

Does winter cooling lead to the subsurface salinity minimum off Saurashtra, India?

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Abstract- Cold and dry winds of the northeast monsoon cool the northern Arabian Sea during November-January. The intensity of cooling is highest in the proximity of the peninsula of Saurashtra, India. Using hydrographic data, we propose that the cooling in this region, particularly during cold outbreaks, increases the density of shelf waters sufficiently to form a water mass which sinks and spreads at a depth of about 150 m and is characterized by a weak salinity minimum with sigma-theta in the range of 25.5-26.5 gm/cm³.

It is not possible at the present to estimate the amount of subsurface waters formed nor to determine its role during winter in recharging the subsurface salinity minimum observed over the entire N. Arabian Sea basin. It appears that the advection of lower salinity water into the basin by the northeast monsoon coastal current and subsequent evaporation in the mixed-layer also plays a role in recharge of the salinity minimum.

INTRODUCTION

The semiannual reversal of winds is a special feature of the Arabian Sea. During the southwest monsoon, the northern summer, the low level atmospheric circulation is characterized by generally southwesterly winds and a strong cross-equatorial flow, the Somali jet, over the east African coastal region. During the northeast monsoon (approximately November-February) the winds are northeasterly and weaker than those during the southwest monsoon. In response to this cycle, the circulation in the western and southern parts of the Arabian Sea is much more energetic during the southwest monsoon than during the northeast monsoon (SCHOTT, 1983). In contrast, in the eastern and northern parts of the Arabian Sea, the coastal region off India and Pakistan, the circulation is more energetic during the northeast monsoon.

The winds along the eastern boundary of the Arabian Sea during the southwest monsoon vary between west-northwesterly near the southern end to west-southwesterly in the northern part of the coast. The longshore component of the wind stress is generally equatorward, and its magnitude is maximal, around 0.5 dyne/cm² near the southern end. The coastal circulation during this season, though weak, is similar to a wind-driven eastern boundary current (SHETYE *et al.*, 1990). The equatorward surface current is approximately 150 km wide, 75-100 m deep, and its transport increases from less than 1×10^6 m³/s in the north to 4×10^6 m³/s near the southern end. A northward undercurrent hugs the continental slope and carries lower salinity waters.

During the northeast monsoon a poleward coastal current flows along the west coast of India against weak winds (SHETYE *et al.*, 1991). Near the southern end of the coast the current is approximately 400 km wide, 200 m deep and carries the low salinity Equatorial Surface Water. As it moves northward, the current gets narrower and is restricted mainly to the vicinity of the continental slope. At about 22° N, off the coast of Saurashtra, the current turns into a narrow (100 km), 400 m deep jet with a transport of about 7×10^6 m³/s. It appears that an equatorward undercurrent occurs below the poleward flow. Because the surface coastal flow moves against the local

winds, they cannot be driving it. Neither can the current be explained by the the Sverdrup flow computed using the climatology of the curl of wind stress (SHETYE and SHENOI, 1988). There are remarkable similarities between the northeast monsoon coastal current off India and the Leeuwin current off western Australia. Both seem to be driven by a longshore pressure gradient which overwhelms an opposing wind stress. The overall structure of the northeast monsoon current is consistent with that predicted in the analytic model proposed by McCREARY *et al.* (1986) to explain the Leeuwin Current. In the model a poleward baroclinic pressure gradient is generated by a density gradient along the coast. To understand the driving mechanism of the current, it is therefore necessary to understand the processes that lead to the density gradient.

A part of the density gradient is of course due to the meridional salinity gradient that occurs in the Arabian Sea. During the northeast monsoon the temperature field too contributes because the northeast monsoon winds, though weak, carry dry cold continental air, which induces convective cooling in the northern Arabian Sea (BANSE, 1984). The purpose of this paper is to examine the consequence of this cooling on the structure of the near surface waters of the N. Arabian Sea in general and in particular on the waters off Saurashtra where the intensity of the cooling is the highest.

