

Inventory of released inorganic carbon from organic matter remineralization in the deeper Arabian Sea

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Abstract. An attempt is made to quantify the biological carbon pump in Arabian Sea subsurface waters by estimating the total concentrations of remineralized dissolved inorganic carbon (DIC_{rem}) and its water column inventory. The influence of different sets of $-\Delta\text{O}_2/\Delta\text{C}_{\text{org}}$ ratios, which are either constant or variable with depth, on the estimate is assessed. Throughout the water column the horizontally mapped DIC_{rem} concentrations increase northward due to enlarged export fluxes of organic matter and subsequently enhanced remineralization processes as well as to the accumulation of remineralization products along the trajectory path of the water masses ventilating the Arabian Sea from the southern Indian Ocean. The choice of the remineralization ratios generates significant differences in the DIC_{rem} concentrations at specific depth horizons. The DIC_{rem} inventory of the Arabian Sea between 500 and 4500 m in the years 1995–1997 amounts to $\sim 39\text{--}44$ Gt C depending on the applied remineralization ratios.

1. Introduction

The monsoon-forced nutrient supply to the mixed layer by coastal upwelling in the summer and vertical convection in the winter is the prime factor responsible for the high rates of primary and new production in the Arabian Sea [e.g., *Smith et al.*, 1998; *Morrison et al.*, 1998; *Brink et al.*, 1998; *Bhattachari et al.*, 1996; *Brock et al.*, 1991]. Part of the produced organic matter is exported to the deep Arabian Sea, where most of it is remineralized to dissolved inorganic carbon (DIC), nitrate, and phosphate. As the biologically fixed DIC in the exported organic matter is replenished from the atmospheric CO_2 reservoir, the DIC released within the interior of the ocean reflects, in general, the drawdown of atmospheric CO_2 via the biological carbon pump. For upwelling areas such as the Arabian Sea, showing a CO_2 supersaturation with respect to the atmosphere [e.g., *Goyet et al.*, 1998; *Körtzinger et al.*, 1997; *Sarma et al.*, 1998; R. Lendt et al., The response of the near-surface carbonate system of the northwestern Arabian Sea to the SW monsoon and related biological forcing, submitted to *Journal of Geophysical Research*, 2000], this in turn means that the oceanic gross release of CO_2 to the atmosphere is reduced and should thus be understood as an oceanic net uptake. Many efforts have been made to estimate the total concentrations of remineralized DIC (DIC_{rem}) within the Arabian Sea [*Goyet et al.*, 1999; *Sabine et al.*, 1999; *George et al.*, 1994; *Millero et al.*, 1998; *Kumar et al.*, 1990; *Mintrop et al.*, 1999; *Takahashi et al.*, 1985]; however, no values of its oceanic inventory are currently available to quantify the biological pump in this area.

DIC_{rem} is commonly assessed by converting the biological changes in the concentrations of nutrients or apparent oxygen utilization (AOU) into the release of DIC using the Redfield

ratios, which reflect the stoichiometric composition of particulate organic matter [*Redfield et al.*, 1963]. Here we determine the DIC_{rem} inventory of the Arabian Sea at the time of the surveys (1995–1997) between 500 and 4500 m with reference to different sets of stoichiometric ratios. In order to investigate the impact of the remineralization ratios on DIC_{rem} , we compare DIC_{rem} estimates relying on depth-dependent ratios obtained from an extended data set using the technique of *Hupe and Karstensen* [2000] with DIC_{rem} estimates employing constant ratios of *Redfield et al.* [1963] and *Anderson and Sarmiento* [1994].

