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Particles size distribution and carbon flux across the Arabian Sea Oxygen Minimum Zone

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Abstract

The goal of the Arabian Sea section of the TARA oceans expedition was to study Large Particulate Matter (LPM > 100 µm) distributions and possible impact of associated midwater biological processes on vertical carbon export through the Oxygen Minimum
 ⁵ Zone (OMZ) of this region. We found that spatial patterns in LPM distribution resulted from the timing and location of surface phytoplankton bloom, lateral transport, microbial processes in the core of the OMZ, and zooplankton activity at the lower oxycline. Indeed, satellite-derived net primary production maps showed that the northern stations of the transect were under the influence of a previous major bloom event while, the most southern stations were in a more oligotrophic situation. Lagrangian simulations of particle transport showed that deep particles of the northern stations could originate from the surface bloom while the southern stations could be considered as driven by 1-D vertical processes. In the first 200 m of the OMZ core, minima in nitrate concentra-

tions and the Intermediate Nepheloid Layer (INL) coincided with high concentrations

- of 100 μm < LPM < 200 μm. These particles could correspond to colonies of bacteria or detritus produced by anaerobic microbial activity. However, the calculated carbon flux through this layer was not affected. Vertical profiles of carbon flux indicate low flux attenuation in the OMZ, with a Martin model b exponent value of 0.22. At the lower oxycline, a deep nepheloid layer was associated to an increase of carbon flux and an
- increase in mesozooplankton abundance. Zooplankton feeding on un-mineralized sinking particles in the OMZ is proposed as a mechanism for the observed deep particle aggregation. These results suggest that OMZ may be regions of enhanced carbon flux to the deep sea relative to non-OMZ regions.

1 Introduction

²⁵ In the coming decades, ocean's biogeochemical cycles and ecosystems will become increasingly stressed by the extending spatial distribution of Oxygen Minimum Zones



(OMZ; Stramma et al., 2010). One particular concern is the retroactions of low oxygen on the biological pump by affecting plankton communities and their ability to produce and transform the vertical flux of organic matter to the ocean's interior.

- OMZs are mainly localized in the Eastern Boundary Upwelling Systems. The most intense and the largest are in subsurface of the upwelling regions in the Eastern Pacific and the Arabian Sea of the Northern Indian Oceans (Paulmier and Ruiz-Pino, 2008). In particular, in the semi-enclosed Arabian Sea, the development of oxygen-deficient conditions is attributed to excessive oxygen consumption triggered by the supply of organic matter from high surface productivity, combined with weak renewal of mesopelagic wators (Nagyi 1987; Javakumar et al. 2004; Anderson et al. 2007). In that oceasistem
- ¹⁰ ters (Naqvi, 1987; Jayakumar et al., 2004; Anderson et al., 2007). In that ecosystem, surface produced particles are crossing different layers of bacteria and zooplankton on their way to the bottom, possibly altering their physical properties (geometry, size, composition) and therefore impacting the efficiency of the biological pump. However, vertical changes in Particle Size Distribution (PSD) and carbon flux across hypoxic and anoxic layers are poorly known.

The few sediment traps studies focusing on flux attenuation through OMZs revealed a much lower attenuation coefficient (Haake et al., 1992; Van Mooy et al., 2002) and even in some cases a significant midwater source of carbon production with depth (Taylor et al., 2001; references in Wishner et al., 2008), compared to well oxygenated waters. Recently it has been suggested that organic matter sinking through an oxygen-

- waters. Recently it has been suggested that organic matter sinking through an oxygendeficient zone is metabolized differently than similar material sedimenting through oxygenated water columns (Kristensen et al., 1999; Devol and Hartnett, 2001; Van Mooy et al., 2002). However these differences are not yet included in biogeochemical model simulations of the global ocean.
- In order to understand the fate of particles through the OMZ, backscattering sensors have been extensively used to study microscopic particles spatial patterns, revealing large and permanent Intermediate Nepheloid Layers (INL; Whitmire et al., 2009). However, to our knowledge, no information exists on the vertical distribution of large (> 100 µm to a few mm) particles that are the main vector of carbon flux to depth (All-



dredge and Silver, 1988; Stemmann et al., 2002; Guidi et al., 2008). The goal of this study is to refine our knowledge on particle origin and fate in low oxygen zones using a comprehensive set of PSD measurements and biogeochemical characterization of the environment across the OMZ of the Arabian Sea. We propose new hypotheses on the impact of bacterial and zooplankton activities on the production and transformation of PSD and subsequent carbon flux through the OMZ of the Arabian Sea.

2 Material and methods

2.1 Studied area

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The 2000 km transect in the Arabian Sea was covered in 3 weeks and included 7 stations of which 6 were directly inside the strong oxygen depletion zone (between 200–800 m) and the last one (station 42) was located at the eastern boundary near the Maldives (Fig. 1 and Table 1). A total of 45 CTD rosette casts were performed (from 3 to 12 profiles at each station) and approximately 20% of the casts were done at night.