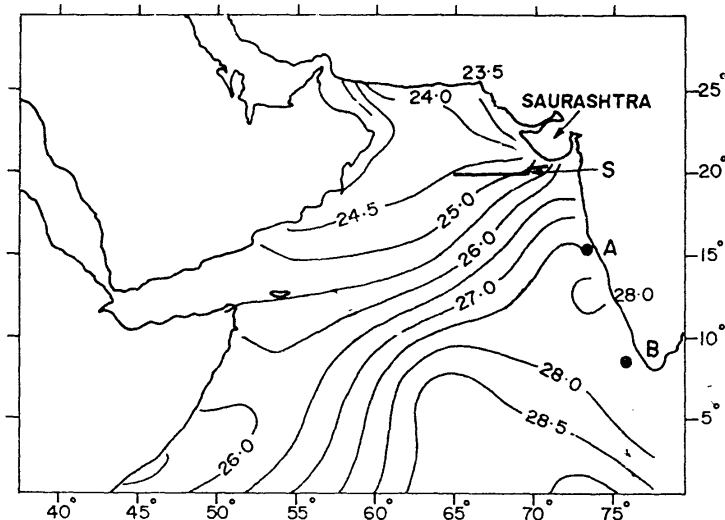


Fig. 1. Sea surface temperature (degree C) over the Arabian Sea during January. Data are taken from LEVITUS (1982). Also shown are the locations of hydrographic stations and section used in figures 2, 3 and 4. The Gulf of Kutch lies to the north of the peninsula of Saurashtra. The Gulf of Cambay is to the east of Saurashtra.

Winter cooling of the N. Arabian Sea

The northeast monsoon begins to set in November and is fully developed by January. During this month the mean daily minimum temperature on land in the coastal region of the N. Arabian Sea is in the range of 15°-20° C and the mean daily maximum temperature is around 25° C (RAO, 1981). The monthly-mean winds are weak, in the range of 1-4 m/s from the north-northeast direction. The winds at this time are highest in the vicinity of the peninsula of Saurashtra (HASTENRATH and LAMB, 1979). The occurrence of the cold, dry continental northeast monsoon winds results in lowering of the sea surface temperature with a distinct minimum to the

north of Saurashtra (Fig. 1). The climatology compiled by LEVITUS (1982) shows that at this time the monthly-mean mixed layer in the coastal region of Saurashtra is between 75 m and 100 m. Farther north, in the coastal region off Pakistan, the mixed-layer is as deep as 125 m which implies an increase of almost 100 m from the conditions during November. A part of the deepening could be the result of geostrophic adjustment to the northeast monsoon coastal current. But convection driven by the cold winds must be playing a role. BANSE (1984) has pointed out that this cooling and the resulting entrainment of the nutrients into the surface layer results in increased productivity of this region.

Though the SST's in figure 1 suggest a minimum of about 23.5° C, SST's lower than this value do occur in the region. Monthly mean SST's for January given in HASTENRATH and LAMB (1979) shows a minimum of 22° C in the same region. Note that in these climatologies the observations are averaged over one-degree-square and features with scales smaller than about 100 km get filtered out. SST's derived from AVHRR imagery generally show pockets of cool waters having temperatures less than 19° C hugging the coastline. The locations where these are observed most frequently are, the coastline north of the Gulf of Kutch, and the shallow region of this gulf and in the Gulf of Cambay. There have also been direct observations that show the presence of cool waters. Minimum temperatures of 15°-16° C have been reported by DHAVAN (1972) at a 12 m deep station in the Kandla Harbour in the Gulf of Kutch. JOHN *et al.* (1979) have reported that temperatures off Narara Bet (approximately 22° 30'N and 69° 40' E) are minimal in November, about 20° C. All this suggests that in the vicinity of Saurashtra, in the shallow region close to the coastline, pockets of waters with temperatures in the range of 16°-20° C appear. Farther offshore, in the core of the northeast monsoon current, temperatures exceed 26° C. The effect of the winds, with mean daily minimum temperature of about 15° C is the largest off Saurashtra, most probably because the winds are the strongest there.

The sub-surface salinity minimum off Saurashtra and the role of winter cooling in its formation

A feature of the salinity distribution off the west coast of India is a salinity minimum at a depth of about 150 m. It hugs the continental slope as can be seen in the section perpendicular to the coast of Saurashtra (Fig. 2). The sigma-theta in the salinity minimum layer is in the range 25.5-26.5 gm/cm³. The intensity of the minimum changes seasonally. During the southwest monsoon it is developed best near the southern tip of the coast and is related to the northward moving undercurrent (SHETYE *et al.*, 1990). Off Saurashtra it is developed best during the northeast monsoon (Fig. 3). We shall see later (Fig. 5) that this feature of the salinity minimum is robust enough to appear in seasonal climatology. Note that in figure 3 the value of the salinity in the salinity minimum layer off Saurashtra (southwest coast) is lower (higher) during the northeast (southwest) monsoon.

