

Regionally variable chemistry, auto-heterotrophic coupling and vertical carbon flux in the northwestern Indian Ocean: A case study for biochemical pump

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Large scale regional differences in surface productivity as well as water column chemistry exist in the Arabian Sea environment in north-south direction. The available primary productivity data are incorporated into existing global ocean carbon flux models to estimate the potential vertical flux of carbon, and speculate on the nature of the autotrophic and heterotrophic processes, in the mixed layer and below, within the context of the observed regional chemical dichotomy. Based on these considerations, hypothetical scenarios relating to regionally variable primary productivity, retention/loss of carbon in the water column, variable mineralization in the deep sea, etc. are formulated. Field testing of these hypotheses should provide a general framework for regional Arabian Sea oceanography in the coming years, especially with respect to the Global Ocean Flux Studies.

Circulation in the northwestern Indian Ocean (Arabian Sea) is forced by seasonally reversing winds associated with monsoons. Consequently, biological and physicochemical variability in this part of the world ocean is strongly phase-locked to the monsoon cycle. The Arabian Sea shows maximum productivity within the Indian Ocean region and is amongst the highest of any region in the world ocean¹. Surface productivity shows a north-south gradient with the northern region being highly productive (15°-25°N; 26-2084 g C. m⁻².y⁻¹) than the southern (0°-10°N; 0.4-248 g C. m⁻².y⁻¹) region². Recent sediment trap collections from the Arabian Sea have indicated large subsurface particle flux which is closely linked to primary production and the degree of monsoon induced upwelling³. Coupled with the high surface productivity and resultant high particle flux, the presence of a persistent and extensive sub-surface oxygen minimum layer⁴ is another distinctive feature in the Arabian Sea. Kumar *et al.*⁵ have documented that the total carbon dioxide (TCO₂) increases in proportion to the oxygen utilized, revealing the dominant biological role in the carbon turnover.

The chemistry of carbon species in the ocean is controlled by biologically mediated processes of production and destruction of organic matter that collectively make up the biological pump⁶ or more appropriately, the biochemical pump. The sinking

particulate organic matter (POM) links food webs beneath the euphotic zone to surface production, transports elements to the ocean interior, controls nutrient cycling, fuels deep sea and benthic life and affects burial of carbon in the sediment⁷. Further, the sinking of surface derived POM is the significant mechanism for much of the vertical transport of organic carbon to the deep sea⁸, although the vertical advection of dissolved organic carbon (DOC) can also be equally important⁹. However, the loss of particulate organic carbon (POC) to the deep sea is a variable and seasonal process, closely linked to surface primary productivity¹⁰.

Oceanic DOC is the largest pool of reduced carbon in the biosphere¹¹, amounting to approximately 50 times the atmospheric stock. The turnover rate of oceanic DOC pool has therefore implications for the long term changes in atmospheric carbon dioxide (CO₂) levels. Preliminary budget calculations for the Arabian Sea¹² have shown that carbon is negatively balanced approximately by 84 Tg.y⁻¹, implying that the region is a net source for atmospheric CO₂. Concentrations of DOC in the Arabian Sea are 3-4 times higher⁵ than those reported earlier. Further, the northern Arabian Sea has been shown to be a region of unusually high methane concentrations, where the flux of methane to the atmosphere is up to five times greater than the average for the world

ocean¹³. Recently, Rajendran *et al.*¹⁴ have provided evidence for large scale regional variabilities in the relationships between DOC and apparent oxygen utilization (AOU) in the Arabian Sea, highlighting considerable differences in both the production as well as the destruction of organic matter within this region.

In this paper, the biological basis for the regional chemical dichotomy within the Arabian Sea is presented. In this attempt, the available data on biogeochemical rate processes are collected and incorporated into the carbon flux models developed for global oceans. Based on these, some scenarios regarding the nature of the food webs that operate differently within the Arabian Sea are suggested.

Data

Data used in the present study were collected during different cruises of *ORV Sagar Kanya*, *RV Sonme* and *RV Gaveshani* from 1984 to 1989. DOC and CO₂ data from various cruises were selected so that they covered the entire Arabian Sea and different seasons. With respect to spatial variations, the present study concentrates especially on the northern (15°-25°N) and the southern (5°-10°N) Arabian Sea (Fig. 1). Average values of DOC and other carbon components were used in the flux calculations. Analytical methods adopted for various physico-chemical parameters and DOC and titration alkalinity (TA) have been described elsewhere^{5,15}. Briefly, DOC was analysed by high temperature catalytic oxidation and TA by back titration methods. The precisions of these analyses were 2.67% for DOC and 0.2% for TA. UNESCO¹⁶ equations were used for the computation of total CO₂ (TCO₂) and other carbonate species from pH and alkalinity. CO₂ released due to the regeneration processes (ΔCO_2) was estimated using the generalised equations of Kroopnick¹⁷ for the world oceans.

