Physical control of primary productivity on a seasonal scale in central and eastern Arabian Sea

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Using *in situ* data collected during 1992–1997, under the Indian programme of Joint Global Ocean Flux Study (JGOFS), we show that the biological productivity of the Arabian Sea is tightly coupled to the physical forcing mediated through nutrient availability. The Arabian Sea becomes productive in summer not only along the coastal regions of Somalia, Arabia and southern parts of the west coast of India due to coastal upwelling but also in the open waters of the central region. The open waters in the north are fertilized by a combination of divergence driven by cyclonic wind stress curl to the north of the Findlater Jet and lateral advection of nutrient-rich upwelled waters from Arabia. Productivity in the southern part of the central Arabian Sea, on the other hand, is driven by advection from the Somalia upwelling. Surface cooling and convection resulting from reduced solar radiation and increased evaporation make the northern region productive in winter. During both spring and fall inter-monsoons, this sea remains warm and stratified with low production as surface waters are oligotrophic. Inter-annual variability in physical forcing during winter resulted in one-and-a-half times higher production in 1997 than in 1995.

1. Introduction

The Arabian Sea experiences extremes in atmospheric forcing which leads to one of the largest intra-annual variability compared to other ocean basins of the world. The semi-annual reversals in atmospheric and ocean circulation, the inflow of warm high saline waters from the Persian Gulf and the Red Sea, and the zone of oxygen deficient waters (∼150–1000 m) make the Arabian Sea a unique tropical basin. Plankton blooms occur during both summer and winter monsoons and we are only beginning to understand the processes that regulate biological production in the area. In this paper we attempt to focus on the overall physical forcing that controls productivity in the central and eastern Arabian Sea on a seasonal scale, based on the ship-board measurements during 1992–1997 (see figure 1 for location and table 1 for cruise details). An important question is, how well the relationship between physical forcing and biological production on a seasonal scale can be established with data collected over 6 years? The rationale behind it is based on the fact that though the semi-annual switching of the winds may have inter-annual variability, on the whole, it is highly regular on a seasonal basis (Fieux and Stommel 1977). Apart from this, the amplitude of the seasonal signal is much higher than the inter-annual signal (Unnikrishnan *et al* 1997; Prasanna Kumar *et al* 1998).

The classification of seasons considered in this study is

- Spring Inter-monsoon – March – May
- Summer monsoon – June – August
- Fall Inter-monsoon – September – October
- Winter monsoon – November – February

It may be noted that though June to September is generally considered as summer monsoon, we chose to include September into fall inter-monsoon based on the property distribution in the central Arabian Sea along 64°E.

Keywords. Primary production; upwelling; winter cooling; Ekman-pumping, nutrient transport; Arabian Sea.

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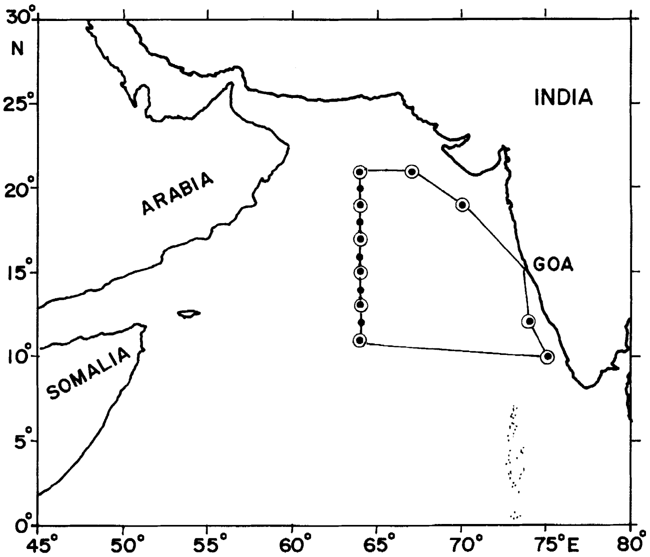

Figure 1. Cruise track of ORV *Sagar Kanya* in the eastern Arabian Sea under Indian JGOFS programme. Dark circles indicate the station location and data from these were used in the study. The section along 64°E was sampled in all the cruises during 1994–1997, except in winter 1997 (SK-121) when time series station was occupied at 21°N, 64°E. Temperature, salinity and nutrients were sampled at every degree (dark circles) while biological measurements were made at every two degrees (open circles). During 1992 stations were occupied along 65°E, while in 1993 it was along 66°E (not shown). See table 1 for details of individual cruises.

2. Data and method

Under the Indian programme of the Joint Global Ocean Flux Study (JGOFS) 7 cruises were undertaken on-board ORV *Sagar Kanya* : two minor (SK-77 along 65°E and SK-87 along 66°E) during 1992–1993 and five major during 1994–1997 (table 1). A more or less common transect along 64°E (figure 1) was followed in all the major cruises except during winter 1997 (SK-121) when a time series station was occupied at 21°N and 64°E.