2. Data

For the inventory estimates we use temperature, salinity, and oxygen data of the following cruises in the Arabian Sea in 1995 and 1997 (Figure 1): German R/V *Meteor* World Ocean Circulation Experiment (WOCE) cruises M32/1 and M32/4; U.S. R/V *Thomas G. Thompson* Joint Global Ocean Flux Study (JGOFS) cruises TTN/043, TTN/045, TTN/049, TTN/053, and TTN/054; German JGOFS expeditions M31/3 and M32/3; and R/V *Sonne* cruise SO119. To fill the data gap in the eastern Arabian Sea ($>65^\circ\text{E}$), we incorporated selected data of the analyzed mean fields of the World Ocean Atlas 1998 (asterisks) extracted from the Web site http://www.nodc.noaa.gov/OC5/data_woa.html. In addition, we use nutrient, DIC, and alkalinity data from M32/4 and U.S. JGOFS cruises to recalculate the remineralization ratios. The precision of hydrochemical tracers involved in the DIC_{rem} calculations from respective cruises is summarized in Table 1. Although the uncertainty of the field data is given here on a per-mass basis, in the further context, volumetric units are used because of the integration routines. Estimates above 500 m were omitted, as the situation became too complex owing to the strong monsoonal reversal in the Arabian Sea.

3. Approach

Recently, *Hupe and Karstensen* [2000] have applied a linear inverse mixing model, the extended optimum multiparameter (OMP) analysis [*Karstensen and Tomczak*, 1998; *Karstensen*,

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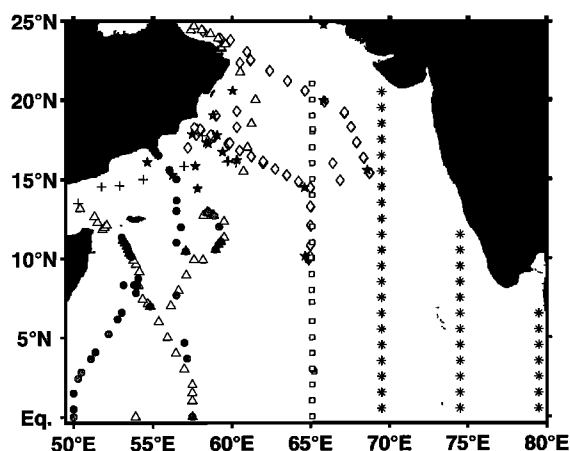


Figure 1. Map of cruises between 1995 and 1997 involved in this study: German World Ocean Circulation Experiment (WOCE) cruises M32/1 (triangles) and M32/4 (circles); U.S. Joint Global Ocean Flux Study (JGOFS) expeditions TTN/043, TTN/045, TTN/049, TTN/053, and TTN/054 (diamonds); and German JGOFS cruises M31/3 (plus signs), M32/3 (squares), and SO119 (stars). Additionally, data from the World Ocean Atlas 1998 are incorporated (asterisks).

1999], to observational hydrographic, nutrient, and carbon data in order to derive a new set of $\Delta C_{\text{org}}/\Delta N/\Delta P/-\Delta O_2$ remineralization ratios for Arabian Sea subsurface waters between 550 and 4500 m. In summary, the model predicts the mixing fractions of predefined source waters, the time- and space-integrated amount of biogeochemical changes in oxygen, nutrient, and inorganic carbon properties due to remineralization processes, and the nitrate deficit due to denitrification. Additionally, the effects of calcium carbonate dissolution and anthropogenic CO_2 , which decouple the DIC concentrations from biological nutrient and oxygen changes, are accounted for. The main advantage of this method is that it takes into account mixing of water masses by all processes such as diapycnal mixing which, in turn, plays a vital role in the northern Indian Ocean [Anderson and Sarmiento, 1994; Tomczak and Godfrey, 1994]. The main disadvantage is that the estimated biological changes in oxygen, nutrients, and DIC cannot be taken as total concentrations because the presumed source-water types are already mixtures of other water masses and do not represent preformed concentrations of the biogeochemical tracers. Consequently, the OMP results are restricted to be