2.2 Primary production estimates from satellite

- Estimations of primary production were extracted from the 8 days averages products of surface Net Primary Production (NPP) downloaded from the Ocean Productivity website (http://www.science.oregonstate.edu/ocean.productivity/index.php). These products are based on MODIS chlorophyll and temperature data, SeaWiFS PAR, and estimates of the depth of the euphotic zone from a model developed by Morel and Berthon (1989) and Behrenfeld and Falkowski (1997). Mean NPP values were calcu-
- 20 Berthon (1989) and Behrenfeld and Falkowski (1997). Mean NPP values were call lated by defining a squared area of 1° centered on each station.



2.3 Hydrological, biogeochemical and particle data

Temperature and conductivity were measured from surface to a maximum of 1500 m depth using a Seabird 911 CTD mounted on Sea-Bird Carousel sampler with 10 Niskin bottles. Additional sensors were added for the measure of water optical properties used as biogeochemical proxies; fluorometer (Wetlab ECO-AFL/FL model), Dissolved 5 Oxygen sensor (model SBE 43), nitrate sensor (ISUS with a maximum rating depth of 1000 m Satlantic SA) and a Wetlabs C-star transmissometer (660 nm with a 25 cm pathlength). The beam attenuation signal was converted to particulate attenuation coefficient $c_{\rm p}$ by removing influence of deep (< 700 m) signal considered as the instrumental offset. 10

The ISUS sensor was calibrated using nitrate measurements at 10 depths at each station computing linear regressions between sensor and water measurements. Because no water samples was available for station 37 and 40 at the same depth than the ISUS sensor, median of slopes and intercept coefficients of the others stations were used to adjust nitrate values at these two stations.

Oxygen sensor calibration was done prior departure in Nice, France and in Cape Town, South Africa in August 2010. Unfortunately, water could not be sampled and stored on the ship to correct dissolved oxygen concentration estimations. Between calibrations, we ensured that the sensor did not present evidence of default and drift. Oxygen concentrations were compared to WOA09 climatology (Garcia et al., 2010) and, 20 for the Arabian Sea transect, the mean difference measured was about 6 µmol kg⁻¹ and 90% of all values showed a maximum difference of $33 \,\mu$ molkg⁻¹. However, raw oxygen estimates could not be used as absolute values preventing the detection of the vertical extent of the suboxic core. This issue was overcome by introducing the concept

of deoxygenation intensity (DI) defined by: 25

$$DI_z = (oxygen_{max} - oxygen_z)/oxygen_{max} (0 \le DI_z \le 1)$$

 $OMZ \rightarrow max(DI) \ge 0.975$



(1)

(2)

For each oxygen cast, DI represents the intensity of oxygen reduction computing the normalized difference between the oxygen maximum between 0 and 100 m (i.e. before the upper oxycline) and the oxygen value at a current depth *z*. The 0.975 threshold was chosen to fit the absolute limit used in previous works ($O_2 < 20 \mu$ mol, Paulmier and Ruiz-Pino, 2008) and determine the upper/lower oxycline depths and the thickness of

5 Ruiz-Pino, 2008) and determine the upper/lower oxycline depths and the thickness of the OMZ layer.

The vertical distribution of large marine particles was investigated with the Underwater Vision Profiler (UVP, Picheral et al., 2010) mounted on the CTD-Rosette. The UVP acquires images in a coherent volume of water delimited by a light sheet issued from red light-emitting diodes (LEDs). The analysis of images provides quantitative information on the sizes and shapes of particles (> 100 μ m) and zooplankton organisms (> 500 μ m). Only images from recognizable objects larger than 500 μ m were sorted using an automatic classification followed by manual validation (Picheral et al., 2010).

Hereafter, particles detected by the transmissometer will be referred as suspended particulate matter (SPM) while those detected by the UVP will be referred as Large Particulate Matter (LPM).

2.4 Phytoplankton size fractions

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We used the method proposed by Claustre (1994) and further improved by Uitz et al. (2006) to estimate the contribution of three HPLC pigment-based size classes (microplankton, nanoplankton, and picophytoplankton; f_{micro}, f_{nano}, and f_{pico}, respectively) to the total phytoplankton biomass. Briefly, this method (detailed in Uitz et al., 2006) takes into consideration seven diagnostic pigments representative of the major phytoplankton taxa [i.e., fucoxanthin (Fuco), peridinin (Peri), 19'hexanoyloxyfucoxanthin (19'HF), 19'butanoyloxyfucoxanthin (19'BF), alloxanthin (Allo), zeaxanthin (Zea), and total chlorophyll b (TChlb), here defined as the sum of chlorophyll b and divinyl-chlorophyll b] to compute the fractions of three pigment-based size classes with the



following empirical equations:

fmicro = (1.41 Fuco + 1.41 Peri)/wDPfnano = (0.60 Allo + 0.3519'BF + 1.2719'HF)/wDPfpico = (0.86 Zea + 1.01TChl b)/wDP

where wDP is the weighted sum of these concentrations:

wDP = 1.41 Fuco + 1.41 Peri + 0.60 Allo + 0.3519'BF + 1.2719'HF + 0.86 Zea + 1.01 TChl *b*