Measurements taken at one degree interval and up to 1000 m depth included temperature and salinity profiles using a Sea-Bird Electronics CTD (Conductivity-Temperature-Depth) (see Prasanna Kumar and Prasad 1996), and nutrients (nitrite, nitrate, phosphate and silicate) analysed with a SKALAR auto-analyser (see de Sousa *et al* 1996). ^{14}C primary production (PP) was estimated by *in situ* incubation and clean techniques, and chlorophyll *a* by using a Turner Design Flurometer (see Bhattathiri *et al* 1996) at two degree intervals. CTD salinities were calibrated against those in water samples collected simultaneously and analysed with ship-board Guildline 8400 Autosal. Water samples used for nutrients as well as biological measurements were collected by a rosette fitted with 10/30 litre Go Flo bottles and attached to the CTD system. Surface meteorological observations were carried out along the track at 6 hourly intervals and at stations.

3. Results

3.1 *Spring inter-monsoon*

Spring inter-monsoon was characterised by light (< 4 m s^{-1}) and variable winds predominantly from the west (figure 2). Being the primary heating season of the year, as the incoming solar radiation peaks to about 260 W m^{-2} in April-May (Hastenrath and Lamb 1979), the air temperature increased to more than 28°C along 64°E and at times reached 30°C (not presented). Consequently, the sea surface temperature (SST) rose to about 28°C. The mixed layer depth (MLD) remained very shallow, varying from about 35 m in the south to 10 m in the north. Increased SST, due to increased insolation, combined with weak winds during this season led to the formation of the observed shallow and (highly stratified upper layer with) uniform mixed layer.

Nitrate in the surface layers was below detection limit and 2 μM occurred at depths greater than 50m when nutracline was situated in the upper thermocline (figure 3a). This was in general applicable to the entire Arabian Sea except during summer and winter monsoons, as we would see later, when prevailing physical forcing supplies nutrients from subsurface to nutrient depleted surface layer. Consistent with oligotrophic nutrient distribution, the surface as well as

Table 1. *Cruise details of the Indian Joint Global Ocean Flux Study (JGOFS) programme in the eastern Arabian Sea during 1992-1997. See figure 1 for station locations.*

Serial number	Cruise number	Period	Region of sampling	Representative season
1	SK-77	20th September–7th October, 1992	Along 65°E from 3°N to 15°N	Fall inter-monsoon
2	SK-87	11th–20th September, 1993	Along 66°E from 16°N to 21°N	Fall inter-monsoon
3	SK-91	12th April–12th May, 1994	Along 64°E from 11°N to 21°N	Spring inter-monsoon
4	SK-99	3rd February–5th March, 1995	Along 64°E from 11°N to 21°N	Winter
5	SK-104	20th July–12th August, 1995	Along 64°E from 11°N to 18°N	Summer
6	SK-115	3rd–25th August, 1996	Along 64°E from 13°N to 19°N	Summer
7	SK-121	5th–26th February, 1997	Time series at 12°N, 64°E	Winter

