CHAPTER 3

Hydrographic Features
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This chapter discusses the distributions of hydrographic properties (temperature, salinity, density, dissolved oxygen and nitrate) during different seasons in the northern Indian Ocean.

3.1 The Arabian Sea

3.1.1 Northeast monsoon (January, 1998; SS161)

During the northeast monsoon (November to February) the surface circulation in the Arabian Sea is quite similar to the circulation in the North Pacific and Atlantic. North of equator the flow is from the east to west. Close to the coast (west coast of India) the surface circulation is pole ward. The west India coastal current (WICC) is an extension of the East India coastal current (EICC) that brings in low saline waters from the Bay of Bengal into the southeast Arabian Sea [Shetye, 1998]. Off the coast of Oman and Somali the circulation is towards the equator.

During January 1998, the atmospheric temperature north of 17°N was less than 24°C. Such low atmospheric temperatures lead to low sea surface temperatures (SST) in the study region. The SST in the study region (Fig. 3.1) varied between 24.2 and 27.2°C with an average value of around 25.4°C. The winds during this period were mainly northeasterly with speeds varying from 2.5 to 7 m s\(^{-1}\) (average value of 4.4 m s\(^{-1}\)). These cool dry winds hold extra
Fig. 3.1 Vertical profiles of temperature, salinity, density, dissolved oxygen (DO) and nitrate in the northern Arabian Sea during northeast monsoon (SS161).
moisture and heat that facilitate enhanced evaporation at the Arabian Sea surface leading to the occurrence of winter convection.

Fig. 3.1 depicts the signatures of winter convection in the study region. Temperature, density and dissolved oxygen profiles show clear differences between stations depending on the intensity of convection from south to north. The sea surface temperature and dissolved oxygen fell from 27.2°C to 24.5°C and from 215.8 µM to 191.1 µM, respectively, while the density increased from 1.0237 to 1.0247. Salinity structure showed higher values in the mixed layer of northern stations indicating intensification of evaporation and consequent sinking of high saline waters. This occurrence of winter convection facilitates the introduction of nutrients into the surface layers (Fig. 3.1). The surface nitrate levels varied between undetectable levels in the south (outside the winter convection zone) and 12.5 µM at 20°N and 65°E. The average surface nitrate in the area where convection occurred was found to be around 4.9 µM. Such high nitrate levels promote primary production. In concurrence with the above statement Madhupratap et al. [1996] and Bhattathiri et al. [1996] have observed column productivity of around 643 mgC m⁻² d⁻¹ in the northern Arabian Sea.

3.1.2 Southwest monsoon (July-August, 1998; SK137 and September-October, 1999; SK148)

Very high wind speeds are associated with the southwest monsoon. During the present study wind speeds varied between 0.5 and 5.2 m s⁻¹ and between 1.3 and 7.9 m s⁻¹ during SK137 and SK148 periods, respectively.
The observed wind speeds were in general lower than that expected since speeds > 10 m s\(^{-1}\) is common during this season [Hastenrath and Lamb, 1979]. Nonetheless upwelling is conspicuous during both the cruises. Figure 3.2 shows the hydrographic features observed near 15°N for SK137 as an example. Shoaling of isotherms is observed very close to the coast. The isotherm of 27°C shoals to 8m near the coast. The low saline cap formed from land runoff prevented surfacing of this isotherm. The upwelled high saline waters (~35.9) were accompanied by low dissolved oxygen (~90 µM) and high nitrate (4-12 µM).

At 8°N the upwelling was more pronounced with the surfacing of 25°C isotherm (Fig. 3.3). The salinity structure suggests mixing of low saline runoff with the high saline upwelled waters. Runoff also seems to bring in high amount of nitrate into the coastal area. In the present case the major part of nutrients was apparently introduced by the upwelled waters since the surface waters were found to contain low oxygen (<100 µM). If the nutrients were of land origin the oxygen levels should have been higher because of effective air-sea exchange.