2.5 Zooplankton vertical distribution

Net collection using a Hydrobios multinet (5 nets, mesh size 330 µm; aperture 0.25 m²) at all stations were used estimate vertical distribution of zooplankton. Samples were preserved in buffered formaldehyde (4 %) and further analysed in the laboratory using the ZOOSCAN imaging system (Gorsky et al., 2010). Zooplankton sorting was performed using an automatic recognition algorithm and validated by a specialist into 20 taxonomic groups.

2.6 Data analysis

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All CTD data were smoothed and interpolated to the nearest 5 m intervals to be used for statistical data processing. After ensuring the homogeneity between profiles inside a station they were pooled together by calculating the mean profiles for each parameter. The Mixed Layer Depth (MLD) was estimated as the depth at which a there was a density difference of 0.03 kgm^{-3} relative to near-surface value at 10 m depth (de Boyer Montegut et al., 2004).

Particle Size Distribution (PSD) computation is based on 27 size classes of Equivalent Spherical Diameter (ESD) sorted in a logarithmic scale from 60 µm to 26.79 mm



(Guidi et al., 2009). Particle concentrations are converted to biovolume assuming spherical particles. Abundance concentrations are normalized by dividing them by the range of their size-class. The slopes of the size spectra on a log-log scale were calculated with values at either end of their size ranges excluded to avoid bias due to low

5 efficiency of particles detection at the two end of the size spectrum. The slope of the PSD has been calculated over the size range 100 μm to 2 mm. Finally, profiles of each station were averaged after checking for intra-site homogeneity.

Empiric relationships between particle size and flux were used in order to calculate vertical profiles of flux through the water column (Guidi et al., 2008). The vertical profiles of flux were adjusted by the Martin Model (Martin et al., 1987):

 $F_z = F_{zref}(z/zref)^{-b}$

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where z is the depth and b is the proxy for the flux attenuation. In our case F_{zref} was calculated as being the surface maximum of flux at zref = 50 m.

2.7 Circulation model and lagrangian experiments set up

- ¹⁵ We assessed the statistical funnel of possible particle source (Siegel et al., 2008) in order to evaluate the role of particle lateral transport by water masses in the studied area. Velocity, temperature and salinity fields were given by the MERCATOR Oceans forecast system. Outputs are extracted from the PSY3V3R1 version, a global high-resolution circulation model configuration forced by realistic daily surface inputs (Bahurel, 2006).
- The domain covers the north western Indian Ocean (north of 5° N) with a horizontal resolution of 1/12° (~ 9.2 km) and 40 vertical levels with higher resolution in the first 100 m to better represent the upper boundary layer. On the longitudinal axis, the domain extends from 49.75 to 75.25° E. Three years of data were used (2009, 2010 and 2011). We checked for the validity of these model outputs by comparing salinity and temper-
- ature with climatology and our observations to ensure that water masses (such as the Persian Gulf Water, hereafter PGW) were correctly represented. Daily averages of the velocity fields were linearly interpolated in time and space during particle tracking.



(7)

The advection of particles was computed using a 4th order Runge Kutta numerical scheme as implemented in the ICHTHYOP software (Lett et al., 2008). ICHTHYOP is a free java lagrangian tool designed at first to study the effects of physical and biological factors on ichthyoplankton dynamics. In addition to the multidimensional model velocity, particles are assumed to have a vertical settling velocity. We explored a range of sottling velocities from 1 md^{-1} to 100 md^{-1} (see Table 2) to represent settling velocities.

- of settling velocities from 1 md⁻¹ to 100 md⁻¹ (see Table 2) to represent settling velocity for particle size from 0.1 mm to 2.5 mm (using size–velocity relationship from Guidi et al., 2008). These estimates are in the range of reported settling rates (Syvitski et al., 1995; Stemmann et al., 2004; Peterson et al., 2005). At the lateral boundaries (coasts and domain boundary) particles were stopped. The position of each particle along the
- trajectory is saved on file every hour. We did not account for subgrid scale dispersion.

For each station, the center of the particles cloud was determined by computing the mean longitude and latitude of all CTD profiles. We choose a horizontal dispersion of a 50 km radius, randomly distributed around its center, in order to encompass all typical mesoscale structures. A total of 500 particles were used for each simulation process,

considered as enough to compute statistics.

