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 ocean. 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\(^{-1}\)) region\(^{5}\). 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 upwelling\(^{3}\). Coupled with the high surface productivity and resultant high particle flux, the presence of a persistant and extensive sub-surface oxygen minimum layer\(^{4}\) is another distinctive feature in the Arabian Sea. Kumar et al.\(^{5}\) have documented that the total carbon dioxide (TCO\(_2\)) 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 pump 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 sediment\(^{7}\). Further, the sinking of surface derived POM is the significant mechanism for much of the vertical transport of organic carbon to the deep sea\(^{8}\), although the vertical advection of dissolved organic carbon (DOC) can also be equally important\(^{9}\). However, the loss of particulate organic carbon (POC) to the deep sea is a variable and seasonal process, closely linked to surface primary productivity\(^{10}\).

Oceanic DOC is the largest pool of reduced carbon in the biosphere\(^{11}\), 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 (CO\(_2\)) levels. Preliminary budget calculations for the Arabian Sea\(^{12}\) have shown that carbon is negatively balanced approximately by 84 Tg.y\(^{-1}\), implying that the region is a net source for atmospheric CO\(_2\). Concentrations of DOC in the Arabian Sea are 3-4 times higher\(^{5}\) 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.
Recent\textsuperscript{13}ly, Rajendran et al.\textsuperscript{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 web that operate differently within the Arabian Sea are suggested.

**Data**

Data used in the present study were collected during different cruises of \textit{ORV Sugar Kanya}, \textit{RV Sonne} and \textit{RV Gaveshani} from 1984 to 1989. DOC and CO\textsubscript{2} 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\textsuperscript{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. UNESCO\textsuperscript{16} equations were used for the computation of total CO\textsubscript{2} (TCO\textsubscript{2}) and other carbonate species from pH and alkalinity. CO\textsubscript{2} released due to the regeneration processes (ΔCO\textsubscript{2}) was estimated using the generalised equations of Kroopnick\textsuperscript{17} for the world oceans.

**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 μmol.dm\textsuperscript{-3}), but with more or less equal concentrations (110 μmol.dm\textsuperscript{-3}) at the surface in both the regions. Vertical distributions of DOC values in the NAS show a uniform concentration around 100 μmol.dm\textsuperscript{-3} and DOC gradually increases in deeper layers in the southern region.

Carbon dioxide added due to regeneration processes (ΔCO\textsubscript{2} = TCO\textsubscript{2} - preformed CO\textsubscript{2}) exceeds 500 μmol.dm\textsuperscript{-3} in the intermediate oxygen minimum layers (150-1000 m) of the northern Arabian Sea (Fig. 2). In NAS, ΔCO\textsubscript{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 CO\textsubscript{2} regeneration (ΔCO\textsubscript{2}) in the intermediate layers of central and NAS than in SAS, partial pressure of CO\textsubscript{2} (pCO\textsubscript{2}) builds up in NAS at a greater level. Significantly, pCO\textsubscript{2} in the oxygen minimum (200-400m) layers of NAS is nearly double of that present at the corresponding depths in SAS\textsuperscript{15}. Increased pCO\textsubscript{2} in surface layers in the NAS than near equator results in enhanced CO\textsubscript{2} ejection to atmosphere in NAS. In order to evaluate the CO\textsubscript{2} partition pattern between air and surface seawater, an indirect parameter f\textsubscript{AIR} is used\textsuperscript{15}. f\textsubscript{AIR} is defined as
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 g C m⁻² y⁻¹ in NAS and 14 g C 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 mg C m⁻² d⁻¹) and SAS (300 mg C m⁻² d⁻¹). The actual values of surface primary productivity showed a very wide variation, with ranges between 109 and 2665 mg C m⁻² d⁻¹ in NAS and 0.33 to 676 mg C 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 biomass¹³. 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 SAG whereas the NAS showed a high rate of 61.5 g C (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 productivity.
productivity and post production biochemical processes. These tabulated data are essentially from Kumar et al.\textsuperscript{13-15} and Rajendran et al.\textsuperscript{14}.

**Models**

In the existing models of carbon flux in the ocean\textsuperscript{9,26-24}, the export flux of organic matter is shown to decrease with depth (Z) due to remineralization, roughly as \( \frac{1}{Z} \). The model of Pace et al.\textsuperscript{22} (Pace model, Fig. 4) although similar to that of Suess\textsuperscript{7}, 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 Peterson\textsuperscript{26}, 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.\textsuperscript{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 production\textsuperscript{10}.

Bishop\textsuperscript{9} has demonstrated that once the export flux at 100 m is known, the Martin model\textsuperscript{23} is the best predictor of J at greater depths, because it considers many post-production processes. While applying the 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 g C m\(^{-2}\) y\(^{-1}\) in SAS (Fig. 6). Total carbon flux measured through sediment traps deployed in the Arabian Sea\textsuperscript{4} 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

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**Fig. 5**—Carbon flux based on the Betzer et al.\textsuperscript{21} model

**Fig. 6**—Carbon flux below the euphotic zone based on Martin et al.\textsuperscript{23} model. (Observed flux from sediment trap data in NAS are from Nair et al.\textsuperscript{21})
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 gC.m^{-2}.y^{-1}) most of it (>90%) is retained/recycled within the SML, resulting in hardly any loss, while at very high PP (>500 gC.m^{-2}.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 gC.m^{-2}.y^{-1}), an extensive subsurface oxygen minimum layer, low and constant DOC level (95 µmol.dm^{-3}), relatively higher concentrations of regenerated carbon dioxide (ΔCO₂) in the water column, and higher organic carbon sedimentation (0.4 gC.m^{-2}.y^{-1}). In contrast, SAS is typified by lower surface PP (mean value of 110 gC.m^{-2}.y^{-1}), a relatively restricted oxygen minimum layer, high and increasing DOC concentrations with depth (120-200 µmol.dm^{-3}), relatively lower concentrations of ΔCO₂ in the water column, and low sedimentation to the sea floor (0.2 gC.m^{-2}.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](image7.png) 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. model.

![Fig. 8](image8.png) 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 Banse and by the recent DARWIN winter survey, indicate that north of 20°N, values range from 0.2 to 0.4 mg.m^{-3} and further south, between 15° and 20°N, maximum surface concentrations are approximately 0.1 – 0.2 mg.m^{-2}. The seasonal responses in mixed-layer depth, vertical velocities due to Ekman flux divergence and chl-a distributions observed by Bauer et al. 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 flux\(^{27}\) 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 temperature\(^{28}\) 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 (\(< 50 \text{gC.m}^{-2}.y^{-1}\)), almost all the surface PP (\(> 90\%\)) was recycled efficiently within the SML, while at higher PP (\(> 200 \text{gC.m}^{-2}.y^{-1}\)), < 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 loosing more than those areas with active ones\(^{29}\).

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 \(\Delta \text{CO}_2\) 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 \(\text{CO}_2\) 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 sinking\(^{30}\). Thus the food web here may be expected to be composed of \(r\)-selected opportunistic species\(^{31}\) (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 doliiolids) dominated heterotrophic grazer community. Azam 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 matter is also of small size. Production of mini faecal pellets by flagellates and ciliates are such examples. 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 origin. The active functioning of the microbial loop retards the vertical flux of material. 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) 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 efficient 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. 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 DOC, protozoan grazing and mineralization, zooplankton consumption of PP and caprophygy, 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 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 pelagial. 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 Wefer 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 backdrop 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 faciliating 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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