Similar features were also noticed off 10°N and 12°N. Around 10°N surface temperature was 25.96°C with a salinity of 33.416 and a nitrate concentration of 10 µM while at 12°N surface temperature was 24.14°C with salinity of 34.552 having a nitrate concentration of 15.37 µM. Therefore the major observation during the southwest monsoon was the occurrence of upwelling all along the coast. Closer observation revealed that stations very
Fig. 3.2. Distributions of temperature, salinity, oxygen and nitrate near 15°N during the southwest monsoon of 1998 (SK137).
Fig. 3.3. Distributions of temperature, salinity, oxygen and nitrate along the section shown during the southwest monsoon of 1998 (SK137).
close to the coast did not show surfacing of isotherms representing subthermocline waters, but away from the coast (~20 km). This is caused by land runoff as discussed above. Though upwelled waters rich in nutrients may not have surfaced at many of the places along the coast, their occurrence within the euphotic zone favours intense biological production. Similar hydrographic features were also observed during southwest monsoon in the following year of 1999 (SK148). Study of the hydrographic features in different months of the southwest monsoon season exhibited the extent of temporal variability. The most interesting observation was that of chlorophyll. During SK137; the surface 50 m chlorophyll averaged to 0.6 mg m\(^{-3}\) whereas during SK148 it averaged to 2.2 mg m\(^{-3}\) indicating the importance of time lag for increased primary production after the monsoonal upwelling.

3.1.3 Fall-Intermonsoon (November, 2000; SK158)

Hydrographic data were presented for tracks near 15°N (Fig. 3.4) and along 72°E (Fig. 3.5). In coastal region wind speeds varied between 2.2 and 12.5 m s\(^{-1}\) while in the open ocean speeds varied between 1.8 and 10.2 m s\(^{-1}\). Temperature contours show a stratified structure unlike in the SW monsoon, with the surface temperatures over 28°C (Fig. 3.4). The low temperature isotherms, indicating upwelling which surface during the SW monsoon, are now observed at deeper depths. The salinity distribution shows a low saline patch in surface waters between 50 and 100 km from the coast suggesting the runoff caused by post monsoon showers. Around 130 km from the coast high saline waters were noticed at a depth of 50 m. This shows the beginning of
Fig. 3.4. Distributions of temperature, salinity, oxygen and nitrate near 15°N during the fall inter monsoon of 2000 (SK158).
Fig. 3.5a. Distributions of temperature, salinity, oxygen and nitrate along 72°E during the fall intermonsoon of 2000 (SK158).
Fig. 3.5b Profiles of temperature, nitrate and chlorophyll (at 9.94°N, 72.44°E, SK158) showing subsurface chlorophyll maxima.
seasonal incursion of ASHWW mass into low saline coastal waters. The 4 μM nitrate isoline was found at 25 m depth (Fig. 3.4), whereas the same had surfaced during the southwest monsoon (Fig. 3.2).

Temperature profile shows a stratified structure. In the upper 50 m the temperatures varied between 23.3°C and 29.7°C with the MLD deepening slightly towards the south (Fig. 3.5a). In contrast to the stratified temperature distribution salinity showed a low saline front at 12°N (35.300 at 300 km). Oxygen also shows a stratified structure with values at ~200 μM in the surface layers but decreased to around 80 μM around 50 m depth. There was no nitrate in the upper 10 m, but increased to the base of the MLD. One of the prominent features of the fall-intermonsoon was the occurrence of high nitrate levels near the base of MLD, but within the euphotic zone. This gives rise to subsurface chlorophyll maximum [SCM, Bhattathiri et al., 1996]. In the present study the SCM was found to occur between 40 and 60 m (Fig. 3.5b).

3.2 Bay of Bengal

In the present study coastal regions off the east coast of India (off Chennai and Paradip) and a stationary position (time series measurement for nearly a month) in the northern Bay have been covered during the southwest monsoon (July-August, SK147) while open southern Bay of Bengal was occupied during fall-intermonsoon (October-November, SK138C).