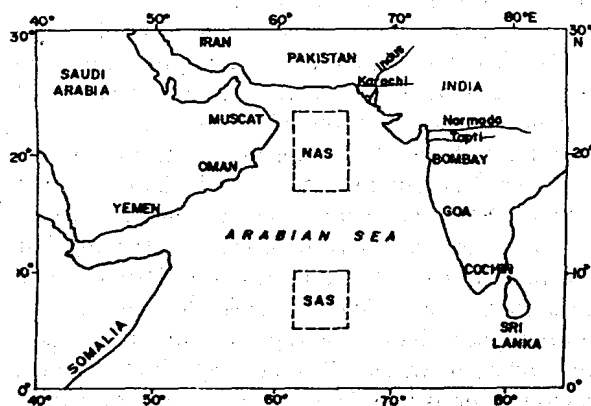


Fig. 1—Northern Arabian Sea (NAS) and southern Arabian Sea (SAS) and their major study areas

Results

Fig. 2 depicts nearly uniform concentrations of DOC throughout the water column in the northern Arabian Sea (NAS), showing a small decrease in concentration from surface to 100 m, whereas in the southern Arabian Sea (SAS) the values at greater depths are higher (between 180 and 260 $\mu\text{mol}\cdot\text{dm}^{-3}$), but with more or less equal concentrations (110 $\mu\text{mol}\cdot\text{dm}^{-3}$) at the surface in both the regions. Vertical distributions of DOC values in the NAS shows a uniform concentration around 100 $\mu\text{mol}\cdot\text{dm}^{-3}$ and DOC gradually increases in deeper layers in the southern region.

Carbon dioxide added due to regeneration processes ($\Delta\text{CO}_2 = \text{TCO}_2 - \text{preformed CO}_2$) exceeds 500 $\mu\text{mol}\cdot\text{dm}^{-3}$ in the intermediate oxygen minimum layers (150-1000 m) of the northern Arabian Sea (Fig. 2). In NAS, ΔCO_2 is about 1.5 times higher than that found at SAS where the oxygen minimum layer is much shallower (300-700m). Because of the enhanced CO₂ regeneration (ΔCO_2) in the intermediate layers of central and NAS than in SAS, partial pressure of CO₂ (pCO₂) builds up in NAS at a greater level. Significantly, pCO₂ in the oxygen minimum (200-400m) layers of NAS is nearly double of that present at the corresponding depths in SAS¹⁵. Increased pCO₂ in surface layers in the NAS than near equator results in enhanced CO₂ ejection to atmosphere in NAS. In order to evaluate the CO₂ partition pattern between air and surface seawater, an indirect parameter f_{AIR} is used¹⁵. f_{AIR} is defined as

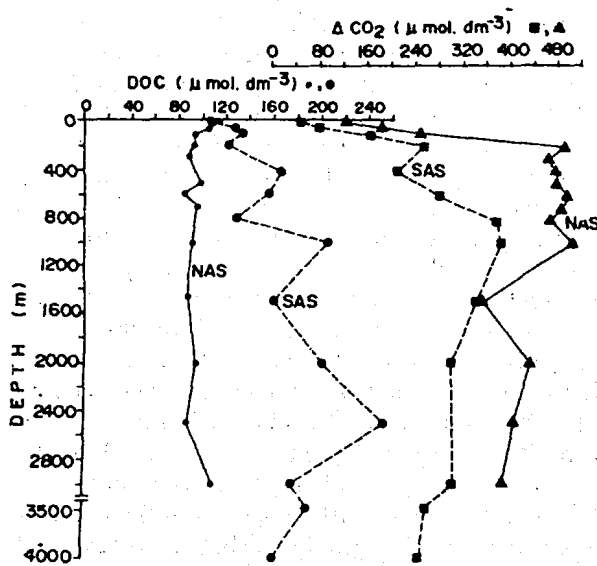


Fig. 2—Vertical profiles of mean values of DOC and ΔCO_2 from different stations in NAS and SAS

the ratio of CO₂ in air to the total present in air and seawater and is higher (0.86) in NAS. The carbon that escapes into the atmosphere in the form of CO₂ is estimated¹² and is 29 gC.m⁻².y⁻¹ in NAS and 14 gC.m⁻².y⁻¹ in SAS (Fig. 3). Fig. 3 depicts the available data both in NAS and SAS, namely the primary production, CO₂ outflux to the atmosphere, average DOC in the ocean interior and sedimentation flux of carbon.