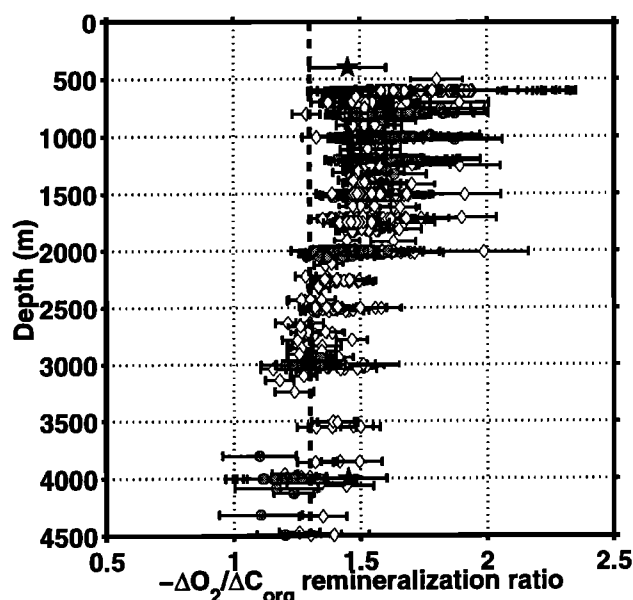


Figure 2. Plot of $-\Delta O_2/\Delta C_{\text{org}}$ ratios obtained by an extended optimum multiparameter (OMP) analysis [Hupe and Karstensen, 2000] from expedition M32/4 (circles) and all U.S. JGOFS cruises (diamonds). For positions, see Figure 1. The depth-invariant ratios by Redfield *et al.* [1963] (RKR63) and Anderson and Sarmiento [1994] (AS94) are indicated by the dashed line and the stars, respectively.

relative values with respect to the source-water definitions and are applicable only in terms of ratios of particulate organic matter remineralization. For clarification, if the source-water types would be defined further away from the investigation area (“upstream”), the values of the time- and space-integrated biological changes increase while the remineralization ratios should be still the same.

To improve the results of this study, data of the cruises TTN/043, TTN/045, TTN/053, and TTN/054 were incorporated additionally in the OMP analysis to reassess the remineralization ratios. As listed in Table 1, at least one of the required tracers (temperature, salinity, oxygen, nitrate, silicate, phosphate, DIC, and alkalinity) is missing in the data sets of the remaining cruises. The OMP analysis is thus not applicable to these data sets. Figure 2 shows the mean $-\Delta O_2/\Delta C_{\text{org}}$ ratios versus depth, as well as the standard deviations (error bars)

Table 1. Precision of Hydrochemical Data Involved in the DIC_{rem} Calculations of This Study^a

| Cruises | Hydrochemical Tracer | | | | | |
|---------|----------------------|-------------|--------------|--------------------------|--------------------|-----------------|
| | DIC | TA | O_2 | $\text{Si}(\text{OH})_4$ | PO_4^{3-} | NO_3^- |
| TTN | $\pm 1.2^b$ | $\pm 3.2^b$ | $\pm 0.05^c$ | $\pm 0.3^d$ | $\pm 0.01^d$ | $\pm 0.1^d$ |
| M32/4 | ± 2 | ± 5 | ± 0.1 | ± 0.5 | ± 0.01 | ± 0.1 |
| M32/1 | na | na | ± 0.1 | ... | ... | ... |
| M32/3 | ... | na | $\pm 0.1^e$ | ... | ... | ... |
| M31/3 | ... | ... | ± 0.2 | na | na | na |
| SO119 | ... | ... | ± 0.1 | na | na | na |
| WOA1998 | na | na | $\pm ?$ | ... | ... | ... |

^aHydrochemical data given in $\mu\text{mol kg}^{-1}$; na, not available; ellipsis dots, data available but not used in this approach.

^bFrom *Müller et al.* [1998].

^cFrom *Morrison et al.* [1999].

^dApproximately $\pm 0.2\%$ of full-scale ranges for nutrients (data available at <http://usjgofs.whoi.edu/jg/dir/jgofs/arabian/>).

^eFrom H. Thomas *et al.* DIC/NO_3^- relationship as a tool for the determination of denitrification, (submitted to *Deep Sea Research*, 1999).

