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The movement and implications of the Ganges–Bramhaputra runoff on entering the Bay of Bengal

Satish R. Shetye

The Ganges–Brahmaputra rivers discharge annually approximately 10^2 *m*^{3} *of freshwater into the Bay of Bengal at its northern end. We propose that the spread of this water, accompanied by mixing with the ambient waters, occurs in three phases. The Ganges–Brahmaputra discharge appears to lead to cooler sea surface temperatures in the northern Bay and to a stronger coastal current along the west coast of India, both during the northeast monsoon.*

THE Earth's hydrologic cycle is maintained in a quasi-steady state by a complex network of pathways transporting water between various natural reservoirs—oceans, atmosphere, rivers, etc. One component of this system is the riverine freshwater runoff to the ocean. It is of interest to determine how such a runoff spreads on reaching a sea, the dynamics underlying the spread and the impact it has on the ocean.

The Bay of Bengal offers an eminently suitable location to address these issues. The four major rivers bordering the Bay—Brahmaputra, Irrawady, Ganges and Godavari—discharge approximately 1.5×10^{12} m^3 of freshwater into the Bay[1]. About two thirds of this discharge comes from the Ganges-Brahmaputra (GB) rivers. Only three other rivers—Amazon, Congo and Orinoco—have annual discharge higher than the discharge of GB, which drains into the Bay at its northern end (Figure 1). Most of the discharge (72%) occurs during 5 months, June–October (Figure 2), a consequence of the southwest monsoon. The discharge carries with it a heavy load of sediments, but very little of it appears to escape the continental shelf; it most probably accumulates on the subaerial parts of the GB delta[2]. The path that the discharge follows as it moves in the Bay away from the mouth of GB is not known. In this paper we use hydrographic data and theoretical estimates of wind-driven circulation in the Bay to speculate on how the GB discharge may be spreading and the impact it might have on the Bay and surrounding region.

Seasonal cycle of surface salinity in the Bay of Bengal

A useful tracer to record spread of freshwater in the sea is salinity (weight of dissolved salts expressed as parts per thousand[3]). Freshwater being lighter than sea water

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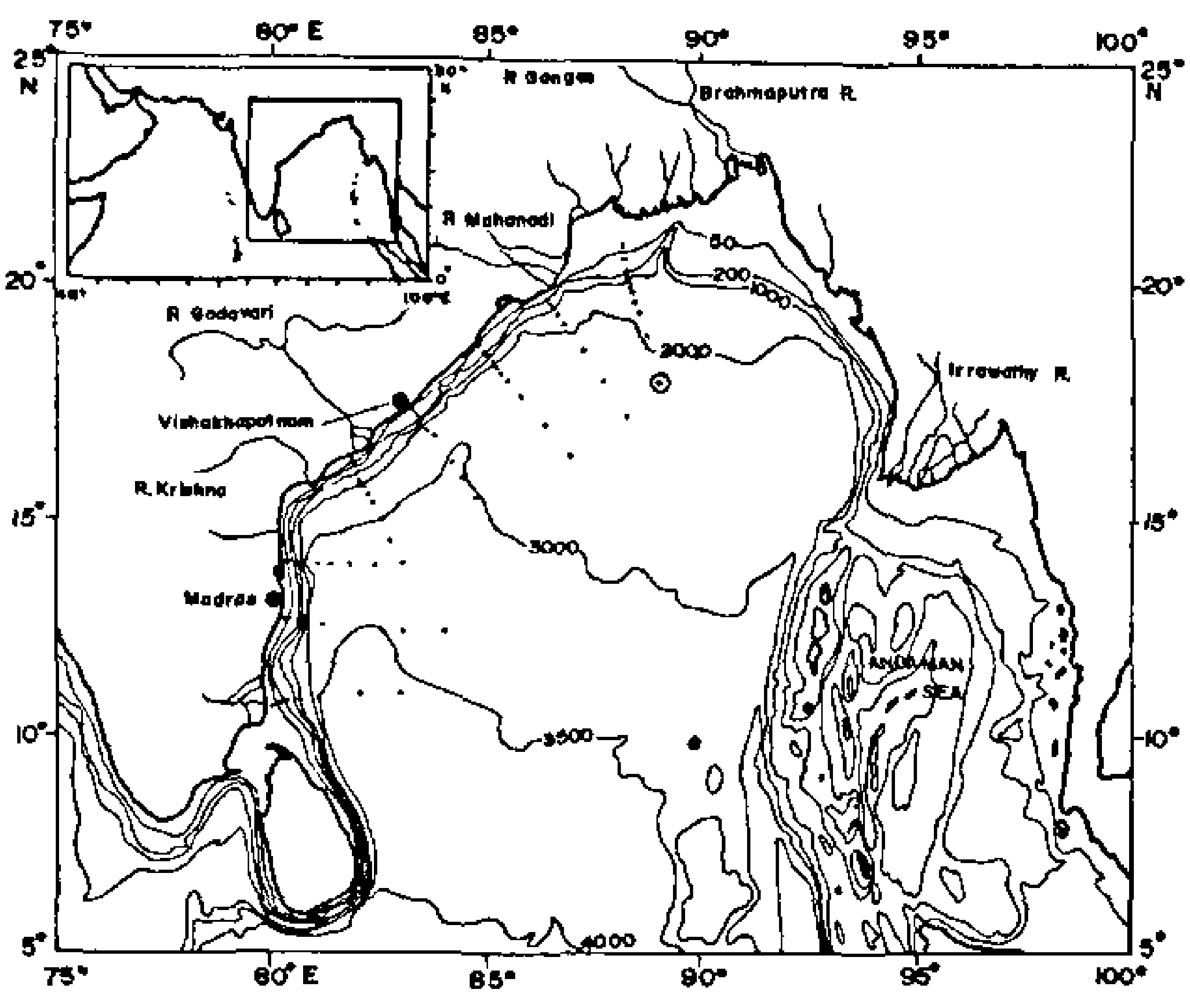


Figure 1. The Bay of Bengal. The bottom topography contours are in metres. The hydrographic stations where vertical profiles of temperature and salinity were measured are shown by dots. Observations from station at 18° 57′ N and 88° 44′ E, which is circled, have been used in Figures 3 and 8..