3.2.1 Southwest monsoon (July-August, 1999; SK147)

The transect off Chennai (Fig. 3.6) shows surface stratification, which is reflected in all properties. Closer to the coast upward sloping in contours is
3.6 Distributions of temperature, salinity, oxygen and nitrate along 13°N during the southwest monsoon of 1999 (SK147B).
obvious that suggest surfacing of isolines. The 28°C isotherm reached the surface near the coast, whereas the same was found at 40-50 m depth further from the coast. The lowest oxygen found in the upper within 50 m was 108.37 μM indicating the influence of possible upwelling, as can be seen from upward sloping in contours. This process during the southwest monsoon introduces nutrients into the euphotic layers. In the upper 50 m nitrate varied between undetectable levels and 23.3 μM.

In contrast to this the transect off Paradip (Fig. 3.7) shows a low saline cap with a salinity variation between 24.581 and 32.962 in the upper 25 m clearly indicating the influence of runoff during the SW monsoon season. The temperature showed clear layering all along the transect with no signs of upwelling near the coast. Surface oxygen levels were higher by 20 μM in comparison to the levels off Chennai coast. Nitrate profiles also showed a stratified structure with the nutricline occurred around 40 m.

The time series observation in the northern Bay was divided into two phases; Phase I was from 16th July to 8th of August and phase II was from 10th to 31st of August. Phase I was convectively more active in comparison to Phase II. This was due to a deep depression at the head Bay. Wind speeds varied between 6 and 18.2 m s⁻¹ with an average value of 11 m s⁻¹ in phase I while in phase II it varied from 4 to 12 m s⁻¹ with a mean value of 7.8 m s⁻¹. Phase I also experienced good amount of cloud cover. Figure 3.8a shows variations in temperature, salinity and dissolved oxygen during the time series experiment. Temperature profiles did not show much variation exhibiting
Fig. 3.7 Distributions of temperature, salinity, oxygen and nitrate off Paradip during the southwest monsoon of 1999 (SK147B).
Fig. 3.8a Variations in temperature, salinity and dissolved oxygen at the time series station (17.5°N and 89°E) during the southwest monsoon of 1999 (SK147A&B). Station location is shown in Fig. 2.1.
persistent stratification. Surface (upper 20 m) temperatures were around 28.5°C during both the phases. On the other hand salinity exhibited significant variability. During phase I a flow of low saline water was found at the time series location at the beginning of the fourth day. Prior to the entry of these low saline waters the surface salinity (upper 20 m) in the study area varied between 32.586 and 32.648. With the incursion of the low saline water the salinity decreased to as low as 27.000. The low saline cap remained throughout phase II also, during which the surface salinity decreased further to 24.000. Associated along with the low saline cap were pockets of very high oxygen levels (~220 µM); which otherwise was around 200 µM. The high oxygen pockets were found to be associated with high wind speeds indicating the extent of turbulent mixing. According to Vinaychandran et al. [in press] the arrival of the fresh water plume divides the upper 30 m in to a two layer in which the top 15 m layer moves southward under the influence of Ekman flow and the lower geostrophic layer moves northward. Under these conditions upward pumping of nitrate occurred. Nitrate levels of ~10 µM were found at 10 m depth during phase I (Fig. 3.8b). This phenomena is responsible for upward pumping of nutrients throughout the first phase. Phase II also experienced a similar feature, but the extent is somewhat suppressed due to the existence of intense fresh water cap. Surface as well as mixed layer depth averaged chlorophyll levels were affected by changes in UV levels. Low levels of UV were associated with high chlorophyll and vice-versa (Fig. 3.9). Surface chlorophyll during phase I varied between 0.2 and 0.65 mg m⁻³ and between
Fig. 3.8b Variations as in Fig. 3.8a but for nitrate, chlorophyll and DMS.
Fig. 3.9 Variations in DMS, chlorophyll and UV radiation at 17.5°N and 89°E during the southwest monsoon of 1999 (SK147A&B); open symbols indicate surface values and bold symbols indicate MLD averaged values. The weather was cloudy during 31 July – 1 August 1999.
0.3 and 0.83 mg m\(^{-3}\) in phase II. Chlorophyll maxima were found to occur between 40 and 60 m with higher levels during phase II than in phase I.