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Initial vertical positions for the backward calculation were chosen as a 10 m layer centered at the depth of the deep maximum particles abundance given by the UVP. The depth of the maximum was shallower at the beginning of the transect, thus the initial position ranged from 200 m to 1000 m between first and last stations. The time

²⁰ Initial position ranged from 200 m to 1000 m between first and last stations. The time step (Table 2) of particle tracking was chosen to satisfy the Courant–Friedrichs–Levy criteria (Courant et al., 1967).

From the trajectories we quantified the statistical funnel, i.e. the backward in time trajectories from their initial depth to the surface. Then we computed the envelope con-

 $_{25}$ taining 75 % of the particles to quantify the possible source of particles at the surface.



3 Results

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3.1 Hydrology

Temperature and salinity transects (Table 1 and Fig. 2) reveal a strong zonation from North to South. Sea Surface Salinity (SSS) decreases between the first and the last station from 36.5 to 34.6 (Table 1) whereas Sea Surface Temperature (SST) increases from 25.7 to 30 °C (Table 1). The MLD deepens slightly from coastal area towards the open ocean (Table 1) and reaches 20 m at station 42. In the water column, outflow of the Persian Gulf Water (PGW) is visible along the first 3 stations (stations 36, 37 and 38) between 200 and 400 m and is associated with salinity greater than 36 and temperature between 16 and 17 °C. Signature of the PGW is more evident near the coastal area (station 36 and 37) and is also characterized by an increase of oxygen concentration at same depth (200–400 m).

3.2 Time course of average net primary production

The analysis of NPP time-series of the region reveals that a bloom started in the Per-¹⁵ sian Gulf around the beginning of February (Fig. 3a), and persisted 6 weeks. At the time of sampling, the bloom was declining (Fig. 3b) and at the end of the cruise, surface production was low (Fig. 3c). A southward decline of surface production was visible from coastal areas (Oman Strait and Persian Gulf) toward the open ocean (Fig. 3a and b). The depth of Deep Chlorophyll Maximum (DCM) also decreased with time and distance ²⁰ from the depth of 20 m to 70 m (Table 1).

3.3 Vertical distribution of oxygen and nitrate

The OMZ was detected at all stations but vertical distribution of oxygen changed among stations (Fig. 4). At stations 36 and 37 oxygen concentrations showed 2 sub-layers associated with slight oxygen increases between 200 and 400 m and between 600 and 850 m. The signature of the deeper oxygenated sub-layer is also weakly detected at



stations 38 and 39 and could be attributed to the Red Sea Water (Schott and Mc Creary, 2001). Using the DI criterion defined in Eqs. (1) and (2), the OMZ layer extents from approximately 110–160 m to more than 1000 m depth for the central stations (stations 38, 39 and 40). At stations 36 and 37, the upper oxycline was detected between 400 ⁵ and 600 m, and at the southern station 42, OMZ layer is about 140 m thick with oxygen

concentration slightly higher than other stations of the transect.

Vertical profiles of nitrate concentrations superimposed on oxygen distribution showed maximum values close to the upper oxycline (150–200 m depth, Fig. 4). Inside the OMZ layer, all profiles showed a systematic minimum of nitrate concentrations

- just below the oxycline, except station 42. Nitrate concentrations were consistent with reported values (Anderson et al., 2007; Ward et al., 2009). At the upper oxycline, nitrate concentration was about 30 μmol kg⁻¹ and less than 20 μmol kg⁻¹ in the core of the OMZ (station 38-39-40). The nitrate minimum was less pronounced and deeper at the beginning of the transect (around 300 m depth) but towards the central Arabian Sea, the minimum was closer to the surface (200 m depth) and more pronounced. Following
- the minimum was closer to the surface (200 m depth) and more pronounced. Following this minimum, nitrate concentrations increase again towards greater depth.

3.4 Vertical distribution of phytoplankton

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Fluorescence peaks deepen and integrated chlorophyll *a* decreased towards the open Arabian Sea (Figs. 5 and 6). These observations were completed by HPLC analysis, which showed a change of the size class composition between the first and last station (Fig. 6). Proportion of microphytoplankton decreased twofold from 22.7% (station 36) to less than 10% (station 40 and 42). Nanophytoplankton proportion exhibited a similar trend although the 3 last stations were more contrasted (range between 29 and 42%). The smallest size class, i.e. picophytoplankton, increased southward from 41 to 64%.



3.5 Vertical distribution of zooplankton

Overall, zooplanktons were slightly more abundant in the 0–200 m depth interval of the northern stations than at the central stations (Fig. 7). For example, abundance decreased from 250 to 150 ind m^{-3} at station 36 and station 41, respectively (Fig. 7).

⁵ The upper oxycline (below 150 m depth) showed a sharp decrease in mesozooplankton abundances (Fig. 7). The lower oxycline (below 700 m depth) where oxygen increases with increasing depth is marked by an increase in total mesozooplankton abundance, especially in copepod abundances (Fig. 7).