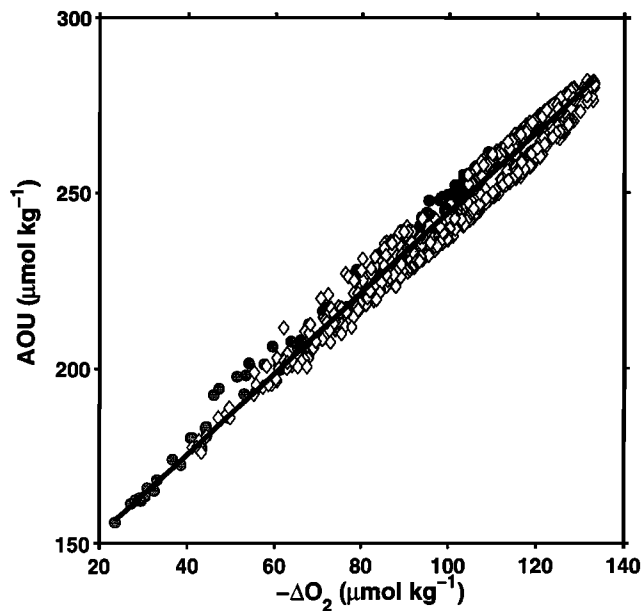


Figure 3. Correlation between $-\Delta\text{O}_2$ from the OMP analysis and apparent oxygen utilization (AOU) at depths ranging from 500 to 4500 m using M32/4 (circles) and all U.S. JGOFS cruises (diamonds). For positions, see Figure 1.

obtained by adding 100 times random noise on source-water types and observational data simultaneously (for details, see *Hupe and Karstensen* [2000]). These ratios reflect the biological oxygen consumption related to the released DIC during organic matter remineralization relative to the predefined source-water types. Note that the model-based $\Delta\text{C}_{\text{org}}$ values used for the ratios are not equal to the total concentrations (DIC_{rem}), the determination of which is the objective of this manuscript. The $-\Delta\text{O}_2/\Delta\text{C}_{\text{org}}$ ratios confirm the depth-dependent trend of remineralization suggested by *Hupe and Karstensen* [2000] and reveal mean values of 1.56 ± 0.16 at 500–1200 m, 1.49 ± 0.11 at 1200–2000 m, and 1.35 ± 0.12 below 2000 m. These values, subdivided into three depth ranges, are denoted hereinafter as HK00.

As a first approximation, an observed DIC concentration (DIC_{obs}) in the interior of the ocean is made up of the fractions of individual water masses having a definite physical (mixing, solubility) and biogeochemical (remineralization, CaCO_3 dissolution) history:

$$\text{DIC}_{\text{obs}} = \sum_{j=1}^n k_j (\text{DIC}_{\text{pref}} + \text{DIC}_{\text{rem}} + \text{DIC}_{\text{CaCO}_3})_j, \quad (1)$$

where

- k_j mixing coefficient of source water j with $\sum k_j = 1$;
- n number of source waters;
- DIC_{pref} preformed DIC determined by preformed alkalinity and air-sea interaction;
- DIC_{rem} DIC release due to remineralization of organic matter;
- $\text{DIC}_{\text{CaCO}_3}$ DIC release due to dissolution of CaCO_3 .

In order to convert the relative $\Delta\text{C}_{\text{org}}$ values to total concentrations of DIC_{rem} , we apply a tight correlation between the

Table 2. Summary of $-\Delta\text{O}_2/\Delta\text{C}_{\text{org}}$ Remineralization Ratios Involved in the DIC_{rem} Inventory Estimates

| Depth Range, m | HK00 | AS94 | RKR63 |
|----------------|-----------------|-----------------|-------|
| 500–1200 | 1.56 ± 0.16 | 1.45 ± 0.15 | 1.30 |
| 1200–2000 | 1.49 ± 0.11 | 1.45 ± 0.15 | 1.30 |
| >2000 | 1.35 ± 0.12 | 1.45 ± 0.15 | 1.30 |

oxygen consumption $-\Delta\text{O}_2$ yielded by the OMP analysis and the AOU (Figure 3):