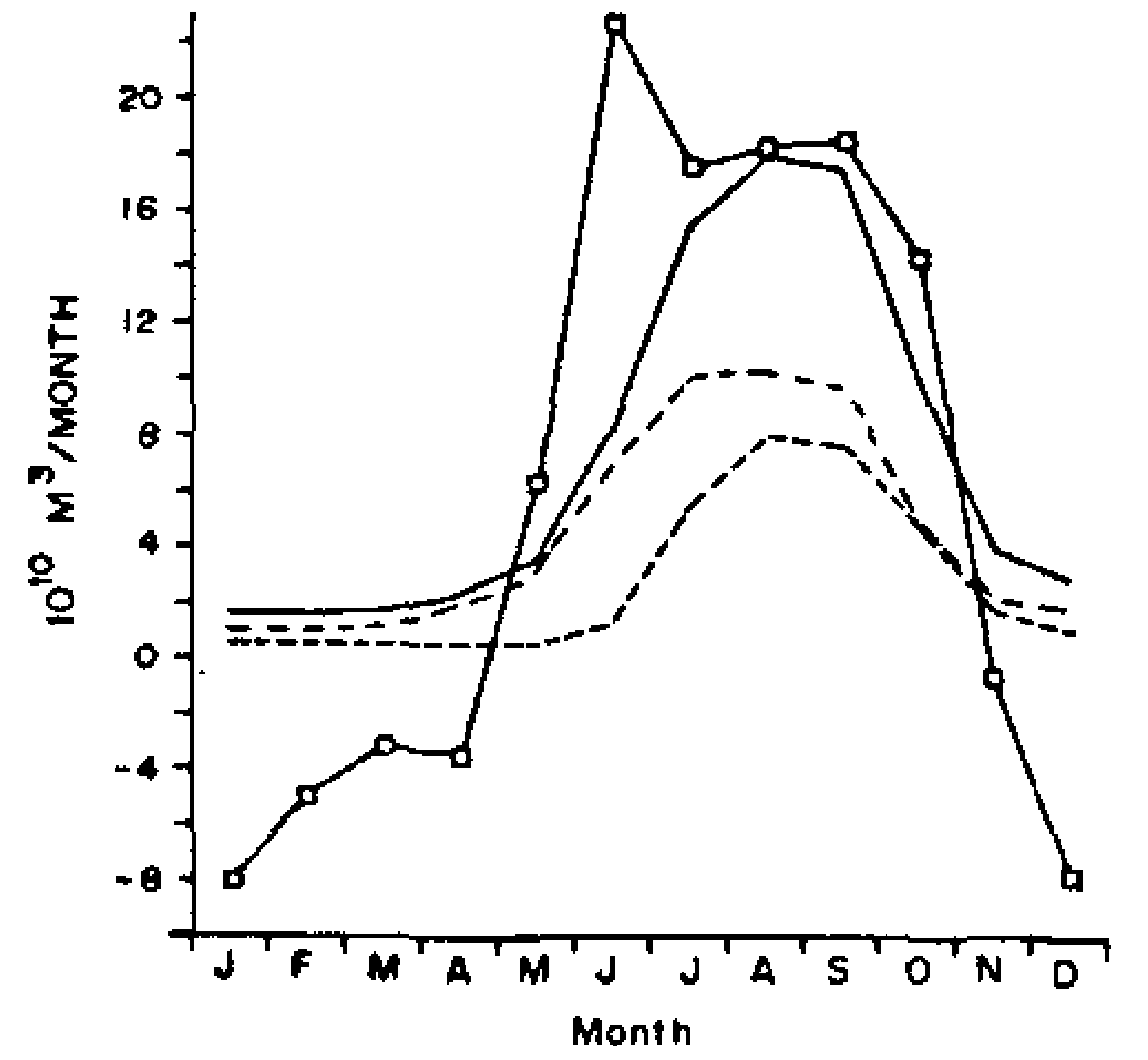


Figure 2. Monthly-mean freshwater influx (10^{10} m^3/month) to the northern Bay. Ganges (– – –), Brahmaputra (— — —) and sum of the two (————); data source; ref. 22. Integral of monthly-mean precipitation minus evaporation over the region north of 14° N in the Bay is shown by —□—□—; data source: ref. 10.

(typical salinity 35 ppt), tends to spread horizontally at surface, its salinity gradually increasing due to turbulent mixing with underlying waters. The mixing, however, is sufficiently slow to leave a trail in horizontal salinity sections. Our main data source to construct such sections is derived from the observations carried out in the western boundary region of the Bay of Bengal as part of a programme to study the annual cycle of the system of coastal currents around India[4-7]. The data, collected on board *ORV Sagar Kanya*, consist of vertical profiles of temperature and salinity at approximately 90 locations each (Figure 1) during three periods, March-April 1991, July-August 1989 and December 1991. A typical profile (Figure 3) shows a region of rapid increase in salinity in the uppermost 100 M, which is a peculiarity of this region arising from high freshwater influx to the Bay (see Box 1). In the world oceans it is generally the temperature variation which dominates vertical stratification. In the Bay this holds for depths greater than about 100 M. But for shallower depths, salinity dominates and often supports temperature inversions which are not commonly observed elsewhere (see Implications).

Before the southwest monsoon sets in, surface salinity in the western Bay is generally higher than 32 ppt and shows a marginal decrease from south to north (Figure 4*a*). During February–May a basin-wide anticyclonic gyre dominates the surface circulation in the Bay[7]. A well-developed, approximately 100 km wide, western boundary current along the coast of India transports northward about 10×10^6 m^3/s of southern warmer and more saline waters. A weak southward flow occurs over the rest of the basin.