3.6 Vertical distribution of SPM and LPM

- All SPM and LPM profiles showed maxima between 0 and 100 m (Fig. 8). LPM inte-10 grated concentrations in that layer decrease by two from the north to the south (from 60 to 30 particles m^{-2} at respectively station 36/37 and station 39 to 41). Deeper particles concentrations decreased and reached their first minimum in the upper oxycline between 100 and 200 m depth (Fig. 8). From that layer, SPM and LPM abundance increased at all stations forming a distinct Intermediate Nepheloid Layer (INL) at station 15 39, 40 and 41 and 38 to a lesser extent. This INL was not evident at stations 36, 37 and 42. The INL peaks ranged from 250 to 300 m being shallower at the most central stations. Detailed analysis of LPM vertical profiles for increasing size classes revealed that only LPM $< 200 \,\mu m$ participated to the INL. Below the peaks, particle concentrations decreased down to the depth of the lower oxycline (700–800 m depth). From this 20 depth, LPM and particularly SPM concentrations increased again forming a less pronounced Deep Nepheloid Layer (DNL). It is noticeable that the southward shoaling of
 - INL and reduction of the depth range match the vertical patterns of the upper oxycline.



3.7 Vertical distribution of LPM > 500 μ m

Concentrations of LPM > 500 μ m decreased southward. However, the two size classes of LPM, 500 μ m < LPM < 1.06 mm and LPM > 1.06 mm show different patterns. Maxima of 500 μ m < ESD < 1.06 mm are observed in the upper 100 m depth at all stations $_{5}$ except at stations 38 and 42. The INL observed for particles < 200 μ m was not observed for LPM > 500 μ m. At stations 36 and 37, vertical distribution of LPM > 1.06 mm to 2.66 mm shows a subsurface centred at 250 m while this maximum was observed at 500 m at station 38 and completely disappeared southward of station 38. LPM > 1.06 mm to 2.66 mm concentrations increased slightly at the lower OMZ boundary at stations 39 and 40.

3.8 Vertical distribution of carbon fluxes at two selected stations

The vertical carbon flux profiles calculated at station 37 and 40 decreased strongly in the upper 150 m layer, above the upper oxycline. At the deeper oxycline, a slight increase of flux was observed as the result of an increase in LPM > 500 μ m concentrations. In addition, station 37 showed an intermediate zone where the flux increased in the core of the PGW.

4 Discussion

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4.1 Impact of the ocean surface primary production on particles formation and export

The sampling took place at the end of the spring bloom, which started in late January and lasted until the end of February. By the 17–24 January 2010, a large phytoplankton bloom developed near the Somalia coasts and inside the Oman Gulf (Fig. 3a). Stations 36, 37 and 38 were located in the bloom area (NPP close to 3 gCm⁻² d⁻¹, Fig. 3c)



while the southward stations were located outside this bloom. Stations 41 and 42 were located in the most oligotrophic waters (NPP less than $0.5 \,\text{gCm}^{-2} \,\text{d}^{-1}$).

The chronology of the observed bloom development is in agreement with previous studies showing large phytoplankton bloom during winter in the coastal upwelling re-

- gions (Schott and Mc Creary, 2001; Gomes et al., 2008). This bloom can be followed by an enhanced export in the bloom area potentially explaining the observation of LPM > 500 μm in the deep layers (as deep as 400 m) of the northern stations (station 36, 37 and 38) and their absence in the southern stations far from the source region. As a consequence, PSD slopes were steeper in the whole water column at stations 41
- and 42 compared to stations 37 and 38 (Table 3). The similar patterns between surface and deep PSD observed between these two groups of stations reinforce the concept of strong vertical coupling in particle production and carbon flux reported elsewhere (Boyd et al., 1997; Guidi et al., 2009). However, LPM vertical profiles also reveal an unexpected variability within the northern stations (see the peak in LPM > 500 µm at 15 250 m at station 38 in association with the PGW) that may not only be related to spe-
- 15 250 m at station 38 in association with the PGW) that may not only be related to specific OMZ or local processes. The impact of lateral transport by surface or subsurface (PGW) current may impact particle spatial distribution and account for the observed patterns.

4.2 Impact of horizontal advection on observed PSD

- The PGW spread out between 200 and 400 m (Morrison et al., 1999; Levin, 2002; Swift and Bower, 2003) and its signature was observed as south as station 38. In addition, we observed high concentrations of particles > 1 mm at station 36 and 37 between 200 and 250 m (Fig. 9) suggesting a potential lateral transport by the PGW. In order to test this hypothesis, we used a 3-D backward lagrangian transport simulation. The catching areas of the statistical funnels are presented on Fig. 12. The results suggest
- that for stations 36, 37 at 200 and 250 m the possibility that the source of particles could be the surface bloom that took place 15 days before the cruise in the northern area cannot be ruled out. In contrast, the results suggest that transport of surface



particles from the northern bloom area to the southern stations (39 and mostly 40 and 41) is low. For example, the lagrangian modelling indicates that slowly settling particles (5 md⁻¹) found at 1000 m at station 40 could originate near station 38 but only if we admit a transport time of more than 250 days. This seems unlikely when taking into account the short life of aggregates before being consumed or transformed (few weeks, Ploug, 2001; Iversen and Ploug, 2010). In addition, none of the simulation indicates a successful transport of particles from the coastal zones north or east of the stations. Therefore, stations 37 and 40 have been chosen for a detailed analysis of PSD as representative of the northern post bloom (possibly under the influence of particle transport by advection), and oligotrophic open ocean conditions, respectively.