Can the recharging of the salinity minimum off Saurashtra during the northeast monsoon be related to the cold water pools? We raise this possibility in view of the fact that, water of the same T-S characteristic as that found in the salinity minimum is found on the shelf at a depth of about 75 m (Fig. 2). The surface salinity on the shelf close to the coast is generally lower than that found offshore. For example, JOHN *et al.* (1979) have reported minimum salinities of less than 35.6 ppt in the Gulf of Kutch during November-January. The T-S structure of the waters off Saurashtra is shown in figure 4. The salinity in the salinity minimum layer is little less than 35.8 ppt. Salinities of this order can be found on the shelf close to the coast. If these waters are cooled to about 19° C, they would have sufficiently high density to sink and spread at a

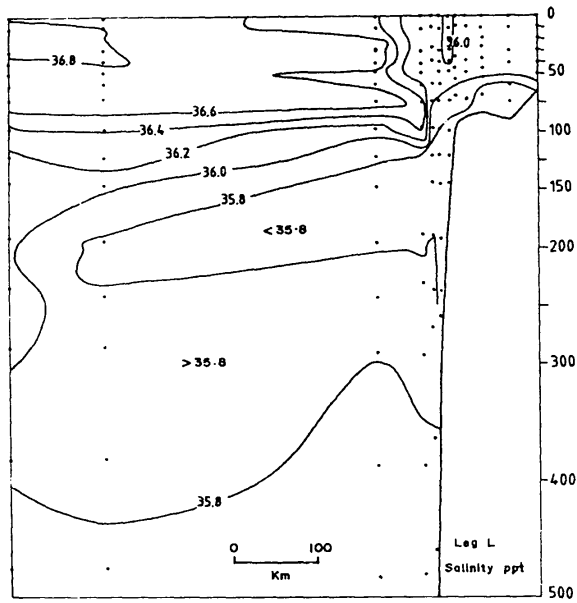


Fig. 2. Salinity section off Saurashtra. Location is given by section "S" in figure 1. The section was covered during 13-16 January 1988.