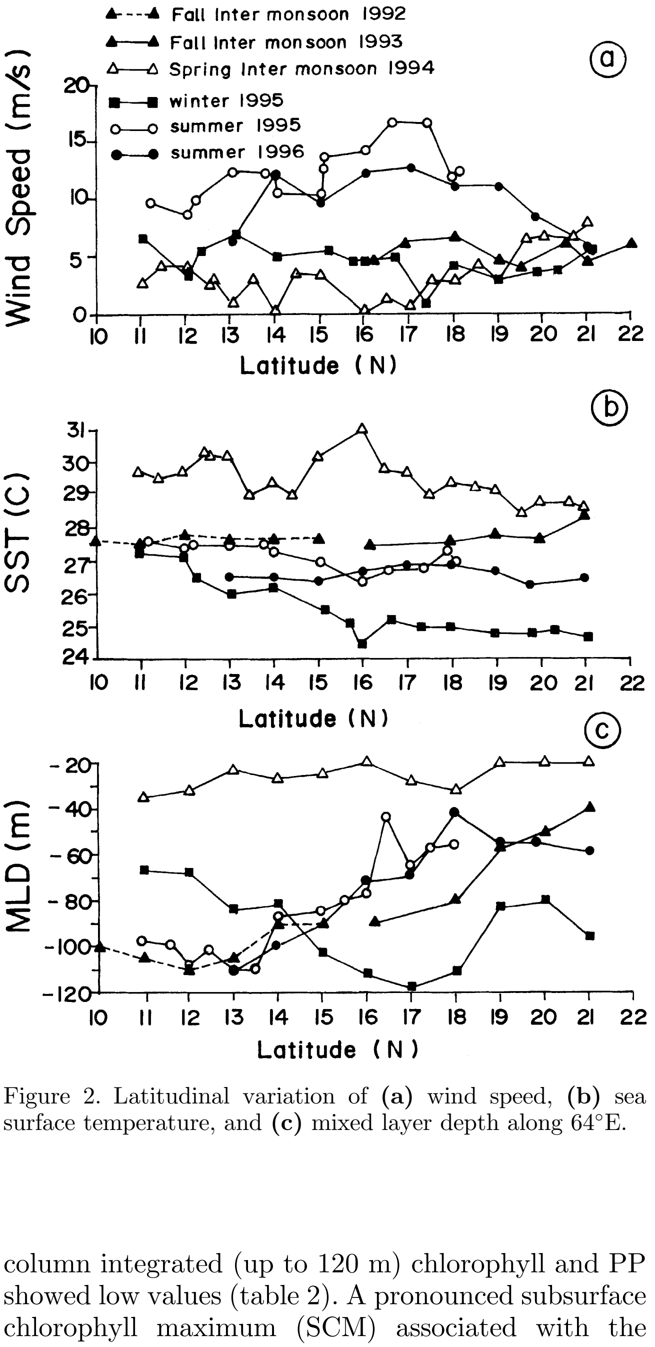

Figure 2. Latitudinal variation of **(a)** wind speed, **(b)** sea surface temperature, and **(c)** mixed layer depth along 64°E.

column integrated (up to 120 m) chlorophyll and PP showed low values (table 2). A pronounced subsurface chlorophyll maximum (SCM) associated with the nitracline (~60 m) was also found during this time of the year (figure 4a). Productivity in central Arabian Sea was relatively lower than that in coastal waters (table 2).

3.2 *Summer monsoon*

During summer 1995 south-westerly winds persisted with speeds increasing from 9 m s^{-1} at 11°N to 17 m s^{-1} at around 16.5°N, and declined beyond this latitude (figure 2). The trend remained similar during 1996 but for the speeds, which were, lower (6 m s^{-1}) in the south and the highest at 17°N (13 m s^{-1}). The maximum wind speed indicates the position of the axis of the Findlater Jet (Findlater 1969) which becomes active during summer monsoon. Based on the wind distribution for both the years, the axis of the Findlater Jet along 64°E was found to occur between 16 and 17°N. SST was about 27.5°C in the south and dropped by 1°C towards the axis of the Findlater Jet in 1995. However, SST did not show any significant north-south variation in 1996 with values around 26.5°C. Most significant changes occurred in the MLD in both years, which shoaled from 100 m depth in the south to about 45 m near the axis of the Findlater Jet and remained shallow north of it.

Nitrate was undetectable or at very low levels in the upper 50 m in the south (< 15°N), in both the years. A lens of high nitrate (2–4 μM) was observed within 15–17°N in 1995 (figure 3b). This lens of water was 0.5°C colder and 0.1 PSU fresher than the ambient water. During 1996, however, this lens was absent, but in the north the nitrate in the upper 50 m was about 1 μM (figure 3c). Vertical distribution during both 1995 and 1996 showed a shoaling of nitrate isopleths towards the north, especially north of the Findlalet Jet axis. Contrary to earlier general observations in the open central Arabian Sea during this period, we found higher column chlorophyll *a* values up to 60 mg m^{-2} and PP up to 1780 mg C m^{-2} d^{-1} along 64°E which were comparable with values in near shore waters (table 3). Interestingly, high productivity was not confined to the north where both thermocline and nutracline shoaled, but occurred in the southern areas as well. The chlorophyll *a* concentrations and production rates were comparable to those in the active upwelling fields off Somalia coast (Smith and Codispoti 1980; Hitchcock and Olson 1992; Veldhuis *et al* 1997). Incidentally, high chlorophyll *a* concentrations were also reported by Mara *et al* (1998) in the central Arabian Sea (15.5°N, 61.5°E) during summer, based on moored sensors. Vertical profiles of chlorophyll *a* and PP (figure 4b) showed that about 80% of the pigment concentrations and 85% of the production in summer in the southern areas occurred in apparently nutrient-poor waters in the upper 60 m along 64°E. However, nutrients must have been available in the upper water column in order to attain such levels of chlorophyll and PP. We speculate that the low/undetectable levels of nitrate in the south (figure 3b and c) were presumably due to rapid biological uptake.

3.3 *Fall inter-monsoon*

Winds during 1993 fall inter-monsoon were predominantly westerlies, varying from west-southwesterlies to west-northwesterlies with speeds between 4 and 7 m s^{-1} (figure 2). SST during both 1992 and 1993 was on an average 28°C, and increased to 28.5°C in 1993 at around 21°N, which was similar to that in spring inter-monsoon. Signatures of Findlater Jet disappeared along 64°E but MLDs still remained deep in the south and shoaled to 40 m at 21°N.