4.3 Biological processes in intermediate and deep nepheloid layers

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The vertical distribution of c_p and small LPM showed two distinct layers, an Intermediate Nepheloid Layer (INL) and a Deep Nepheloid Layer (DNL).

- The INL developed between 150 and 300 m, at stations 39, 40 and 41 and with ¹⁵ less extent at station 38. Intermediate depth particles maxima (revealed by light transmission) have been observed earlier in OMZ off the Peruvian coast (Pak et al., 1980; Whitmire et al., 2009), off Mexico (Garfield et al., 1983), in the Carioca basin of the Gulf of Mexico (Taylor et al., 2001), and in the Indian Ocean (Naqvi et al., 1993; Shailaja, 2001). However, these studies could not unambiguously identify the nature and sources
- of these INL (local production vs. advective transport). Here, Lagrangian transport simulations ruled out lateral transport of continental nepheloid layer from the Indian or the Oman coast as one of the important process at the origin of the INL. Garfield et al. (1983) proposed that denitrifying and ammonium oxidizing bacteria could partly explain the persistence of a subsurface particle maximum in OMZ. Later on, Naqvi
- et al. (1993) linked denitrification, light transmission, and bacterial abundance in the OMZ of the Arabian Sea, and suggested that this link could occur globally. Since then, this characteristic has been observed in all OMZ where high bacterial abundances have been reported (Jayakumar et al., 2004; Gonsalves et al., 2011). Jayakumar et al. (2009)



and Ward et al. (2009) found that near 200 m below the upper oxycline, denitrifying bacteria dominate the biomass. The upper oxycline has also been shown to be a layer of high DOC accumulation (Naqvi and Shailaja, 1993; Azam et al., 1994; Ramaiah et al., 1996; Ward et al., 2008; Paulmier et al., 2011), which could enhance the production of

- ⁵ Transparent Exopolymer Particles (TEP) further triggering the formation of aggregates much larger than individual bacteria (Chin et al., 1998; Verdugo, 2012) thus in the size range of LPM. Another plausible explanation is that these discrete particle layers are formed by transformations of redox-sensitive elements, such as Mn and Fe, which precipitate when oxidized (Tuttle and Jannasch, 1973; Nealson and Myers, 1992). There-
- ¹⁰ fore, one could deduce that INL are controlled by local bacterial activity. The apparent restriction of INL to the upper part of the OMZ implies that active microbial metabolic processes may be more important below the surface production layer than deeper in the OMZ.
- At the lower base of the OMZ, a second rich particle layer is observed at almost all stations. This DNL is observed below 900 m depth with the transmissometer data and also to a lesser extent in the larger particles fraction observed by the UVP (Figs. 8 and 9, stations 38, 39 and 40 deeper that 800 m depth). The DNL occurs in the layer showing an increase of oxygen concentrations and also an increase of zooplankton abundance at stations 38, 39, 40 and 41 (Fig. 7). According to Wishner et al. (1995), elevated POC and scatter in the light transmission data suggested the existence of a thin, particle-rich, and carbon-rich pelagic layer at the base of the Equatorial Pacific OMZ. Naqvi et al. (1993) observed that this bottom nepheloïd layer occurred close to
- the Indian continental margin and was attenuated offshore, being absent in the central Arabian Sea. Our observations and numerical simulations (Fig. 12) do not sup-
- ²⁵ port the hypothesis of lateral transport. Instead we suggest that this deep increase in SPM and LPM results from the activity of permanently resident zooplankton and could be enhanced by bacterial communities. Under the OMZ core, oxygen concentrations could be sufficient to allow the presence of zooplankton. According to Wishner et al. (1998, 2008) and Levin (2002), the biological habitat of the lower oxycline in-



cludes different organisms such as foraminifera, copepods, chaetognaths, gelatinous zooplankton, numerous non-migrating fish, and shrimp. Copepods living at depth in this region appeared to be persistent residents (Wishner et al., 2008). Many of the lower oxycline copepods are probably omnivorous particle feeders, able to feed on bacteria,
 as shown by gut contents of *S. antarcticus* and *L. grandis* (Wishner et al., 2008). Lee at al. (1008) also abaued that particulate argania earbon flux aculd increase in this

- et al. (1998) also showed that particulate organic carbon flux could increase in this layer during JGOFS studies in the Arabian Sea. Particle increases could result from repackaging of suspended material by midwater zooplankton into larger aggregates. Coupling between surface particle production and DNL by settling of fresh organic par-
- ticles through the oxygen depletion layer may be re-inforced because of low metazoan abundance able to transform them in the OMZ core (Wishner et al., 1995, 2008), hence feeding deep zooplankton.