A large amount of data on surface productivity and chlorophyll-*a* (chl-*a*) collected during the cruises of *RV Gaveshani* and *ORV Sagar Kanya* have been used to arrive at a reasonable mean values of carbon fixation for both NAS (770 mgC.m⁻².d⁻¹) and SAS (300 mgC.m⁻².d⁻¹). The actual values of surface primary productivity showed a very wide variation, with ranges between 109 and 2665 mgC.m⁻².d⁻¹ in NAS and 0.33 to 676 mgC.m⁻².d⁻¹ in SAS. Chlorophyll-*a* specific photosynthetic rate, namely productivity per unit chl-*a* (calculated using integrated photic zone values) is an index of mean photic zone growth rate of phytoplankton biomass¹⁸. The mean values for chl-*a* specific productivity for 5° latitudinal intervals from equator to 25°N between 60°E and 70°E (Table 1) clearly indicate a lower growth rate of 26.8 g C. (g chl-*a*)⁻¹.d⁻¹ in the SAS whereas the NAS showed a high rate of 61.5 gC. (g chl-*a*)⁻¹.d⁻¹. However, chl-*a* specific photosynthetic rates calculated from the recent estimations (Dr. P.M.A. Bhattathiri, Personal communication) show a range of variation between

20 and 65 g C.(g. chl-*a*)⁻¹.d⁻¹ (mean 42) near the equator and a wider variation between 23 and 154 g C. (g. chl-*a*)⁻¹.d⁻¹ (mean 59) in the Arabian Sea north of 15°N.

The sedimentation flux of carbon was calculated using the data on total accumulation rate of carbon, sedimentation rate and dry density for 3 stations in NAS and for 3 stations in SAS and these data are essentially from Sirocko¹⁹. The mean sedimentation flux of carbon (Table 2) was 0.435 g.m⁻².y⁻¹ in NAS and 0.187 g C. m⁻².y⁻¹ in SAS. Variations in chemical and productivity parameters between the 2 regions of the Arabian Sea (Table 2) clearly depict a dichotomy and reflect the pattern in primary

Table 1—Latitudinal variation of the photic zone growth rate of phytoplankton biomass (chl-*a* specific photosynthetic rate) in the Arabian Sea.

Latitude	Number of stations	Chl- <i>a</i> specific photosynthetic rate [g C(g chl- <i>a</i>) ⁻¹ .d ⁻¹]	
		Range	Mean
0°-5°N	5	15.2-39.4	26.8
5°-10°N	9	5.3-45.5	28.3
10°-15°N	13	9.9-70.0	36.9
15°-20°N	14	12.9-168.6	58.8
20°-25°N	14	34.8-110.0	61.5

Table 2—Variable chemical and productivity parameters in the Arabian Sea

Parameter/Property	Range of variation in	
	North Arabian Sea	South Arabian Sea
Oxygen min. layer (m)	150 to 1000	300 to 700
Pr. prod. (mgC.m ⁻² .d ⁻¹)	109 to 2665	0.33 to 676
Chl- <i>a</i> (mg. m ⁻³)	0.2 to 0.4	0.1 to 0.2
DOC (μmol.dm ⁻³)		
(a) Upper 150 m	102 to 119	115 to 309
(b) Deeper layers	55 to 94	120 to 310
TCO ₂ (μmol.dm ⁻³)		
(a) Upper 150 m	2500 to 2550	2200 to 2300
(b) Deeper layers	2600 to 2700	2400 to 2450
ΔCO ₂ (μmol.dm ⁻³) at 1000m	500 to 600	350 to 370
f _{AIR}	0.86	0.72
AOU (μmol.dm ⁻³)		
(a) Upper 150m	-57 to 28	-22 to -6
(b) Deeper layers	203 to 262	47 to 223
Nitrate deficit (μmol.dm ⁻³) in the oxygen minimum layers	~8	No positive ΔN
Bacterial population (CFU no × 10 ³ .l ⁻¹)		
(a) Surface	280	18
(b) 100 m	99	9
Sedimentation flux (g m ⁻² .y ⁻¹)	0.435	0.187