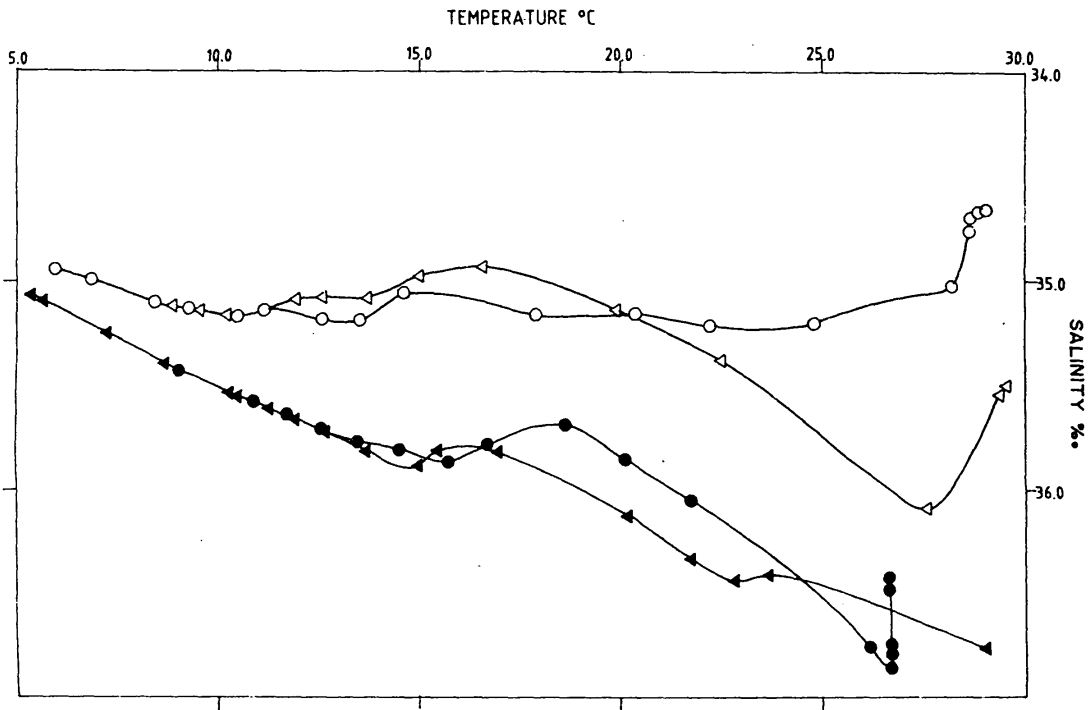


Fig. 3. T-S diagrams of two stations on the continental slope during southwest and northeast monsoons. The locations of the stations are shown in figure 1. The hollow symbols represent the station off the southwest coast of India (see "B" in Fig. 1) and the solid symbols off Saurashtra (see "S" in Fig. 1). Circles (triangles) represent the northeast (southwest) monsoon conditions.

depth of about 150 m. In view of the fact that cooling by the northeast monsoon winds to temperatures such as this does occur, local recharging of the salinity minimum by convective cooling seems feasible.

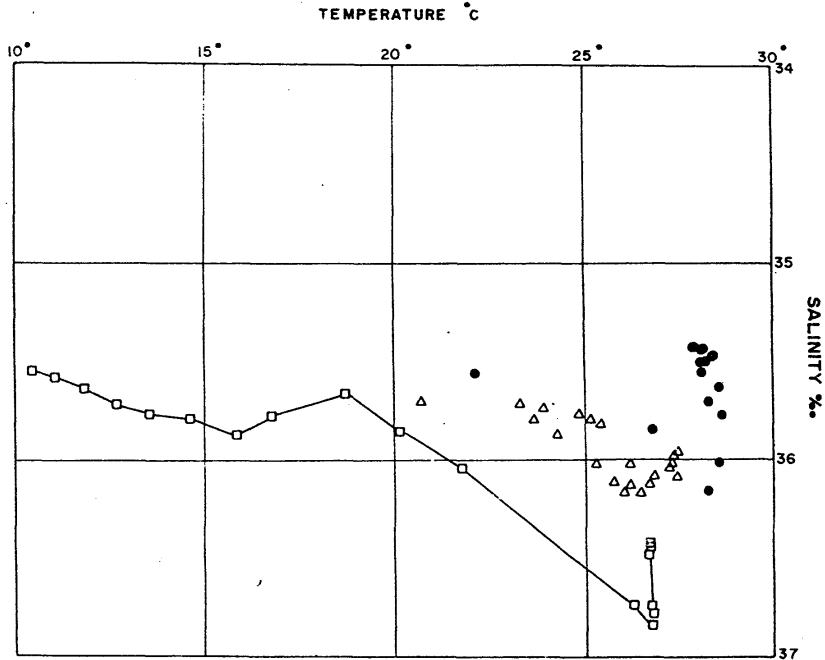


Fig. 4. T-S characteristics of the waters on the shelf (triangles) and just off the continental slope (squares) off Saurashtra (Fig. 1), and on the shelf (solid circles) at about 15°N ("A" in Fig. 1).

The cold 19° C pools, that are often seen in the AVHRR imagery, seem to occur routinely. It is expected that when outbreaks of cold dry air occur, the cooling of the waters would be further enhanced. The minimum air temperature in the coastal region can drop by about 10° C during such outbreaks. For example, the mean minimum daily temperatures for January at Bhuj (23° 15'N, 69° 48'E) is 10.1° C and Karachi (24° 54'N, 67° 09'E) is 10.4 C; but during the cold outbreaks it can be as low as 0.49° C and 0° C respectively (RAO, 1981). Subsurface water formation during cold air outbreaks has been suggested elsewhere too. NOWLIN and PARKER (1974) have noted that on the shelf of Gulf of Mexico (latitude approximately 28° N) during a 15 day outbreak when mean air temperatures decreased by 15° C, the sea surface temperatures close to the shore decreased by nearly 5° C. At a distance of approximately 200 km from the shore the temperatures dropped by 1-2 degrees. The authors suggest that subsurface water types generally found beneath the Subtropical Underwater core in the Gulf of Mexico were formed locally over the shelf during the outbreak.