As the southwest monsoon winds set in, the gyre begins to break down[7]. Simultaneously, the river runoff builds up (Figure 2). When the monsoon reaches its peak, as seen in the July–August 1989 data (Figure 4*b*), a 200–300 km wide low salinity tongue forms and migrates southward parallel to the coast, but does not hug the coastline[6]. An interesting feature of this tongue is the rapid change in salinity with depth. This is brought out by the contrast between salinity at the

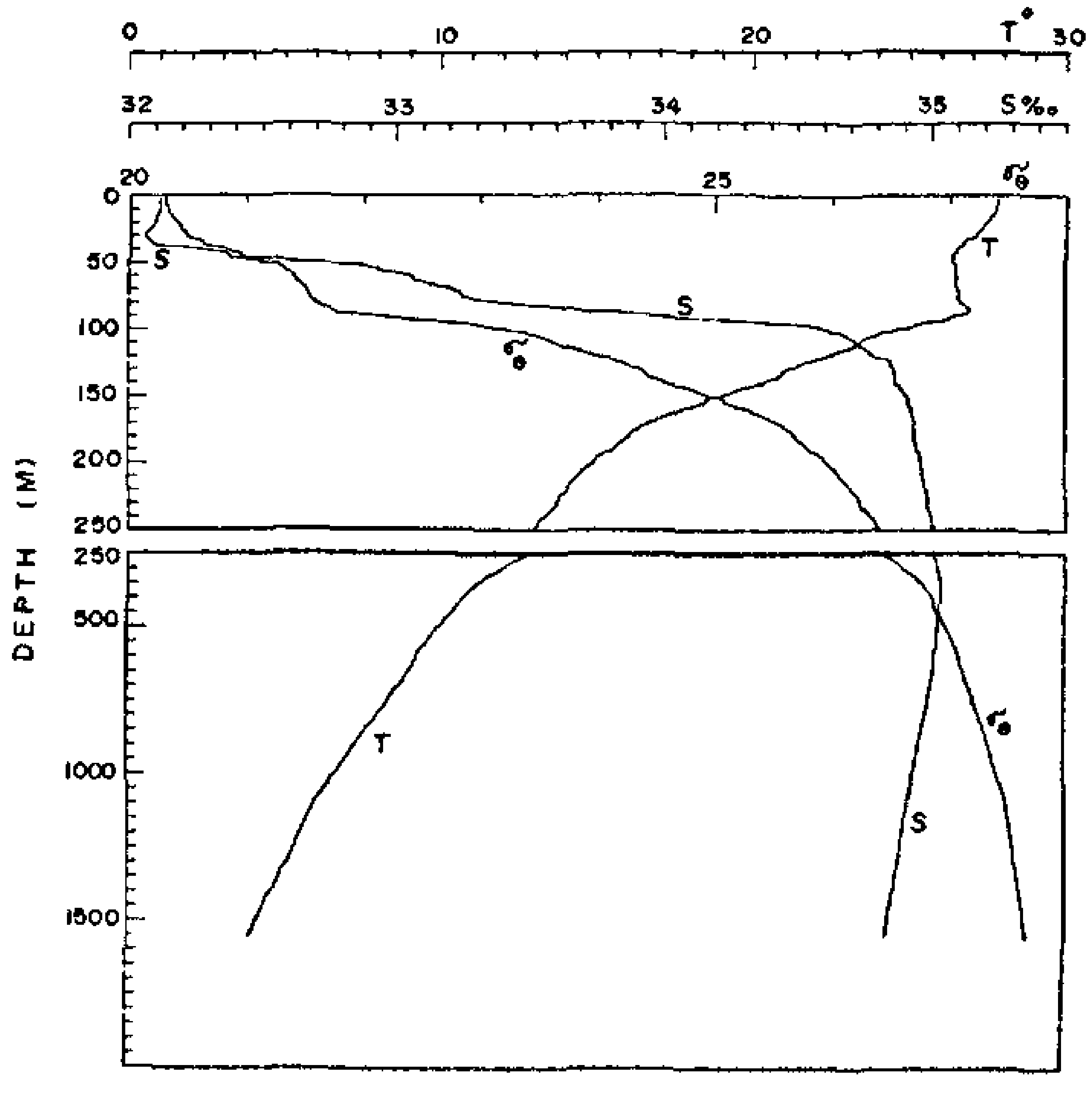
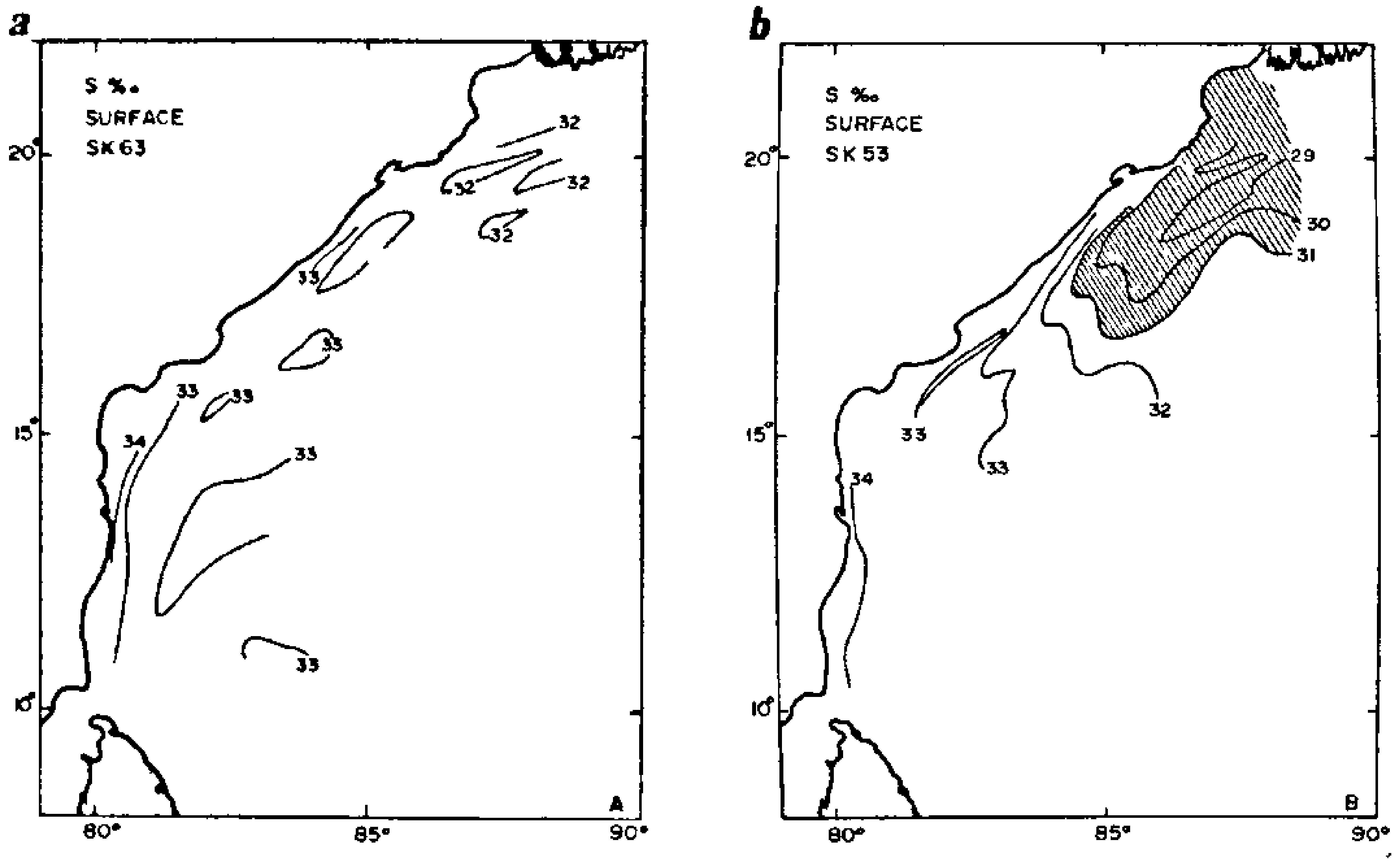