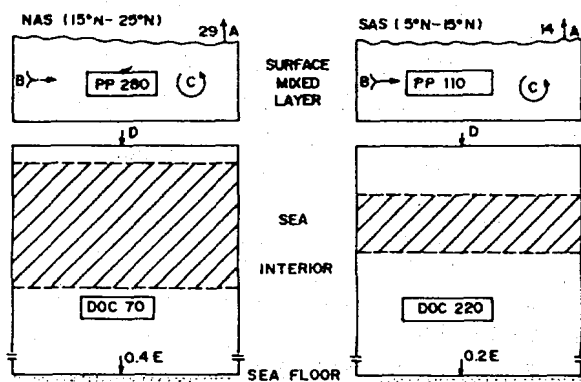


Fig. 3—Schematic model diagram of annual fluxes (gC.m⁻².y⁻¹) in 2 regions of the Arabian Sea [Shaded portion representing the oxygen minimum layer, mean primary production (PP) in gC.m⁻².y⁻¹ and the average concentration of dissolved organic carbon (DOC) in μmol.dm⁻³. (A) CO₂ flux from sea surface to the atmosphere; (B) Carbon fixation in the surface mixed layer; (C) carbon recycled within surface mixed layer; (D) carbon flux out of mixed layer to the sea interior and (E) Organic Carbon sedimentation to sea floor]

productivity and post production biochemical processes. These tabulated data are essentially from Kumar *et al.*^{5,15} and Rajendran *et al.*¹⁴.

Models

In the existing models of carbon flux in the ocean^{7,20-24}, the export flux of organic matter is shown to decrease with depth (Z) due to remineralization, roughly as 1/Z. The model of Pace *et al.*²² (Pace model, Fig. 4) although similar to that of Suess⁷, It predicts higher carbon flux and provides a better fit based on sediment trap data from the Pacific. The Pace model, following closely that of Eppley and Peterson²⁰, assumes a linear relationship between primary productivity (PP) and vertical flux of carbon (J), and does not take into account the possibility of variable post-PP biological transformations. However, this simple linear model has served as a basic background model of carbon flux for the present study.

The Betzer *et al.*²¹ model (Betzer model, Fig. 5) accommodates effectively through a power law the above postulations that J increases exponentially with increasing PP. For the Arabian Sea region with generally high PP values, the application of the Betzer model predicts J values that are several times higher than those based on Pace model. The Betzer model is applied to the Arabian Sea, and especially found useful for the J values at 100 m. It is assumed that the J at 100 or 110 m, the export flux at the base of the surface mixed layer (SML) is equivalent to new production²⁰.

Bishop⁹ has demonstrated that once the export flux at 100m is known, the Martin model²³ is 'the best predictor of J at greater depths, because it considers many post-production processes. While applying the

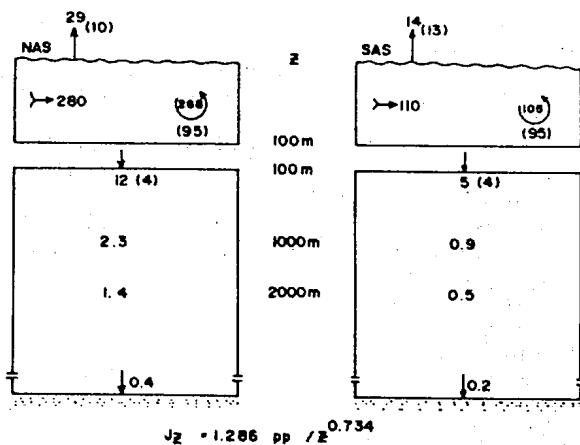


Fig. 4—Carbon flux based on Pace *et al.*²² model (Values in parenthesis are the % of PP)

Martin model (Fig. 6) in this study the J values have been used at 100 m based on the Betzer model in order to calculate the subsequent J through the ocean interior and to serve as a reference for the discussion of food web models in conjunction with other available information. The carbon flux at 3000 m, according to Martin model, is 3.4 g C.m⁻².y⁻¹ in NAS and 0.9 gC.m⁻².y⁻¹ in SAS (Fig. 6). Total carbon flux measured through sediment traps deployed in the Arabian Sea³ also range very closely to these model values, namely from 3.5 to 4.1 g C.m⁻².y⁻¹.