Our conclusion, supporting the possibility of local recharge of subsurface salinity minimum needs to be verified with field observations. Distribution of chemical tracers, dissolved oxygen for example, would be very helpful in such studies. Also, at the present we have no idea about the amount of the subsurface water that may be forming. To make an estimate of this, it is necessary to determine the heat budget of the shelf waters. Available data do not permit this. Nonetheless, the fact, that available data do suggest the possibility of subsurface water formation, is important from a few con-

siderations. It means that convective cooling can enhance the density of water up to a depth of about 150 m. The resulting deep longshore density gradient can enhance the northeast monsoon coastal current in the fashion suggested by McCREARY *et al.* (1986). Interestingly, WEAVER and GODFREY (1990) have proposed that convective cooling in the coastal region of southwestern Australia helps to set up a density gradient to drive the Leeuwin current. The subsurface water formation is also of interest from couple of other considerations. First, processes such as subsurface water formation have significant implications to the ventilation of this highly reducing region. Second, it is believed that during the Last Glacial Maximum, about 18,000 years ago, the northeast monsoon was much more energetic than today, whereas the southwest monsoon was weaker (DUPLESSEY, 1982). It seems that processes such as the subsurface water formation would have been much more active at that time. This would need to be taken into account in deciphering the kind of ocean circulation that might have existed then.

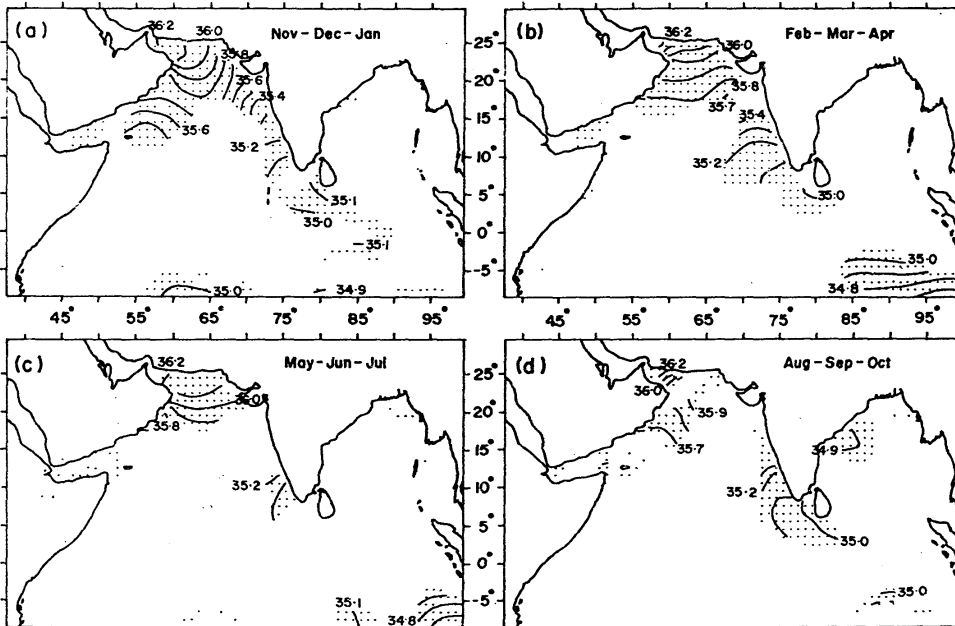


Fig. 5. Locations where a salinity minimum, with sigma-theta in the range 25.5-26.5 gm/cm³, occurs are shown by dots. The contours show value of the salinity in the salinity minimum. (a) November-January, (b) February-April, (c) May-July, (d) August-October. Data source: LEVITUS (1982).

Salinity minimum in the N. Arabian Sea

The salinity minimum at the depth of about 150 m is not restricted to the coast of India alone, but can be found over the Arabian Sea north of about 20° N. The layer

containing the minimum is only a few tens of metres thick. BANSE (1990) has pointed out to its occurrence in the northwestern Arabian Sea. In figure 5a-d we see its areal extent, and its variation from season to season. The figures, based on the LEVITUS seasonal climatology (LEVITUS, 1982), show that the horizontal extent of the layer is maximal during November-January.