$$\text{AOU} = 1.149(-\Delta\text{O}_2) + 129.61 \quad (r^2 = 0.97). \quad (2)$$

This relationship may be expected because $-\Delta\text{O}_2$ corresponds to a source-water-related AOU. The standard error of the estimates averages only $\pm 4.3 \mu\text{mol kg}^{-1}$ or 1.7% related to the mean AOU value. The total amount of remineralized DIC can only be assessed indirectly via the substitution of $-\Delta\text{O}_2$ in the $-\Delta\text{O}_2/\Delta\text{C}_{\text{org}}$ ratio with AOU. Hence the knowledge of the remineralization ratios is crucial in calculating DIC_{rem} . We assume that the $-\Delta\text{O}_2/\Delta\text{C}_{\text{org}}$ ratios as well as the $-\Delta\text{O}_2/\text{AOU}$ correlation hold true for data that could not be analyzed with the OMP model. For comparison we calculated the DIC_{rem} concentrations using the constant $-\Delta\text{O}_2/\Delta\text{C}_{\text{org}}$ ratios of *Anderson and Sarmiento* [1994] (Figure 2, stars) and the classical Redfield ratio [*Redfield et al.*, 1963] (Figure 2, dashed line), abbreviated hereinafter as AS94 and RKR63, respectively. All $-\Delta\text{O}_2/\Delta\text{C}_{\text{org}}$ remineralization ratios involved in the DIC_{rem} inventory estimates of this study are summarized in Table 2.

We start the inventory estimates by interpolating AOU onto 15 standard depths (500:100:1000, 1250:250:2000, and 2500:500:4500 m; adopted from HK00) and calculate DIC_{rem} on those depths with reference to the HK00, AS94, and RKR63 remineralization ratios of $-\Delta\text{O}_2/\Delta\text{C}_{\text{org}}$. The values of each of the 15 depth levels are projected onto a 1° grid to the horizontal area of the Arabian Sea using an objective mapping technique. DIC_{rem} was mapped over an area from 0° to 25°N and 50° to 80°E according to *Somasundar et al.* [1990]. For a better characterization the investigation area is divided into a northern (17° – 25°N), a central (9° – 17°N), and a southern (0° – 9°N) latitude belt. In succession, each gridded DIC_{rem} value is then multiplied by the volume of water between adjacent standard depths, i.e., within a 100-m slab between the 500- and 600-m levels. These values are subsequently summed up to generate first the inventories of the latitude belts and finally to the total DIC_{rem} inventory in the Arabian Sea between 500 and 4500 m. For the calculations of the $1^\circ \times 1^\circ$ arrays we applied the TerrainBase 5-min global bathymetry/topography (data available at <ftp://ncardata.ucar.edu/datasets/ds759.2/index.html>) using every twelfth value.

4. Results and Discussion

4.1. Distribution of DIC_{rem}

The results of the DIC_{rem} estimates using three sets of variable and constant remineralization ratios with depth are depicted in Figures 4–6. Figures 4a–4c show horizontally averaged profiles in the northern, central and southern latitude belts, respectively, in the Arabian Sea. Following the vertical distribution of AOU, the maximum concentrations of DIC_{rem} (160 – $220 \mu\text{mol L}^{-1}$) are reached at intermediate depths in all latitude belts, whatever remineralization ratio is involved. To-