Figure 3. Typical vertical variation in salinity and temperature in the northern Bay before onset of the southwest monsoon. The data were collected at the station shown with a circle in Figure 1 during a cruise in March April 1991. Potential density is given by $\sigma_\theta = (\rho - 1)\ 10^3$, where ρ is the density of a fluid parcel brought to the surface adiabatically.

Box 1

In addition to the freshwater received from runoff, the Bay of Bengal receives freshwater from precipitation. The annual rainfall over the Bay varies between 1 m off the east coast of India to more than 3 m in the Andaman Sea and the coastal region north of it[8]. The annual evaporation over the Bay is about 1.5 m (ref. 9). Hence the net impact of precipitation and evaporation in the Bay is that the region off the east coast of India loses about 0.5 m annually, whereas the northern part of eastern Bay gains about 1.5 m. Most of the precipitation occurs during June–October whereas evaporation is fairly evenly spread through the year. The Bay receives[10] annually about 70×10^{10} m^3 as net influx (precipitation minus evaporation) at the surface over the area north of 15° N and about 90×10^{10} m^3 as influx from Ganges–Brahmaputra rivers (see ref. 22). If all this freshwater was spread over the area north of 15° N, it would raise the mean sea level by approximately 180 cm, and most of this increase would take place during June–October. There is, however, no evidence that such a change in volume takes place. The annual cycle of monthly-mean sea level at Visakhapatnam has an amplitude of about 40 cm and most of this variability appears to be related to dynamics of coastal currents[11]. Therefore an implicit assumption in our analysis is that the volume change of the Bay at any time is negligible.



