** 12–21

Landsberg H E, Lippmann H, Paffen K H and Troll C 1965 *World maps of climatology* (Berlin: Springer-Verlag) 228 pp + maps

Legeckis R 1987 Satellite observation of western boundary current in the Bay of Bengal; *J Geophys Res.* **92** 12971–12978

Lennon G W, Bowers D G, Nunes R A, Scott B D, Ali M, Boyle J, Wenju Cai, Herzfeld M and Wijffels S E A 1987 Gravity currents on the release of salt from an inverse estuary; *Nature (London)* **327** 695–697

Mooley D A and Parthasarathy B 1984 Fluctuations in All-India summer monsoon rainfall during 1877–1978; *Climatic Change* **6** 287–301

Murty C S and Varadachari V V R 1967 Upwelling along the east coast of India; *Proc. Symp. of Indian Ocean*, (New Delhi: Natl. Inst. Sci. India) 80–86

Parthasarathy B 1984 Interannual and long-term variability of Indian Summer monsoon rainfall; *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **93** 371–385

Phillips O M 1966 *The dynamics of upper ocean* (New York: Cambridge University Press) 261

Ramage C S, Miller F R and Jefferies C 1972 *Meteorological Atlas of the International Indian Ocean Expedition, Volume 1: Surface climate of 1963 and 1964*; (Washington: National Science Foundation)

Rao D P and Sastry J S 1981 Circulation and distribution of hydrographical properties during the late winter in the Bay of Bengal; *Mahasagar – Bull. Natl. Inst. Oceanogr.* **14** 1–15

Rao K H, Antony M K, Murty C S and Reddy G V 1987 Gyres of the Bay of Bengal; *Indian J. Mar. Sci.* **16** 9–14

Rao K N, George C J, and Ramasastry K S 1971 Climatic classification of India; *Sci. Rep. India Meteorol. Dept* **158** 1–9

Rao Y P 1981 The climate of the Indian subcontinent; in *World Survey of Climatology, Vol. 9: Climate of Southern and Western Asia*; edited by Landsberg H E, Takahasi K and Arakawa H (New York: Elesevier)

Rochford D J 1964 Salinity maxima in the upper 1000 meters of the northern Indian Ocean; *Aust. J. Mar. Fresh Water Res.* **15** 1–24

Sarupria J S, Reddy G V, Ghosh A and Pankajakshan T 1988 *Oceanographic Atlas of the Exclusive Economic Zone of India*; Ref no. 1370, N. I. O (CSIR), India, Figs. 44

Sasamal S K 1989 Hydrography of the northern Bay of Bengal during southwest monsoon; *Mahasagar* **22** 105–112

Sastry J S and Rao D P 1981 A comparative study of vertical stabilities in the Arabian Sea and Bay of Bengal; *Mausam* **32** 159–164

Sastry J S, Rao D P, Murty V S N, Sarma Y V B, Suryanarayana A and Babu M T 1985 Watermass structure in the Bay of Bengal; *Mahasagar – Bull. Natl. Inst. Oceanogr* **18** 153–162

Shetye S R , Shenoi S S C, Antony M K and Krishna Kumar V 1985 Monthly mean wind stress along the coast of the north Indian Ocean; *Proc. Indian. Acad. Sci. (Earth Planet Sci)* **94** 129–137

Subbaramayya I and Rao S R M 1984 Some mean meteorological conditions over the Bay of Bengal; *Mahasagar – Bull. Natl. Inst. Oceanogr* **17** 189–195

Varadachari V V R and Sharma G S 1967 Circulation of the surface waters in the northern Indian Ocean; *J. Ind. Geophys. Un* **4** 61–73

Varadachari V V R, Murty C S and Reddy C V G 1968 Salinity maxima associated with some subsurface watermasses in the upper layers of the Bay of Bengal; *Bull. Natl. Inst. Sci. Acad* **38** 339–343

Varkey M J 1986 *Salt balance and mixing in the Bay of Bengal*; Ph D Thesis, University of Kerala, Kerala (unpublished)

Wyrtki K 1971 *Oceanographic Atlas of the International Indian Ocean Expedition*, (Washington: National Science Foundation) pp 531