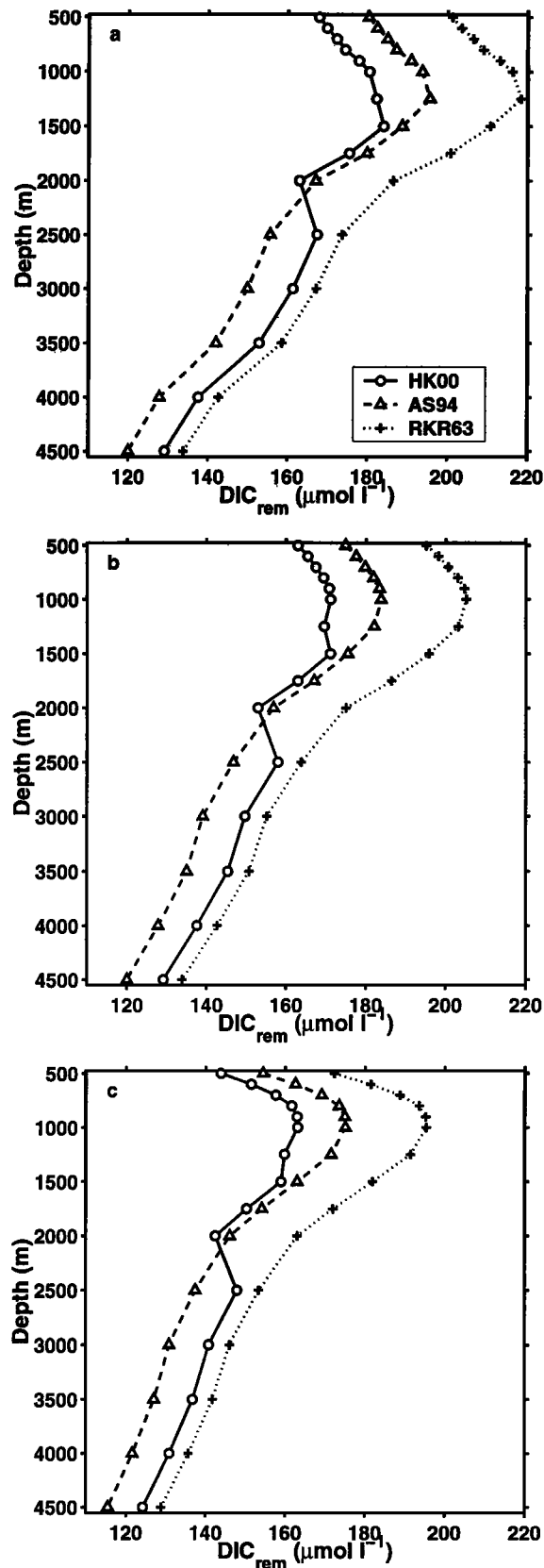


Figure 4. Horizontally averaged remineralized dissolved inorganic carbon (DIC_{rem}) profiles using the remineralization ratios of Hupe and Karstensen [2000] (HK00), AS94, and RKR63 in three latitude belts: (a) 17° – 25°N , (b) 9° – 17°N , and (c) 0° – 9°N .

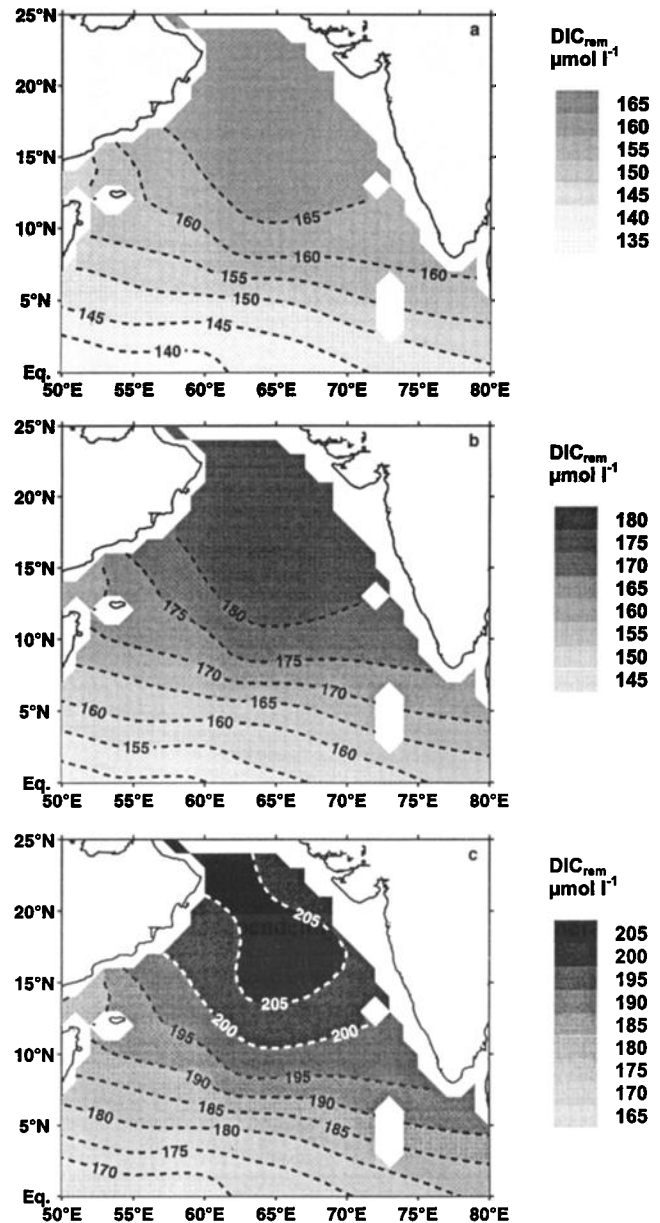


Figure 5. Horizontally mapped DIC_{rem} concentrations ($\mu\text{mol L}^{-1}$) at 600 m using the remineralization ratios of (a) HK00, (b) AS94, and (c) RKR63.