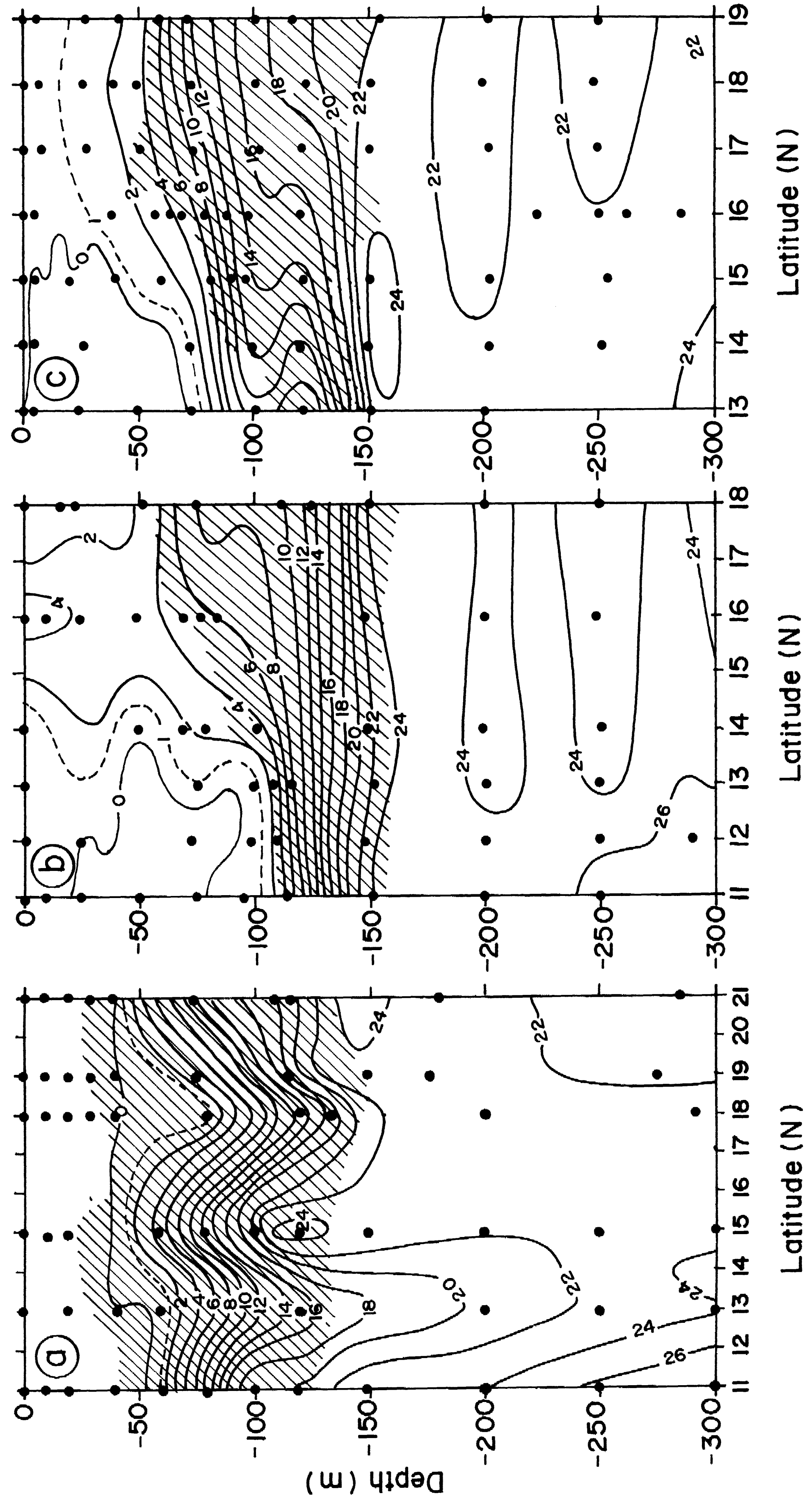

Figure 3. (*Continued*)