4.4 Impact of the OMZ layer on particle and carbon flux

The vertical flux calculated using the UVP profiles (range 1–5 mgCm⁻²d⁻¹ at station 40 in the mesopelagic layer) is well within previous estimates during the same period of the year at similar depth (Lee et al., 1998). The vertical flux derived from the PSD show a strong variability at station 37 compared to station 40 probably due to the temporal dynamics of the surface bloom and lateral particle transport (see large change in PSD associated to the PGW in Fig. 10a). Therefore, 1-D vertical assumption for station 37 cannot be assumed and the Martin model cannot be applied. By contrast, stations 39 and 40 can be considered 1-D and the mean *b* value is equal to 0.22 ± 0.09 (*n* = 5) which is much lower than the value of 0.85 (Martin et al., 1987) obtained using sediment traps in non-OMZ region and more comparable to values found in other OMZs (0.36–0.4, Devol and Hartnet, 2001; Van Mooy et al., 2002). The *b* values at stations 39 and 40 are also in the lower range of values calculated in oligotrophic non-OMZ regions

using similar imaging approach (Guidi et al., 2009). At the upper oxycline, PSD does not show any variability suggesting that the microbial activity as indicated by the change in nitrate or by the INL does not impact the settling of large particles. At the lower



oxycline, change in the PSD and calculated vertical flux suggest that specific biological processes, as discussed previously, may affect the flux.

5 Conclusions

We observed zones of enhanced particle abundance and flux, coupled with high biological and biogeochemical activity at the upper and lower boundaries of the OMZ of the Arabian Sea. In the upper part of the suboxic core, the anaerobic microbial respiration probably enhanced production and accumulation of observed particles < 100 μm but did not modify the calculated particulate vertical flux. No specific vertical change of PSD was observed in the core of the OMZ suggesting that particulate flux transformation was low in that layer. At the lower oxycline, changes of abundances in both small and large particles classes are associated to zooplankton-enriched layers. The accumulation of large particles enhanced the calculated POC vertical flux to the bathy-

accumulation of large particles enhanced the calculated POC vertical flux to the bathypelagic zone of the ocean. The lack or low intensity of large particle remineralisation in the core of the OMZ and possible particulate repackaging in the lower oxycline may further increase the ocean carbon sequestration in the OMZ of Arabian Sea relative to

further increase the ocean carbon sequestration in the OMZ of Arabian Sea relative to non-OMZ situations and should be considered in future biogeochemical model simulations of the global ocean.

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Table 1. Summary of the main information about the sampling in the Arabian Sea during the TARA Oceans expedition in March 2010.

Station ID	Number CTD Rosette profiles	Sampling date (2010)	Sampling Depth max (m)	Distance from first station (km)	Longitude (east)	Latitude (north)	SSS	SST	MLD (m)	DCM (m)
36	3	12 Mar	1005	-	63°30.726' E	20°49.098' N	36.48	25.74	14.5	22
37	6	13 Mar	1505	7	63°36.333' E	20°49.803' N	36.5	25.1	16	24
38	12	15 and 16 Mar	1480	224	66°33.039' E	19°1.656' N	36.62	26.47	16.5	31
39	11	18 and 20 Mar	1500	437	66°23.826' E	18°42.948' N	35.33	27.35	16	36.5
40	6	22 Mar	1440	651	67°59.832' E	17°29.034' N	33.97	27.64	20	49.5
41	4	30 Mar	1490	1033	70°0.534' E	14°34.266' N	36.09	29.19	19	61.5
42	3	4 Apr	1505	2067	73°54.09' E	5°59.982' N	34.57	30.15	23	73

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Table 2. ICHTHYOP model parameters used to carry the simulations of Lagrangian particles advection.