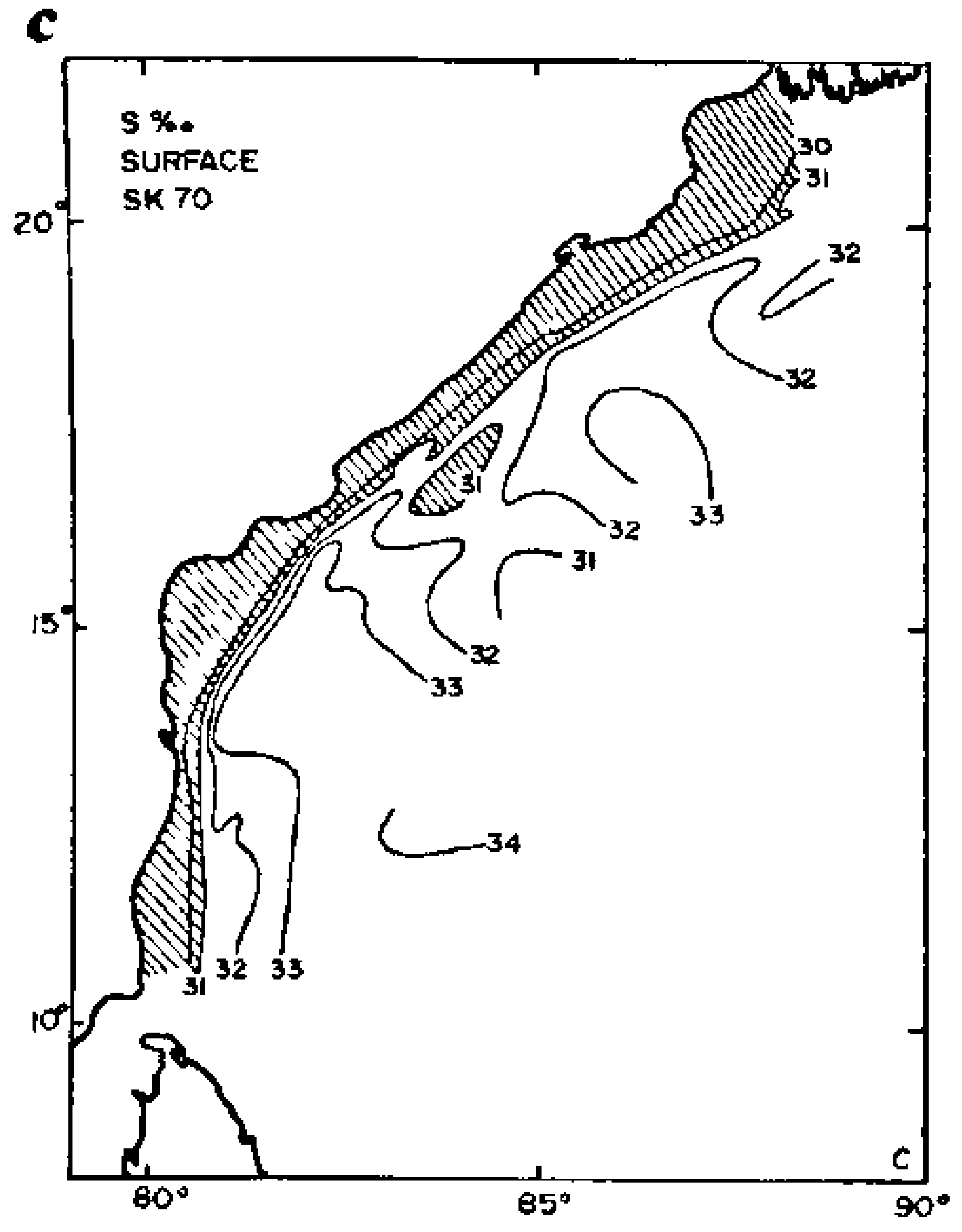


Figure 4. Salient features of the annual cycle of surface salinity in the Bay of Bengal. Contour interval is 1 ppt. Region with salinity less than 31 ppt is shaded. Contours less than 30 ppt are not shown to avoid clutter. *a*, Conditions before onset of the southwest monsoon are represented by data collected during March-April 1991 when salinities less than 31 ppt were not observed; *b*, During southwest monsoon, July-August 1989, salinities less than 31 ppt were found in a tongue which was detached from the coastline south of about 19° N. To avoid clutter contours less than 29 ppt are not shown. Salinities lower than 29 ppt, in fact, as low as 19.79 ppt, were observed close to the coast in northernmost part of the area surveyed[6]; *c*, During northeast monsoon, December 1991, salinities less than 31 ppt were found in a narrow band along the entire east coast of India. Contours less than 30 ppt are not shown to avoid clutter. Lowest salinity, observed close to the coastline, was 23.5 ppt.

surface (Figure 4*b*) and that at 10 m (Figure 5). The rapid variation with depth occurs in spite of the presence of persistent and strong southwest monsoon winds which are expected to introduce considerable turbulent kinetic energy into the ocean and mix the surface layers. The low salinity tongue, at least its part south of about 19° N, is separated from the coast by a 40 km wide band in which the surface flow is swift and northward[6].

The data in Figures 4 and 5 raise the following questions. How is the rapid vertical variation in salinity sustained in the low salinity tongue in spite of vertical mixing? What makes the low salinity tongue in Figure 4*b* migrate southward, and how is it kept separated from the coastline? We propose that the role of the annual cycle of winds over the Bay is crucial to address these questions, and that under the influence of the winds the GB discharge spreads in three distinct phases.

It is well known that, due to the Coriolis effect, winds induce in the ocean surface layer (Ekman layer[3], a few tens of metres deep with rapid velocity decay with depth) a velocity component normal to the winds. Though the vertical structure of the component can be complicated, a robust result is that in the northern hemisphere the vertical integral of velocity in the layer, the Ekman transport, is to the right of the wind direction. Due to the southwesterly monsoon winds the Ekman transport in the coastal region of India is away from the coast[6]. This has two effects. First, it results in divergence of mass at the coast, leading to upwelling of more saline and cooler waters from deeper layers. Second, the southward migrating low salinity waters (Figure 4*b*) are pushed away from the coast. Ekman velocity is strongest at surface. Hence surface waters get pushed most. This we feel is what leads to a much wider low salinity tongue at the surface than at deeper layers.

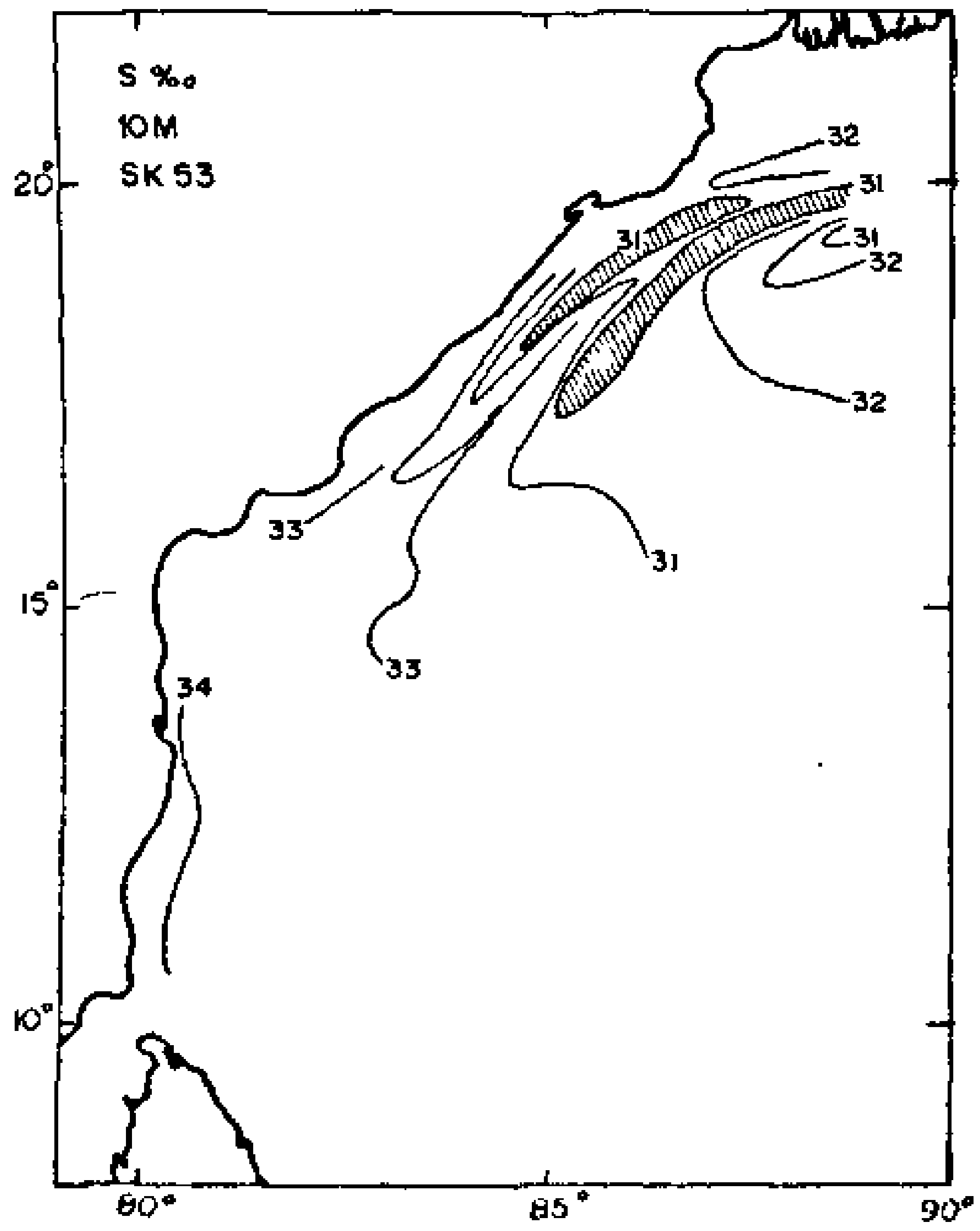


Figure 5. Salinity at 10 m depth during July August 1989. Contour interval is 1 ppt. Areas with less than 31 ppt are shaded. Contrast with Figure 4*b* brings out the rapid change in salinity with depth in the northern part of the area surveyed. Salinity sections at 10 m depth during March-April 1991 and December 1991 showed hardly any deviation from Figures 4*a* and 4*c* respectively.