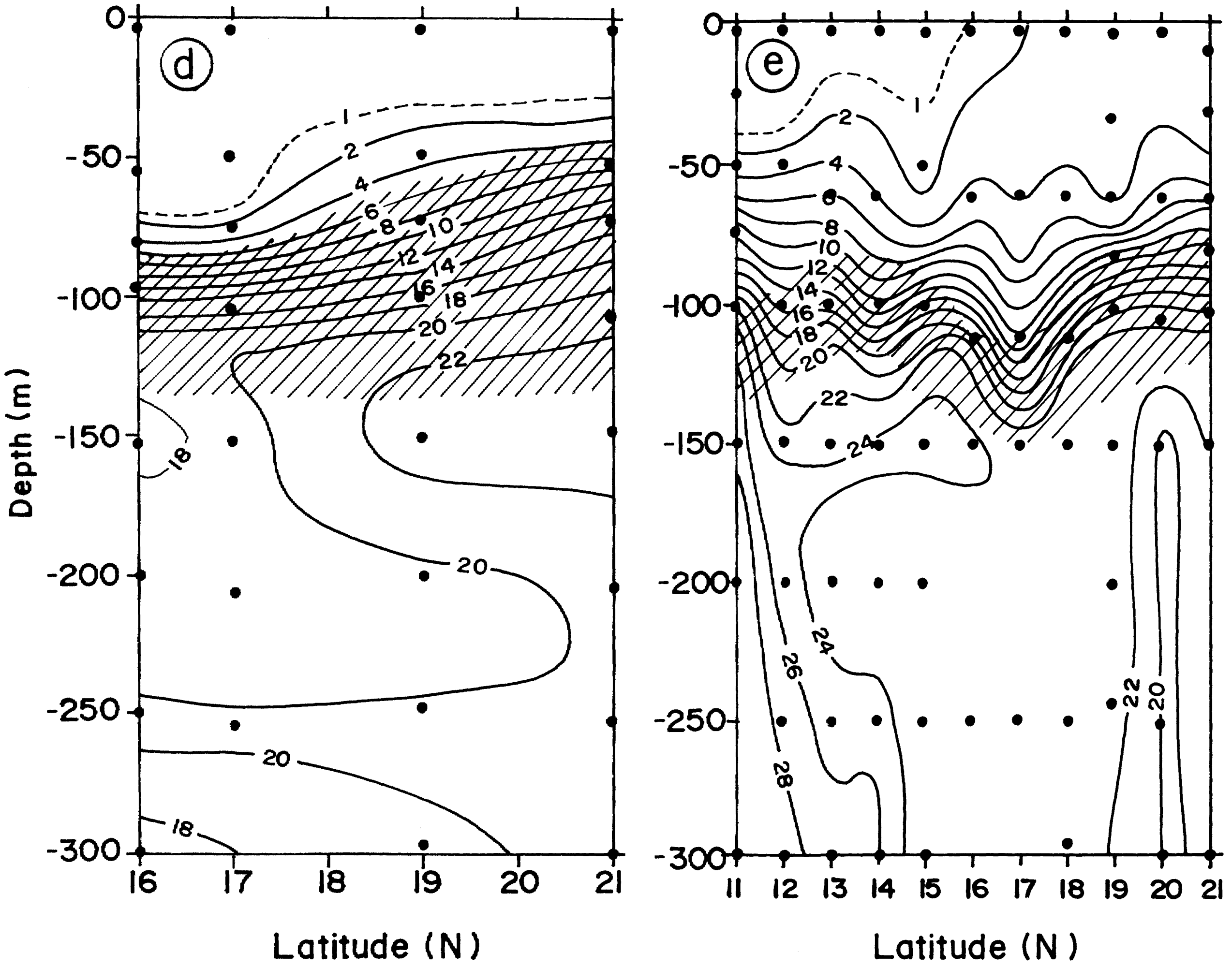

Figure 3. Vertical structure of nitrate (μM) in the upper 300 m water column along 64°E during **(a)** spring inter-monsoon 1994, summer monsoon (b) 1995 and **(c)** 1996, (d) fall inter-monsoon 1993 and **(e)** winter monsoon 1995. Stippled area shows the position of upper thermocline, bounded below by 20°C isotherm.

Nitrate in the surface layer was very low/undetectable with nitrate isopleths showing a shoaling trend towards north (figure 3d), similar to that of thermal structure. Consistent with the generally oligotrophic surface layers, the chlorophyll *a* also showed low values (table 4) which indicated a tapering of biological productivity during this time of the year.

3.4 *Winter monsoon*

During 1995 winter, winds along 64°E were predominantly north/north-easterly with average speed of about 4 m s^{-1} (figure 2). As the incoming solar radiation decreases from its fall inter-monsoon value of 200 W m^{-2} to 160 W m^{-2} in peak winter (Hastenrath and Lamb 1979), air temperature also decreased by an average of 5°C north of 15°N – being 23°C in the north and increased to 26.5°C at 11°N. Consistent with this, the SST was $\sim$ 25°C in the north, a decrease of 3°C from the fall inter-monsoon value, and increased to 27.5°C towards south (figure 2). MLD showed the greatest variability, which was about 120 m north of 15°N but thinned steadily towards the south (to 65 m).

Table 2. *Surface and column integrated (up to 120 m) chlorophyll a* (Chl *a*) *and primary production (PP) in the central and eastern Arabian Sea during spring inter-monsoon. Surface Chl a and PP are in mg m^{-3} and mg C m^{-3} d^{-1} while column integrated values are in mg m^{-2} and mg C $m^{-2}d^{-1}$ respectively.*

Latitude N	Longitude E	Surface Chl *a*	Surface PP	Column Chl *a*	Column PP	Day
21	67	0.05	8.8	10.7	310	9th May 94
15	64	0.05	0.8	16.6	168	15th April 94
11	64	0.04	0.7	9.2	163	23rd April 94
10	75	0.05	3.3	10.5	199	27th April 94