### 3.2.2 Fall-intermonsoon (Oct-Nov, 1998; 138C)

Figure 3.10 depicts variations in temperature, salinity, dissolved oxygen, nitrate and chlorophyll along 87°E in the southern Bay of Bengal. The temperature distribution shows more or less a stratified structure with a variation of 28 – 29.5°C at the surface (upper 25 m). Towards the north deepening of the MLD could be seen based on property distributions. Salinity profile showed the expected trend, i.e. a decrease in salinity towards north. Dissolved nitrate showed downward sloping towards the north. Low oxygen waters (~120 μM) with high nitrate (~8 μM) were observed to shoal upto 20 m at 7°N. The chlorophyll shows a typical high nitrate low chlorophyll (HNLC) situation at 20-40 m, at the southern end and an exactly opposite situation in the north.

### 3.3 Central Indian Ocean

#### 3.3.1 Northeast monsoon (Feb-March, 1998, SK133; Jan-Feb, 1999, SK141)

One of the important features of hydrographic regimes in the Indian Ocean is the occurrence of a front that forms as a result of North and South equatorial current systems [Wyrtki, 1973]. During the period of First Field Phase (FFP '98) the water column hydrography seems to be well stratified (Figure 3.11a&b). Trough like features in temperature, oxygen and nitrate near equator appear to be related to the countercurrent moving from west to
Fig. 3.10 Variations in temperature, salinity, dissolved oxygen, nitrate and chlorophyll along 87°E during the fall intermonsoon of 1998 (SK138C).
Fig. 3.11a. Variations in temperature and salinity during FFP - 98 and IFP - 99 of the INDOEX Experiment.
Fig. 3.11b. Variations in dissolved oxygen (DO), nitrate and chlorophyll during FFP - 98 and IFP - 99 of the INDOEX Experiment.
east. This trough also was marked by relatively higher salinities. Features of sub-surface (>100 m) hydrographic front could be seen in physico-chemical properties at 10° S. Temperature, salinity and oxygen exhibit the occurrence of a front in surface layers across the equator. On either side of the equator average salinity was lower (34.170 at 5°S and 34.182 at 9°N whereas it was 34.981 at the equator) in the upper 50 m due to the respective current systems flowing from east to west. The North and South equatorial current systems carry relatively low salinity waters from the eastern Indian Ocean to Madagascar [Wyrtki, 1973]. To the north of the equator (particularly >5°N) signatures of warm, low oxygen, high salinity and nitrate rich North Indian Ocean waters could be clearly seen below the thermocline (≥100m) in figure 3.11a&b. In contrast, no clear trends in these properties were found during Intensive Field Phase (IFP ‘99, Figure 3.11a&b). The usual hydrographic front at 10° S was not obvious. Physico-chemical properties (T, S, O₂ and NO₃) exhibited pocket like features that clearly indicated higher turbulence in waters due to higher wind speeds during IFP ‘99. Wind driven turbulence together with the frontal circulation should have caused vertical patches in distributions of these properties. Due to this turbulence temperature in the upper 50 m was lower by 2-3°C with concomitant higher salinities in 1999 than 1998. Stratification in FFP ‘98 and turbulence in IFP ‘99 have also led to significant differences in nitrate distributions observed between the two cruises. While nitrate occurred in the upper 50 m, to a maximum of ~9 µM, in 1999 it was mostly below detection limits, except just north of the countercurrent, in 1998.
3.4 Hydrographic features during a time series study in the Zuari estuary