The value of J at > 110 m rises exponentially as pp increases according to the Martin model (Fig. 7). As PP increases, the percent PP respired (utilized or recycled by food web processes) within the mixed

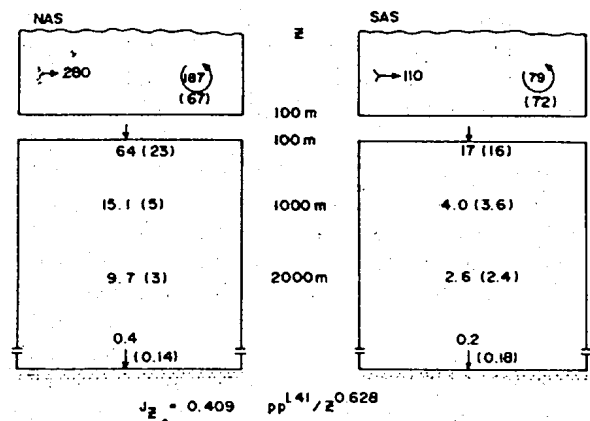


Fig. 5—Carbon flux based on the Betzer *et al.*²¹ model

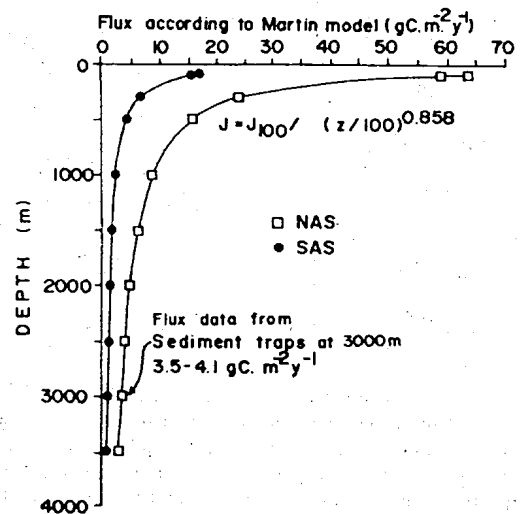


Fig. 6—Carbon flux below the euphotic zone based on Martin *et al.*²³ model. (Observed flux from sediment trap data in NAS are from Nair *et al.*³⁷)

layer decreases exponentially. Thus low PP results in extremely low J, implying efficient recycling of PP within the SML, while high PP results in proportionally very high J, implying inefficient recycling of PP causing an increased proportion of PP to be lost from the surface layer. At very low PP (<50 $\text{gC}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$) most of it (>90%) is retained/recycled within the SML, resulting in hardly any loss, while at very high PP (>500 $\text{gC}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$) with the percent PP retained/recycled within the SML ranging between 60-75%, nearly one third of the PP may be lost to deep sea (Fig. 7).

In the conceptual model of food web structure and function that is being visualized (Fig. 8), the NAS is seasonally variable and high PP system. Here, the SML is characterized by a loosely coupled auto-heterotrophic food web, thus facilitating the export of a large proportion of labile POC (from recent PP presumably) that is respired rapidly and efficiently in the deep sea, as indicated by the observed low deep sea DOC levels (Fig. 2). The SAS is characterized by steady and low PP and a tightly coupled auto-heterotrophic food web in the SML, facilitating the retention of materials with predominant recycling. Consequently, there is a low and steady loss of refractory organic matter to the deep sea that is gradually and inefficiently respired in deep layers, resulting in the observed high accumulation of deep sea DOC (Fig. 2).

Discussion

North-south gradients—The NAS is characterized by high surface PP (mean value of 280 $\text{gC}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$), an extensive subsurface oxygen minimum layer, low and constant DOC level (95 $\mu\text{mol}\cdot\text{dm}^{-3}$), relatively higher concentrations of regenerated carbon dioxide (ΔCO_2) in the water column, and higher organic carbon sedimentation (0.4 $\text{gC}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$). In contrast, SAS is typified by lower surface PP (mean value of 110 $\text{gC}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$), a relatively restricted oxygen minimum layer, high and increasing DOC concentrations with depth (120-200 $\mu\text{mol}\cdot\text{dm}^{-3}$), relatively lower concentrations of ΔCO_2 in the water column, and low sedimentation to the sea floor (0.2 $\text{gC}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$) (Table 2). These are average conditions for the 2 regions (Figs 2 and 3). Actually, there exists a very gradual north-south gradient in all the above parameters, resulting in a strong chemical dichotomy between the NAS and SAS. These differences in chemistry within the ocean interior may be a reflection of the activities of the resident organisms, regional differences in the activities and type of the autotrophs in the surface layer and heterotrophs throughout the water column.