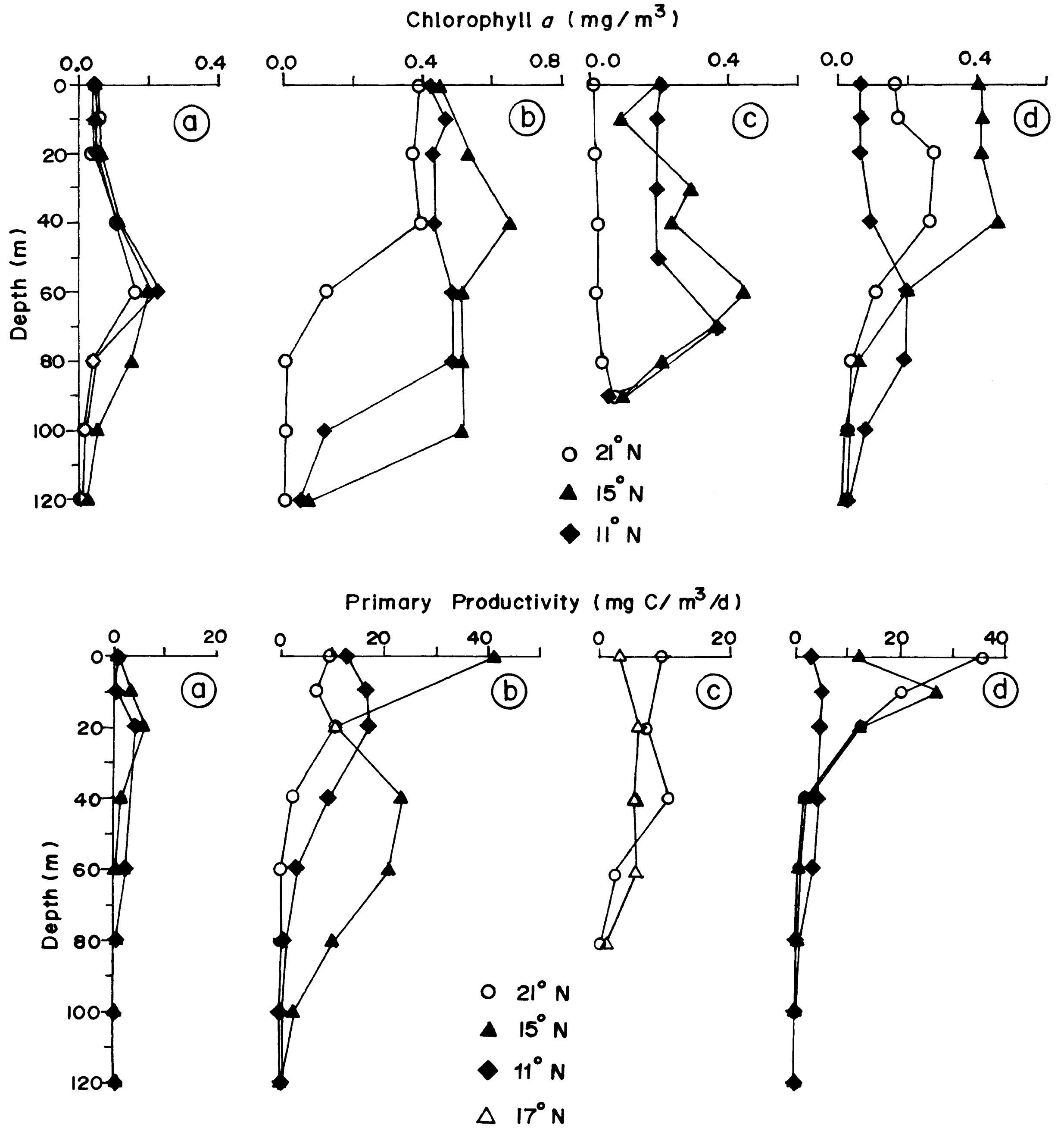

Figure 4. Vertical profiles of chlorophyll *a* and PP during **(a)** spring inter-monsoon 1994, **(b)** summer monsoon 1996 (except at 11°N which was in 1995), **(c)** fall inter-monsoon 1992 (except at 21°N which was in 1993), and **(d)** winter monsoon 1995. Except for fall inter-monsoon (1992 along 65°E and 1993 along 66°E) all stations were along 64°E.

Table 3. *Same as in table 2 but for summer 1995 and 1996.*

Latitude N	Longitude E	Surface Chl *a*	Surface PP	Column Chl *a*	Column PP	Day
19	70	0.29	12.0	21.0	440	10th August 95
12	74	0.09	9.4	88.0	1760	23rd July 95
11	64	0.42	12.8	44.0	770	31st July 95
10	75	1.34	16.0	49.9	660	25th July 95
19	64	0.54	22.0	28.0	830	15th August 96
17	64	1.12	8.9	58.0	1029	13th August 96
15	64	0.45	41.5	60.0	1782	10th August 96
13	64	0.32	8.3	26.0	792	8th August 96

Table 4. *Surface and column integrated (up to 120 m) chlorophyll a in the central Arabian Sea during fall inter-monsoon. Surface Chl a is in mg m^{-3} while column integrated values are in mg m^{-2}.*

Latitude N	Longitude E	Surface Chl *a*	Column Chl *a*	Day
21	66	0.10	11	18th September 93
19	66	0.10	12	16th September 93
17	66	0.35	18	14th September 93
15	65	0.21	19	4th October 92
11	65	0.21	20	3rd October 92

Nitrate distribution showed the surfacing of 2 μM isopleth at 16°N and to the north of this, surface values were between 2 and 4 μM (figure 3e). A general increase in biological productivity was evident in winter, especially in the north, which decreased to the south of 15°N (table 5).