What causes the southward migration of the low salinity tongue? We propose that the winds again play a dominant role, but the mechanics are quite different. An ubiquitous feature of the world ocean circulation is the basin-wide gyre with slow meridional drift over most of the basin and a swift current in the western boundary to compensate for the drift[12]. The overall pattern of horizontal transport in these western intensified gyres can be computed from the steady-state Sverdrup theory which links the meridional transport in the open basin to the wind field. In Figure 6, following reference 7, we use this theory to sketch the expected pattern of transport in the Bay for different months representative of different seasons. According to this figure the northward current in the Bay during March-April is the N. Indian Ocean analog of the permanent western boundary currents, the Gulf stream in the N. Atlantic and the Kuroshio in the N. Pacific. When the wind field over the Bay changes in June a northward boundary current can no more be supported. Instead, a southward boundary current should occur in the Northern Bay (Figure 6*b*). We therefore look at the southward migrating low salinity tongue (Figure 4*b*) to be a consequence of the basin wide winds as anticipated from the Sverdrup theory.

The near surface salinity gradient in the low salinity tongue (Figures 4*b* and 5), in spite of strong winds, can be sustained only if there is a continuous source of freshwater at the surface. It appears that the GB discharge is this source. The southward moving boundary current transports this water, but as it moves south the southwesterly winds push the surface waters away from the coast. The fresher waters at the surface thus get spread as a thin layer. Simple estimates[3] suggest that the Ekman velocity at the surface in the northern Bay would be of the order of 15 cm/s (415 km/month). In essence, under the combined influence of the southward boundary current and the Ekman surface drift, the GB discharge during May-September (about 60×10^{10} m^3) spreads as a thin layer covering the region north of about 15° N, enhancing freshening of the surface layer which receives a net influx of about 80×10^{10} m^3 from the atmosphere during the same period (Figure 2).

With the withdrawal of the southwest monsoon the offshore Ekman drift and the upwelling zone along the east coast of India can no longer be sustained. By early November the northeast monsoon winds set in. The low salinity waters during this season are mainly confined to an approximately 50 km wide southward

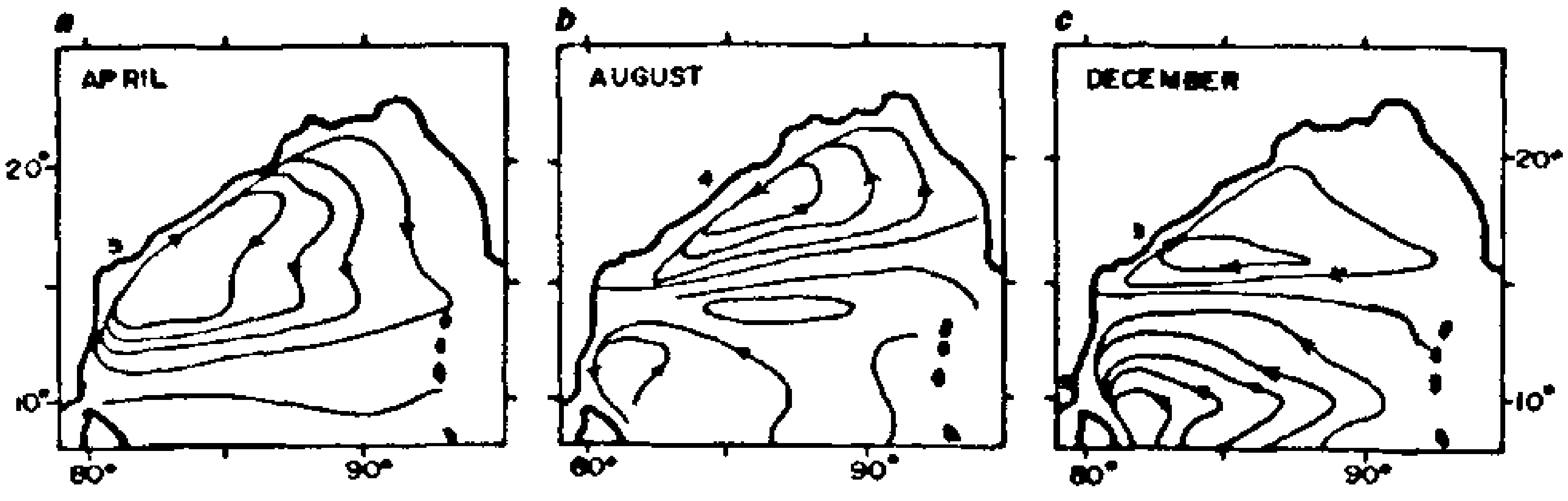


Figure 6. Sketch of the basin-wide monthly mean circulation using the Sverdrup theory. Wind stress field given in ref. 13 was used. Details of the computations can be found in ref. 7. Numbers written close to the coastline give the computed transport (in units of $10^6 m^3/s$) in the western boundary current.

moving plume (Figure 4*c*). This current appears to be the result of northeasterly winds which induce an Ekman flow toward the coast inducing downwelling there. The fresher, lower density water in the plume moves along the coast under the influence of favourable winds in a fashion similar to that in the numerical experiments on similar systems (see, for example, ref. 14). Outside the coastal region we expect a flow similar to that sketched in Figure 6*c*, the Sverdrup flow over the basin.

The approximately $20 \times 10^{10} m^3$ that the GB discharges during October–January thus follows a pattern very different from that in May–September. Rather than spreading as a thin layer over a wide open area of the northern Bay, during the northeast monsoon the discharge is removed by a narrow swift coastal current which carries it out of the Bay all the way to the southwest coast of India.