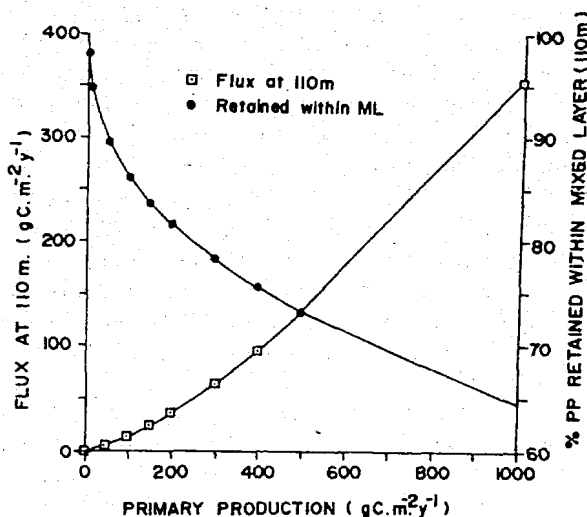


Fig. 7—Relationships between the carbon fixation and carbon retained within the surface mixed layer and the carbon flux out of the surface mixed layer. Flux according to Martin *et al.*²³ model

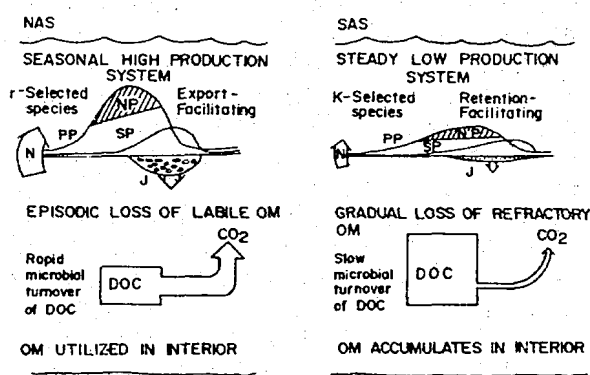


Fig. 8—Differences in the function and structure of auto-heterotrophic coupling in the Arabian Sea (N= upwelled nutrients; PP=primary production (autotrophs); SP=secondary production (heterotrophs); NP=new production; J=downward flux of Carbon out of the SML to the sea interior and OM=organic matter, both dissolved and particulate]

The surface pigment concentrations within the mixed layer of the Arabian Sea, as summarised earlier by Banse²⁵ and by the recent DARWIN winter survey²⁶, indicate that north of 20°N, values range from 0.2 to 0.4 $\text{mg}\cdot\text{m}^{-3}$ and further south, between 15° and 20°N, maximum surface concentrations are approximately 0.1–0.2 $\text{mg}\cdot\text{m}^{-3}$. The seasonal responses in mixed-layer depth, vertical velocities due to Ekman flux divergence and chl-*a* distributions observed by Bauer *et al.*²⁶ suggest that the physical forcing is the primary factor influencing the spatial pattern of mixed-layer depth and pigment biomass in the Arabian Sea. The physical processes such as the

seasonal upwelling in the western Arabian sea, monsoonally forced Ekman dynamics and the monsoonal reversal of the circulation pattern in the surface layers might help to maintain the north-south variabilities in the Arabian Sea triggered by various chemical and biological processes.

Flux model outputs—Applying the Pace model, bearing a linear relationship between PP and J (Fig. 4) J value obtained is 4% of PP for both NAS and SAS at the bottom of the SML. However, based on the Betzer model, that asserts a non-linear relationship between PP and J (Fig. 5), J values obtained are 23% for NAS and 16% for SAS at the base of the SML. The NAS with high PP showed a relatively higher J at 100 m than the SAS with low PP. In the Arabian Sea the J at 100 m is about 16-23% which is around the estimated global average export flux²⁷ from the euphotic zone of 20%. The results of Betzer model indicate that 65-75% of the PP in the Arabian Sea may be recycled within the SML.