The Zuari River stretches 50 upstream km in length and receives large amount of freshwater influx during the southwest monsoon. Being in the tropics the estuary experiences semi-diurnal tides and during the monsoons the tidal influx of salt water together with fresh water discharge leads to the formation of a salt wedge. The tidal amplitude remains unchanged up to nearly 40 kms upstream, but falls rapidly within the last 10 km due to river runoff [Shetye 1999 and references therein]. Heavy precipitation and land runoff from June to September bring about large changes in temperature, salinity, flow pattern, dissolved oxygen and nutrients since the estuary becomes freshwater dominated. The monsoon season (July-September) is followed by a recovery period during the post-monsoon season (October-January) and thereafter a stable period of the pre-monsoon season (February-May) when the estuary becomes marine dominated. Fig. 3.12 shows the monthly variations in temperature, salinity, dissolved oxygen and nitrate at the time series station (Fig. 2.2) at the mouth of the Zuari estuary.

Temperature showed high values during the month of March due to maximum solar insolation. The surface water temperature varied from 28°C to 33°C with an average value of 29.6°C whereas the bottom water temperatures varied from 22°C to 32°C with an average value of 28°C. Bottom water temperatures varied more than at surface. Figure 3.12 depicts low temperatures in bottom waters during June-August. These low values result from upwelling during southwest monsoon, which is intense in August. Afte
Fig. 3.12. Temporal variations in physicochemical parameters in the Dona Paula bay of the Zuari Estuary.
the monsoon the surface and bottom temperatures revert back to pre-
monsoonal values. Similar variations were also seen in case of salinities. Both
surface and bottom salinities did not show much variation throughout the year
except during the monsoon where surface salinities fell drastically during
June-August due to runoff. Due to a break in monsoon rainfall in July surface
salinity almost equaled the bottom value.

The maximal variations in dissolved oxygen were seen during the
southwest monsoon as in the case of temperature and salinity (Fig. 3.12).
During this period bottom oxygen values decreased. A significant difference of
129.5 μM occurred between the surface and bottom values during July. The
surface as well as bottom oxygen average to about 178.6 μM except during
June to September when the bottom DO values average around 111.6 μM. As
the bottom was occupied by upwelled waters the oxygen was low and nitrate
was high in SW monsoon. This signature was pronounced during June. On
the other hand high nitrate can be accompanied by high oxygen in estuaries
since freshwater discharge supplies nutrients In the present study the
maximal oxygen was observed in June 2000 during which the nitrate was
about 10.8 μM. Surface and bottom nitrate values were nearly the same
except at the beginning of the monsoon (June) when the surface nitrate was
higher than the bottom nitrate. From August to September the bottom nitrate
was higher. The inputs of nitrate into the study area were seen not only during
the monsoon season particularly during November and December (Northeast
monsoon) period. This was seen in two consecutive years (i.e. December of
1999 and 2000) and was thus not a mere coincidence. In addition a surface and bottom high of ~7μM was also observed during the April 2000. Nair, [1980] observed two peaks in zooplankton production in the Zuari estuary, one in November and the other in March/April. Higher zooplankton results in higher fecal matter, rich in ammonia. This ammonia in the presence of oxygen might undergo nitrification and thus results in high nitrate observed in the study area during these months. Similar observation from the study area Qasim and SenGupta, 1981] suggested these high concentrations to be of local origin.

The salient features of hydrography during the study period are:

1) In the Arabian Sea winter convection during the northeast monsoon and upwelling during the southwest monsoon introduces nutrients into the euphotic zone thereby inducing high productivity. The fall inter-monsoon showed oligotrophic conditions.

2) Runoff suppressed upwelling along the coasts of Chennai and Paradip during southwest monsoon.

3) Atmospheric depression in the head Bay caused nutrient pumping into the euphotic zone that affected biological production.

4) Cloud cover reduced incident UV radiation but promoted high production.

5) Central Indian Ocean showed marked differences in the hydrographic features between 1998 and 1999 with higher levels of nutrient input and production in 1999.
6) Seasonal circulation resulted in maximal nutrient concentrations in the southwest monsoon in the Zuari estuary.