The southwest monsoon discharge, now spread out and mixed with surface waters of the northern Bay, is expected to begin to move south as the anticyclonic gyre (Figure 6*a*) starts forming sometime around January[7]. During the southwest monsoon approximately $150 \times 10^{10} m^3$ of freshwater (Figure 2) accumulates in the northern Bay due to the GB discharge and due to precipitation (after accounting for loss due to evaporation). During the northeast monsoon this water continues in the northern Bay and mixes with the underlying waters. The gyre during February–May circulates this low salinity water around the basin leading to reduction in salinity in other parts of the basin as well. The schematic diagram in Figure 7 summarizes the proposed three phases for the spread of the GB discharge.

Implications

The net result of the GB discharge is freshening of the surface waters of the Bay of Bengal and the coastal region off Sri Lanka and southwest India. What are its implications? We look at two possibilities—sea surface temperature (SST) in the northern Bay, and, the northeast monsoon coastal current along the west coast of India.

A peculiarity of the Bay of Bengal is the sudden drop in SST, particularly in the north, from approximately

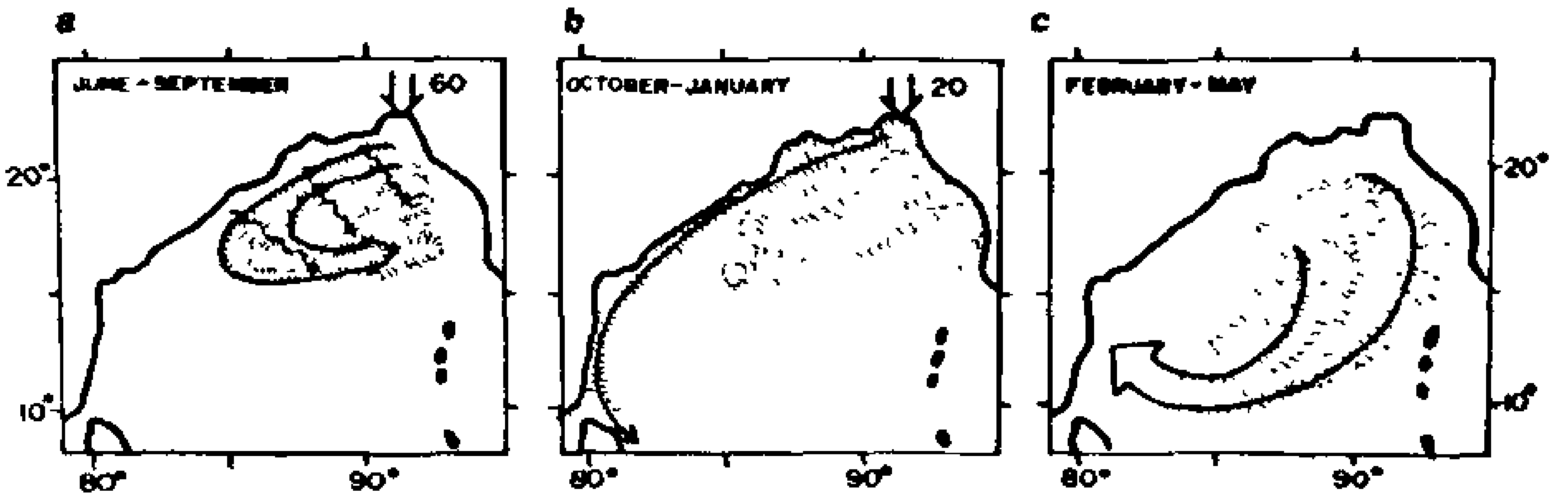


Figure 7. Schematic diagram of the proposed pattern of spread of Ganges–Brahmaputra waters. *a*, Southwest monsoon: the GB discharge of about $60 \times 10^{10} m^3$ during June–September moves southward under the influence of Sverdrup flow (big arrow); the wavy arrows show the direction of surface Ekman velocity which causes the lower salinity waters to spread rapidly in a thin layer; *b*, Northeast monsoon: Discharge of approximately $20 \times 10^{10} m^3$ during October–December is carried swiftly to the south by a narrow current along the east coast of India; *c*, February–May: the subtropical gyre circulates around the Bay, the low salinity northern waters.

29° C to about 26° C with the onset of the northeast monsoon[15]. It is now established that the tropical SST has to be higher than a value of about 28° C to support deep convective activity in the atmosphere[16]. Hence, because of the sudden change in SST, conditions suitable for cyclogenesis no more exist in the northern Bay. This may be one of the reasons why storm activity over the Bay shifts from northern Bay during the southwest monsoon to southern Bay during the northeast monsoon[10]. As seen next, there are good reasons to believe that freshening of the northern Bay during the southwest monsoon has at least a partial role to play in the sudden decrease in SST with the onset of the northeast monsoon.

By end of the southwest monsoon the surface waters of the northern Bay have an isothermal layer about 40 m deep (Figure 8). With the onset of the northeast monsoon cold continental winds blow over the northern Bay cooling the surface waters. Normally such cooling would lead to convective overturning and the resulting mixing would distribute the surface heat loss throughout the mixed-layer. This, however, does not happen in the Bay. The salinity change by over 3 ppt (31 ppt–34 ppt) in the uppermost 40 m by the end of the southwest monsoon provides a stable density background and overturning does not take place. Instead, a sub-surface temperature maximum forms as seen in Figure 8. Using the two temperature profiles in this figure it is easy to see that in the absence of salinity stratification, the SST would be higher by about 1.5° C.

Let us now examine the likely implications of the arrival of lower salinity Bay waters to the west coast of India. A special feature of the coastal circulation off the west coast of India is that during the northeast monsoon a strong coastal current moves northward against weak winds[5]. The transport in this current is higher by a factor of about five than the southward moving coastal current during the southwest monsoon[4]. The pressure gradient which is present along the coast at this time has been invoked to explain the presence of the northeast monsoon current[5]. It has been shown that such a pressure gradient can arise due to a density gradient along the coast[18]. One of the important factors which leads to the density gradient is the salinity variation. The surface salinity of the N. Arabian Sea is high (in excess of 36.5 ppt) throughout the year because it is a region of high evaporation (1.5 m/year) and low precipitation (0.1 m/year). The arrival of Bay of Bengal water in November–December off the southwest coast of India with a salinity of 34.5 ppt helps to enhance the salinity and density gradient and may well be helping to strengthen the coastal current[5]. In short, the implications of GB waters are not restricted to the Bay alone but can be found in the Arabian Sea as well.