Interpolation of the above J at 100 m, which was based on the Betzer model, in the Martin model (Fig. 6) yielded depth-wise profiles of J for NAS and SAS. In NAS, from 100 to 1000 m, J decreases rapidly from 23% of PP to 3.1% PP, whereas from 1000 to 2000 m, it decreases gradually to 1.6% PP. Likewise, in SAS with a J of 16% PP at 100 m rapidly decline to a J of 2.1% at 1000 m, and then gradually to a J of 1.1% PP at 2000 m. It is thus evident that much of the Ocean's surface PP even in high PP environments is likely to be respired within and just below the SML. The rate of carbon loss through the water column (Fig. 6) suggests that degradation of particles sinking through the water column will decrease substantially from surface to deep layers, apparently in response to decreasing temperature²⁸ as well as the increasingly refractory nature of remaining organic matter following initial decomposition.

The modelled export flux from the SML (J at 110 m) showed an exponential increase with increasing PP (Fig. 7). At low PP values ($< 50 \text{ gC.m}^{-2}.\text{y}^{-1}$), almost all the surface PP ($> 90\%$) was recycled efficiently within the SML, while at higher PP ($> 200 \text{ gC.m}^{-2}.\text{y}^{-1}$), $< 80\%$ of PP was recycled within the SML with resulting large losses ($> 20\%$ PP) out of the SML. Therefore, it appears from the model exercise that low PP pelagic systems are relatively more efficient at retaining and recycling their limited local production within the SML and are hence characterized by minimal losses (as percent of PP) from the SML. In contrast, the high PP pelagic systems appear to be inefficient at effectively utilizing the production and are thus characterized by large losses (as percent of PP) from the SML. Berger *et al.*²⁷

find on a global scale that high PP systems export a larger proportion of their PP than low PP systems. This difference between J in high PP and low PP systems appears to be due to the different degrees of food web relationships, primarily the auto-heterotrophic coupling, in the SML of the two systems. The wide range of regional and seasonal variation in quantity and composition of sedimenting photosynthetic carbon is a function of the overlying pelagic system, in those areas with less active food webs losing more than those areas with active ones²⁹.

Export and non-export food webs—Assuming that the "biochemical pump" in the Arabian Sea exhibits a regional (north-south) variability, a conceptual model of food web structure and function (Fig. 8) has been tried to explain the observed chemical dichotomy. According to this, functionally the NAS is a seasonally variable and high PP system whose SML is characterized by a loosely coupled auto-heterotrophic food web. This results in large losses (as percent of PP) of labile organic matter from SML (export food web), that is readily and rapidly respired by heterotrophs in the deep sea NAS. These differences are probably reflected in the relatively low DOC and high regenerated ΔCO_2 levels found in the water column of NAS (Fig. 2 and Table 2). On the other hand, SAS is a relatively steady and low PP system with the SML having a tightly coupled auto-heterotrophic food web. This results in a low and steady loss (as percent of PP) of organic matter from the SML (non-export food web), which is slowly and incompletely respired by heterotrophs in the deep sea of SAS. This explains the high DOC and low regenerated CO_2 levels found in SAS.

The NAS has a food web in the SML that facilitates loss of organic matter to the deep sea. The high seasonality in surface production patterns also may encourage higher J. The resident organisms in surface mixed layers may not be fully co-adapted to the rapidly changing production patterns, and this will result in much loss of percent PP as J out of SML. Seasonal upwelling of nutrients may stimulate the growth of phytoplankton to bloom, which is inefficiently utilized (decomposed and grazed) by the micro-heterotrophs and grazers, leading to aggregate formation and accelerated sinking³⁰. Thus the food web here may be expected to be composed of *r*-selected opportunistic species³¹ (the types that are successful at colonizing unstable environments and have a very high intrinsic rate of growth), leading to rapid increase in PP under favourable conditions. The SML of NAS seems to have the diatom and larger phytoplankton dominated autotroph community,

and larger zooplankton (copepods, swarm grazers such as salps and doliolids) dominated heterotrophic grazer community. Azam³² has hypothesized that grazer dominated systems will accelerate the vertical flux of organic matter in the water column. The NAS deep sea is fuelled by inputs of labile organic matter sinking out of the SML. Rapidly sinking phytoplankton aggregates and faeces of swarm grazers are such examples. Bacterial respiration and growth on sinking POC may contribute to the solubilization of POC and destruction of DOC. Dissolved organic matter is consumed and respired efficiently by resident free-living bacteria leading to the low DOC levels found here. In the NAS water column, while the major portion of the nutrient regeneration occurs within the SML, considerable amount of nutrient regeneration is expected to be taking place below the SML also.