During 1997 winter, the time series data at 21°N and 64°E indicated that the SST was 1°C cooler and MLD deeper by about 30 m in comparison with 1995 winter. Surface nitrate values were about 4 μM with an average PP of about 900 mg C m^{-2} d^{-1} (table 5), about 250 mg higher than the 1995 winter.

4. Discussion

Spring inter-monsoon, the main heating season in the Arabian Sea, showed lowest chlorophyll concentration as well as primary production in the central Arabian Sea. This was primarily because the Arabian Sea being a tropical basin, the biological production is controlled by the availability of nutrients in surface water when light is not a limiting factor in this season. Warm and highly stratified upper ocean, under the influence of peak insolation together with light winds, inhibits vertical mixing and upward transport of subsurface nutrients. Open ocean circulation at this time of the year is weak and zonal, and there is no source of nutrients from lateral advection. This leads to rapid utilisation of available nutrients making the production nutrient limiting.

During summer monsoon, upwelling makes the coastal regions of the Arabian Sea more productive. Observations on chlorophyll *a* as well as PP along the southern shelf of the west coast of India (table 3) provide evidence to this. Open waters of the Arabian Sea were reported to be low productive (Prasanna Kumar *et al* 2000) with chlorophyll *a* typically ranging from 0.1 to 0.5 mg m^{-3} and PP from 100 to 500 mg C m^{-2} d^{-1} (Kabanova 1968; Krey and Babenerd 1976; Banse 1987). However, observed high chlorophyll *a* and PP in the central Arabian Sea (table 3) is contrary to the conventional understanding of the Arabian Sea productivity.

With the onset of the southwest monsoon, wind speeds are generally high (on an average 15 m s^{-1}) during summer. This could induce intense vertical mixing, leading to increase in mixed layer thickness and enrichment of nutrients in the upper layer, which could support higher biological production. However, higher wind speeds in the north did not deepen the MLD; it was shallow (45 m) under the strongest observed winds (17 m s^{-1}) along 64°E but was deeper under comparatively lighter winds in the south. This could be explained with reference to the position of the Findlater Jet and basin scale distribution of wind. Bauer *et al* (1991) showed that cyclonic wind stress curl occurring northwest of the Findlater Jet would induce a divergent Ekman transport in the upper ocean and drive open-ocean upwelling through upward Ekman pumping. Shoaling of MLD (figure 2) as well as nitrate isopleth (figure 3b and c) towards the axis of the Findlater Jet (~16.5–17°N) and further north lend support to this and indicate that upward Ekman pumping is an important mechanism in the vertical transport of nutrients during this season.

However, the observed high production during this season in the south calls for an explanation. In the south (of the Findlater Jet) anticyclonic wind stress curl induced a convergent Ekman transport as is

Table 5. *Same as in table 2 but for winter 1995 and 1997.*

Latitude N	Longitude E	Surface Chl *a*	Surface PP	Column Chl *a*	Column PP	Period
21	64	0.17	35.8	18.9	643	10th February 95
21	67	0.31	21.4	34.4	807	8th February 95
19	64	0.27	6.7	20.9	447	16th February 95
15	64	0.41	12.0	26.7	606	18th February 95
11	64	0.06	3.8	12.7	335	25th February 95
10	75	0.03	1.1	9.6	200	
21	64	0.80	18.9	35.3	985	10th February 97
21	64	0.43	39.1	29.5	945	16th February 97
21	64	0.57	30.5	43.2	845	23rd February 97

evident from the deep mixed layer (figure 2) and would not lift-up the sub-surface nutrients. Based on Advanced Very High Resolution Radiometer (AVHRR) SST data Prasanna Kumar *et al* (2000) suggested that lateral advection from the upwelling regions of the western Arabian Sea is an important mechanism in transporting upwelled nutrients to the central Arabian Sea. Upwelling along the Somalia coast pumps up cold (17–22°C) subsurface waters with about 5 to 20 μM nitrate (Smith and Codispoti 1980). The swift Somali current reduces the residence time of this upwelled, nutrient-rich water and therefore biological productivity in this region remains below its potential (Veldhuis *et al* 1997). Thus, a major part of this unutilised nutrient is transported into open Arabian Sea; that support the biological production in the south. In the north, apart from the open ocean upwelling, lateral advection from Arabia upwelling region would also contribute to enhanced nutrient levels. The lens of 4 μM nitrate at 16°N detached from 4 μM isopleth below 50 m depth, as well as surfacing of 2 μM nitrate isopleth at 14°N is indicative of both the processes.