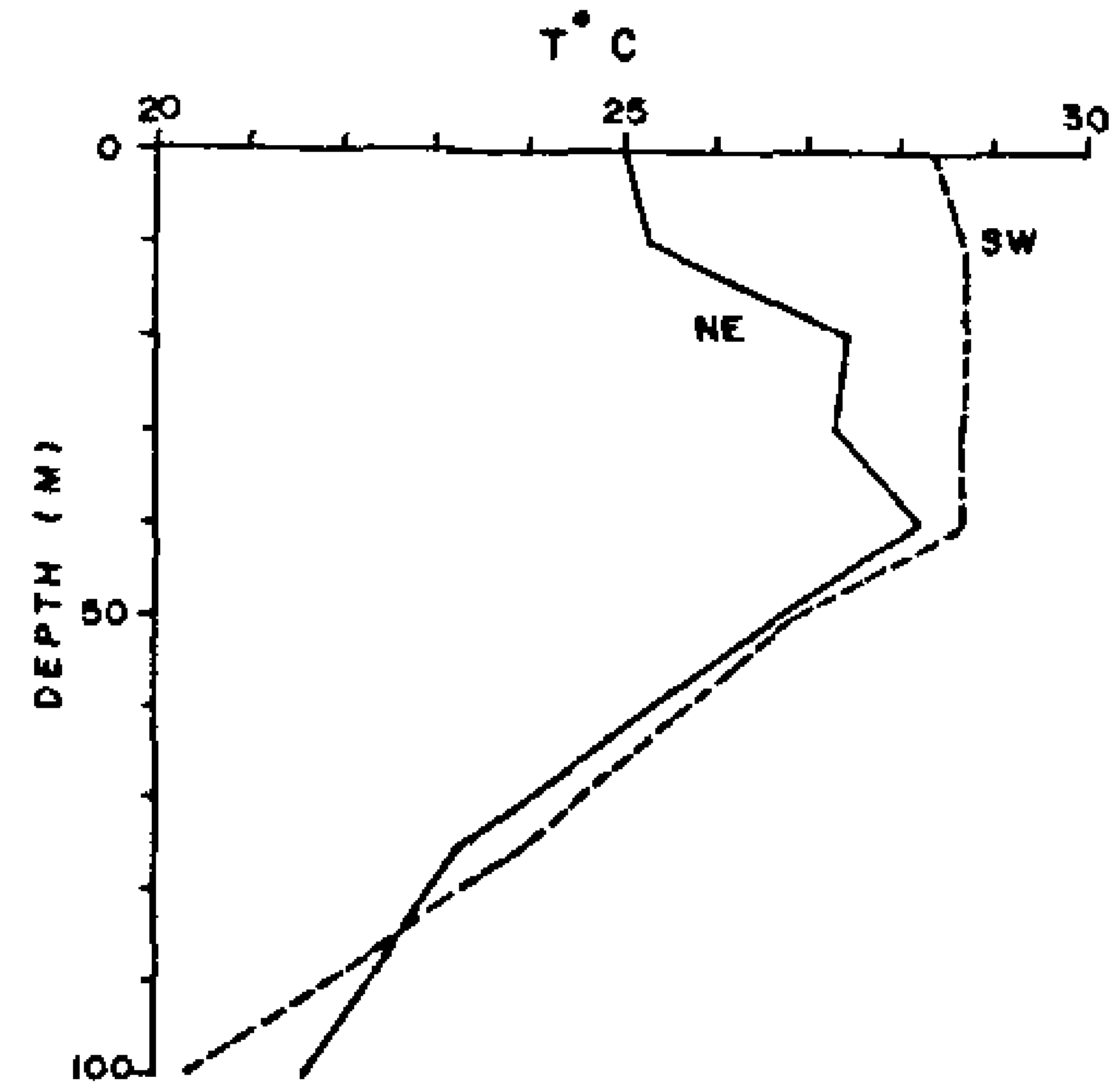


Figure 8. Vertical variation in temperature (°C) in the uppermost 100 m at 18° 57′ N and 88° 44′ E (the circled station in Figure 1). The solid (dashed) curve shows conditions during northeast (southwest) monsoon using data collected during December 1991 (July–August 1989).

Discussion

The study of circulation of the Bay of Bengal is still in its infancy and some of the limitations of the theories which we have used need to be noted. While looking at the large scale pattern of circulation over the Bay of Bengal, we have relied heavily on the Sverdrup theory which gives the vertically integrated transport, i.e. the barotropic mode. The influence of the baroclinic modes, whose vertical integral vanishes, but can contribute to the surface flow, has not been examined and remains an important unknown about the Bay of Bengal circulation.

While speculating on the likely patterns of circulation in the Bay we have used what has come to be known as the 'local forcing' theory, which assumes that forcing functions (winds or density gradient) over a particular region are mainly responsible for the events in the region. Recent numerical experiments suggest that one may have to take into acccount other possibilities called 'remote forcing'. Seasonal variation in winds along the equator can trigger waves whose reflection or transformation and subsequent propagation along the rim of the N. Indian Ocean can have an impact on the events in the Bay of Bengal and along the west coast of India[19–21].

To explain the westward and southward movement of the low salinity tongue during the southwest monsoon (Figure 4*b*) we invoked the Sverdrup theory. There is another possibility. Laboratory and numerical experiments suggest that when lighter water is introduced from the side in a counter-clockwise rotating basin (like the northern hemisphere), the lighter water tends to form a coastal current which moves with the coast on its right. Some numerical results with river discharge much smaller than that of GB suggest that a coastal plume cannot form in presence of strong winds opposing the flow[14]. However, such studies are still not sufficiently comprehensive to make an unequivocal statement in the case when the discharge is as large as that of GB.

Further observational and theoretical studies are therefore needed to validate the three-phase pattern we have proposed for the spread of the GB discharge. Such studies would provide valuable insights into how Nature ensures that a region with excess freshwater exports it and that with deficit, such as the northern Arabian Sea, imports it.

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