Settling speed (mday ⁻¹)	Duration (days)	Time step of particle tracking (s)
1	300	3600
5	250	3600
10	150	1800
30	60	1800
100	30	1200

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Table 3. Mean and standard deviation of size-spectra (100 µm-2 mm) slope for all stations, computed for each layer 200 m thick and on the whole water column (last row of the table). No standard deviation is reported when only one profile was available.

	statio	n 36	statio	n 37	statio	n 38	statio	n 39	statio	n 40	statio	n 41	statio	n 42
Depth (m)	mean	sd												
0–200	-2.53	0.08	-2.53	0.07	-3.19	0.13	-3.12	0.16	-3.04	0.09	-3.20	0.07	-3.42	0.20
200–400	-2.37	0.10	-2.34	0.02	-2.61	0.12	-3.59	0.13	-3.88	0.07	-4.05	0.12	-3.40	0.17
400–600	-2.84	0.09	-2.82	0.05	-2.58	0.11	-3.84	0.26	-3.69	0.13	-4.00	0.09	-3.37	0.14
600–800	-2.79	0.04	-2.95	0.07	-2.47	0.04	-3.19	0.30	-3.07	-	-3.84	0.06	-3.36	0.10
800–1000	-2.87	0.04	-2.90	0.03	-2.57	0.04	-3.00	0.15	-3.03	-	-3.76	0.05	-3.60	0.05
1000–1200	-2.69	-	-2.72	0.22	-2.65	0.06	-3.00	0.04	-2.98	-	-3.81	-	-3.44	-
1200-1400	_	-	-2.61	_	-2.65	-	-3.13	0.09	-2.73	-	-3.92	_	-3.49	_
0–1400	-2.60	0.10	-2.61	0.03	-2.86	0.13	-3.36	0.15	-3.37	0.07	-3.65	0.09	-3.49	0.04









Fig. 2. Vertical profiles of salinity and temperature, with oxygen concentration background (grey color).











Fig. 4. Vertical profiles of nitrate (red) with oxygen concentration background (grey color).





Fig. 5. Vertical profiles of fluorescence and $c_{\rm p}$ with oxygen concentration background (grey color).











Fig. 7. Vertical profiles of zooplankton abundance sampled with the multinet net (station 37 had no data), with oxygen concentration background (grey color).





Fig. 8. Vertical profiles of SPM and total LPM with oxygen concentration background (grey color). The INL and DNL can be observed with peaks at 300 and 900 m depth respectively. Total LPM mainly represents the smallest particle size classes given their dominance.





Fig. 9. Vertical profiles of 2 size classes of particles [0.53-1.06] mm (red) and > 1.06 mm (black), with oxygen concentration background (grey color).



*	æ	P ³	\$	
<u>5.0 mm</u> ,	<u>5.0 mm</u>	<u>5.0 mm</u>	<u>5.0 mm</u>	<u>5.0 mm</u>
tara_036_00_a	tara 036 00 a	tara 036 00 c	tara 036 00 b	tara <u>036 00</u> c
1880_212.2 m	1937 221.7 m	2033 215.3 m	2003 205.7 m	2061 219.8 m
×	4	#		the second
<u>5.0 mm</u>	5.0 mm	5.0 mm	5.0 mm	5.0 mm
tara_037_00_a	tara 037 00_a	tara_037_00_a	tara_037_00_a	tara 037 00 e
1860_203 m	1922 213.5 m	2056_235.9 m	2125_247.8 m	2349 227.4 m
.the	×.	#	1. 1.	6
5.0 mm	<u>5.0 mm</u>	<u>5.0 mm</u>	<u>5.0 mm</u>	5.0 mm
tara 038 00_a	tara 038 00 a	tara 038 00_d	tara 038 00 d	tara 038 00 1
3689 502.3 m	3891 534.3 m	4155 514.8 m	4812 588.5 m	4298 583.9 m
*	*	-1	**	*
<u>5.0 mm</u>	5.0 mm	<u>5.0 mm</u>	5.0 mm,	<u>5.0 mm</u>
tara 039 00_a	tara_039_00_a	tara_039_00_c	tara_039_00_c	tara_039_00_j
4767 523.1 m	4777_524.8 m	4179_558.5 m	4202_561.9 m	4190_522.9 m
*	0	*		-10
<u>5.0 mm</u>	<u>5.0 mm</u>	<u>5.0 mm</u>	<u>5.0 mm</u>	<u>5.0 mm</u>
tara 040 00 a	tara 040 00 a	tara 040 00 a	tara 040 00 a	tara 040 00 a
7631 950.1 m	7674 958.5 m	7685 958.7 m	7739 967.6 m	7812 979.8 m
44	*	64	-	-
<u>5.0 mm</u>	<u>5.0 mm</u>	<u>5.0 mm</u>	<u>5.0 mm</u>	<u>5.0 mm</u> ,
tara 041 00 a	tara 041 00 a	tara 041 00 a	tara 041 00_d	tara 041 00 d
4007 502.5 m	4451 569.4 m	4562 588.5 m	4286_516.2 m	4818 598.1 m



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Fig. 11. (A) Station 37, left panel: vertical profile of LPM fluxes and Martin exponential fit (green dashed line) with oxygen concentration background (grey color). Right panel: PSD in increasing depth layers. The red line has a slope of -4 and is given as a reference line for all PSD. **(B)** same as **(A)** for station 40.





Fig. 12. Results from backward Lagrangian simulations. Each envelope contains the 75 % of the initial particle number locating possible source of particles observed in each vertical profiles. Five settling velocities were used.