In short, in the open Arabian Sea, the wind-driven mixing could be an important mechanism by which nutrients are entrained into the surface layers during the onset period of the summer monsoon. This could initially trigger pulse-like (episodic) primary production in the open Arabian Sea in the beginning of summer monsoon. As the monsoon wind stabilizes, the wind mixing also reaches a steady state with no further input of nutrient from below. With the establishment of basin-wide winds, upward Ekman-pumping north of the Findlater Jet as well as advection from the coastal upwelling regions of Somalia and Arabia, makes open waters of the central Arabian Sea rich in nutrient which supports higher biological production.

As the summer monsoon tapers off and fall intermonsoon sets in, the winds, once again, become lighter ($\sim 5\,\mathrm{m\,s^{-1}}$) and variable. In conjunction with the atmospheric heating, SST showed a second phase of warming in the annual cycle. Wind distribution did not indicate the signature of Findlater Jet, and MLD and isotherms exhibited a decaying part of the summer structure. However, the less shoaling of MLD north of 15°N indicated the cessation of summer monsoon not only in the upper layer but within the thermocline as well.

Winter monsoon is characterised by low wind speeds ($\sim 4\ \mathrm{m\ s^{-1}}$) which should mean low wind mixing and shallow mixed layer. Observed deep MLD (figure 2), high upper layer nitrate (figure 3e) and higher biological production (table 5) in the north (north of 15°N) would thus, appear to be anomalies. Nevertheless, this could be understood in the light of the prevailing physical process operating in the Arabian Sea. The cold SST suggests that sea surface looses heat besides the decrease in incoming solar radiation. The cool, dry continental air brought to the northern Arabian Sea by the trade winds enhances the evaporation and estimated loss due to evaporative cooling is about 3°C (Prasanna Kumar and Prasad 1996). These combined with high ambient salinity ($>$ 36.0 PSU), lead to densification of surface waters and drive a convective mixing (Prasanna Kumar and Prasad 1996). This results in the mixed layer deepening, upward transport of nutrients from the base of the mixed layer and subsequent higher biological production (Madhupratap *et al* 1996).

The 1997 winter time-series data collected at a northern location (21°N, 64°E), while confirming the high biological productivity of the northern Arabian Sea observed in 1995 winter, highlight the interannual variability in temperature and water column processes. The comparison showed that 1997 winter was colder by (SST) 1°C. This increased cooling resulted in more intense convection and vertical mixing as seen from MLD, which was deeper by 30 m and surface nitrate was 2μM higher than that in the 1995 winter. Consequently, both the column integrated chlorophyll *a* and PP were one-and-a-half times more in the 1997 winter.

5. Summary

The JGOFS India programme unambiguously revealed a tight coupling between the physical forcing and biological response in the Arabian Sea on a seasonal scale. This is primarily because, being a tropical basin where light is not usually a limiting factor, the biological production is limited by the availability of nutrient. The basin is forced by semi-annual wind reversal, which controls the nutrient availability in the euphotic zone and alters with season. During the summer monsoon, upwelling occurring along the Somalia, Arabia and southern part of the west coast of India makes the coastal region biologically productive. Apart from this, recent measurements show that open waters of the Arabian Sea also become productive and this happens in the northern region (north of the axis of the Findlater Jet ~16–17°N) via a combination of processes such as open ocean upwelling induced by the cyclonic wind stress curl and advection of nutrient rich waters from the Arabian upwelling zone. In the southern central waters, higher productivity occurs due to advection of nutrient rich, upwelled waters from Somalia. In winter the northern Arabian Sea (north of 15°N) becomes biologically high productive region. This happens due to winter cooling under reduced incoming solar radiation and enhanced evaporation by dry continental air. As the ambient salinity of the northern Arabian Sea is high, the cooling is sufficient to increase the density and initiate convection. This transports nutrients from upper thermocline to euphotic zone and gives rise to winter blooms.

These findings have a bearing on some of the biogeochemical processes occurring in the Arabian Sea. Various hypotheses have been proposed for the maintenance of sub-oxic conditions prevailing at intermediate depths in the Arabian Sea. Recent results on high chlorophyll *a* and primary production in the central regions of the Arabian Sea during summer as well as winter suggest that a primary factor leading to sub-oxic levels of oxygen may arise from the downward transport of high amounts of organic matter. If so, this would also resolve denitrification paradox in the Arabian Sea where intense nitrate reduction occurs in the central regions away from upwelling areas.

Though seasonal signals are easily distinguishable as the dominant signatures, inter-annual signal was clearly inferred between the winters of 1995 and 1997. A small inter-annual variability in cooling showed pronounced effects on biological production. This points to the fact that though inter-annual signal could be small, it can trigger a large variability in biological productivity.

Thus, behaviour of the Arabian Sea is different from the conventionally understood tropical basin due to its high ambient salinity, reversal of monsoons, coastal and open ocean upwelling and winter cooling effects. The Arabian Sea renders itself as one of the most productive regions in the world for a major part of the year (ca. 8 months), due to diverse physical processes during summer and winter.

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