Though convective cooling on the shelf off Saurashtra may be one of the mechanisms that leads to the recharging of the salinity minimum, it is necessary to explore alternative processes because at present there are no estimates of the amount of subsurface water formed, whereas the area covered by the subsurface salinity minimum is extensive. Earlier we have pointed out that a northward moving coastal undercurrent carrying low salinity waters is found off the coast of India during the southwest monsoon. Though this leads to a salinity minimum, it appears to be mainly restricted to the southwestern portion of the coast, and cannot have any major role in the formation of the salinity minimum layer because its recharging occurs during the northeast monsoon.

A mechanism that could be effective during the northeast monsoon and influence the entire northern part of the basin is related to northeast monsoon coastal current. The current which carries low salinity water is about 400 m deep off Saurashtra. Though not much is known about the behaviour of the current north of Saurashtra, SST's derived from AVHRR suggest that the current moves parallel to the coastline of Pakistan. It is also apparent that the current widens and mixes with the ambient waters. The current is expected to influence the waters of the region substantially by the time it reaches the Arabian coast on the western side of the basin. The depth up to which the influence of the current is felt is not known at the present. We presume that it is felt at least up to the depth of about 200 m in view of the fact that the current is about 400 m deep off Saurashtra. The mixed layer in the N. Arabian Sea is generally less than 125 deep during the northeast monsoon. If our assumption that the current is at least 200 m deep in the N. Arabian Sea is valid, the advection of low salinity waters would reduce the salinity at depths between the bottom of the mixed layer and the maximum depth of the current, i.e. between about 125 m and 200 m. In the mixed layer there would be an increase in the salinity due to evaporation which continues even after the withdrawal of the northeast monsoon. Hence the combined effect of advection by the northeast monsoon current and evaporation can lead to recharge of the salinity minimum in a layer few tens of metres thick with a mean depth of about 150 m.

One may, however, raise the following question. To what extent is the salinity minimum simply induced by surface forcing of high salinity above it and intrusion of the Persian Gulf Water beneath it? In this scenario an active influx of low salinity water, either in the form of a coastal current bringing fresher water, or, in the form of dense pockets cascading down the shelf/slope, is not required. We feel couple of considerations make this scenario unlikely. First, it is doubtful that in the absence of an active influx of low salinity water, the salinity minimum will survive the effect of vertical or cross-isopycnal mixing. Note that the salinity minimum layer is only a few tens of metres deep. Second, there is some evidence that intrusion of the high salinity Persian Gulf Water is highest during November-January (Fig. 6 in BANSE, 1990), which is also the time when forcing of high salinity due to evaporation is high. Under the combined influence of the two effects, and if active influx of lower salinity water is absent, it is expected that the value of salinity in the salinity minimum layer would be highest during November-January. We have pointed out earlier (Fig. 3) that this is not the case off Saurashtra. The LEVITUS (1982) climatology also shows (Fig. 5a) that the salinity in the minimum layer is minimum during November-January. In view of

this, we feel that there must be an active influx of lower salinity water to sustain the salinity minimum.

SUMMARY

We do not at the present have a definitive answer to the question which forms the title of this paper. However, our efforts to address it has brought out some interesting features concerning the working of the northern Arabian Sea. Important amongst these are the following:

(1) Unlike the southern and western parts of the Arabian Sea which show high activity during the southwest monsoon, the northern and eastern parts are more active during the northeast monsoon. In the former, it is the direct forcing by the southwest monsoon winds that induces the ocean response; in the latter the convective cooling by northeast monsoon winds plays a role.

(2) Cooling by the cold dry continental northeast monsoon winds form cold pools with temperatures less than 20° C, over the shallow regions of the shelf near Saurashtra. At this time the core of the northeast monsoon coastal current moving along the continental slope carries waters warmer than 26° C. Though there is at present no direct empirical data to show this, it is possible that winter cooling increases the density of the shelf waters to a point where water can sink and spread at a depth of about 150 m, leading to a salinity minimum around that depth. Experiments to check this possibility need to be carried out.

3) A weak salinity minimum at approximately 150 m (in the range 25.5-26.5 gm/cm³) is found in the N. Arabian Sea throughout the year and is recharged during the northeast monsoon. It is not possible at the present to quantify the extent to which the winter cooling off Saurashtra contributes to this recharge. In view of the wide areal extent of the salinity minimum, it appears that there exist other processes that can recharge the minimum. We propose that the combined influence of the advection of low salinity waters by the northeast monsoon coastal current and evaporation leading to increase in salinity in the mixed layer in the northern Arabian Sea is one such mechanism.

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