The SAS with its steady and low PP system is characterized by a microbial loop dominated food web in the SML. Here, the autotrophs and heterotrophs are expected to be in near balance, and consequently most of the organic matter produced by PP is recycled. Much of the recycling of organic matter occurs within a community of very small organisms (microbial loop) whose byproducts are also mostly non-sinking. The organisms comprising the microbial loop are small (0.2-150 μm), non-sinking, exhibit negligible vertical migration, and their faecal material is also of small size^{32,33}. Production of mini faecal pellets by flagellates and ciliates are such examples³⁴. Such small non-sinking faecal matter with their large surface to volume ratios become suitable detrital substrates for utilization by the resident heterotrophic bacteria immediately at the site of their origin³⁵. The active functioning of the microbial loop retards the vertical flux of material³². Thus there is little J out of the SML of the southern Arabian Sea, and it would be mostly of a refractory nature, the more labile fractions already having been utilized in the SML. Here, the PP may chiefly be due to unicellular cyanobacteria, phyto-flagellates and other smaller phytoplankton. Typical species preferring steady environments that maintain relatively constant and low biomass (*K*-selected)³¹ may prevail here. Thus the SAS deep sea is fueled by a steady input of refractory organic matter sinking out of the SML. Slow and inefficient bacterial respiration of this refractory substrate leads to the gradual accumulation of the deep sea DOC levels encountered here. In the SAS water column, most of the nutrient regeneration may be expected to occur within the SML, with little regeneration taking place below the SML.

*Need for incorporating in model studies—(a) seasonality in PP and (b) post-PP processes—*All the models examined here, assume a regular rate of decay for sinking organic matter with depth. However, there is no uniform rate of decay with depth in the sea^{27,28}. Thus there is the need for incorporating into models and studies, the many post-PP processes that influence the fate of PP in the sea: bacterial utilization of POC and DOC, protozoan grazing and mineralization, zooplankton consumption of PP and caprophagy, vertical migration of animals, sinking rates of POC and resuspension. Compositional information on the producer types (autotrophs) and consumer types (heterotrophs) thus becomes essential in future studies.

Export flux out of the SML is sensitive not only to the amount of PP (with high PP systems resulting in high J) but also to its variability in time (highly variable PP yielding more J than PP which is less variable). Long-term trap deployments from different parts of the global ocean reveal that the export flux out of the SML is highly seasonal^{8,10} and that flux from variable/pulsed PP systems may exceed that of constant/steady PP systems by a factor of 2 or more. The background drizzle of particles is thus not steady, and greatly modified by episodic events in the pelagial³⁰. Under such changing conditions, the application of flux equations becomes questionable. The concept of production half time (the length of time in months it takes to produce one half the annual PP) and seasonality index (defined as 6 minus production half time in months) as proposed by Berger and Wefer¹⁰ hold some promise leading to better description of system seasonality, and consequently to more accurate flux predictions under varying system conditions. Accordingly, the NAS would have a high seasonality index but a short production half time, while the SAS would have a lower seasonality index but a longer production half time.

*Framework for regional oceanography: horizontal and vertical variability—*Against the background of the existing differences between the NAS and SAS, the proposed carbon flux and food web models present a framework for the eventual field testing of many exciting hypotheses concerning both horizontal and vertical biogeochemical variability within the Arabian Sea. Two central sets of hypotheses that need field testing in this region are:

(i) The NAS is a highly variable and high PP environment. The SML here is characterized by an export facilitating food web. Thus there are large losses of labile organic carbon to the deep sea. Deep

sea heterotrophs rapidly respire away the incoming carbon.

(ii) The SAS is a relatively steady and low PP environment. The SML here is characterized by a retention facilitating food web. Thus there are small losses of mostly refractory organic carbon to the deep sea. Deep sea heterotrophs slowly respire this incoming carbon supply.

Oceanographic investigations along such a framework should lead to a better understanding of the key mechanisms that control the cycling of carbon and associated elements in the northwestern Indian Ocean. Present findings point to the need for further acquiring regional information on the role of seasonality in primary production and the many significant post-primary production processes that are chiefly mediated by marine heterotrophs throughout the water column in order to better understand the material flux.

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