ward the deep sea the values are generally decreasing to 110 – $135 \mu\text{mol L}^{-1} \text{DIC}_{\text{rem}}$. However, the results depend significantly on the chosen set of $-\Delta\text{O}_2/\Delta\text{C}_{\text{org}}$ ratios. Throughout the water column the highest values are generated by the RKR63 ratios. The lowest limit of the DIC_{rem} concentrations is supplied by the HK00 ratios above 2000 m and by the AS94 configuration below this depth. As expected, the DIC_{rem} profiles using HK00 are not as smooth as AS94 and RKR63 profiles, owing to the step change of ratios at 1200 and 2000 m. Possibly, the $-\Delta\text{O}_2/\Delta\text{C}_{\text{org}}$ ratios at intermediate depth and the deep sea are somewhat too high or too low, respectively.

To emphasize regional aspects of organic matter remineralization, the objectively analyzed DIC_{rem} concentrations are plotted for the depths of 600 and 3000 m (Figures 5 and 6). DIC_{rem} increases independently of the applied remineraliza-

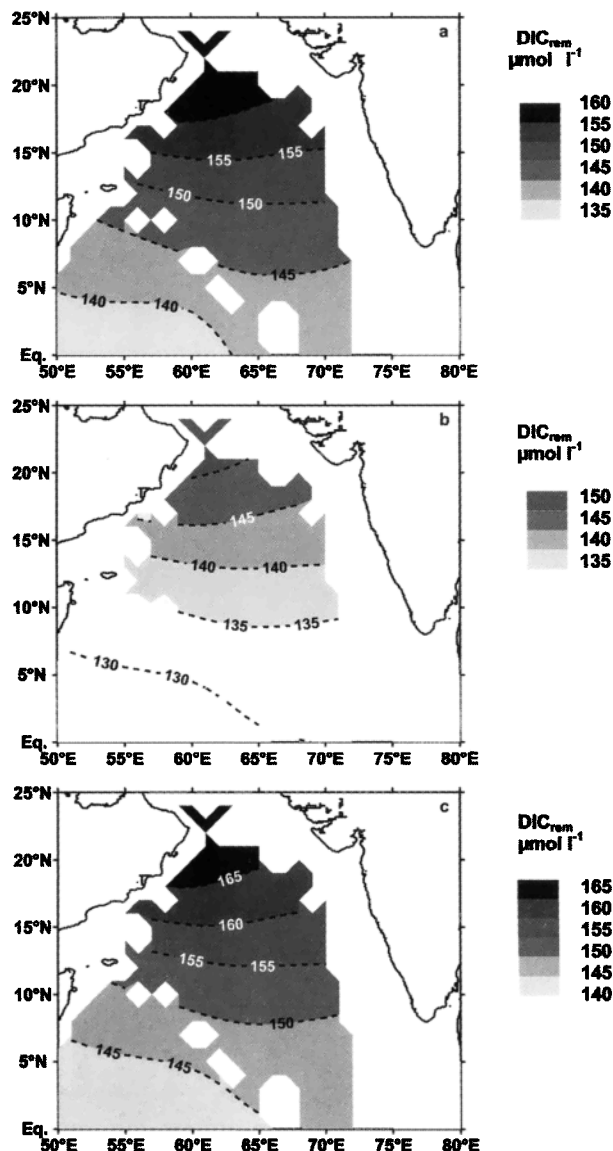


Figure 6. Horizontally mapped DIC_{rem} concentrations ($\mu\text{mol L}^{-1}$) at 3000 m using the remineralization ratios of (a) HK00, (b) AS94, and (c) RKR63.

tion ratios from southwest to northeast, which is attributed to the decomposition of organic matter owing to higher downward exports caused by increasing northward primary productivity and to the longer trajectory path of the water masses

ventilating the Arabian Sea from the southern Indian Ocean [e.g., George et al., 1994; Haake et al., 1993; Mintrop et al., 1999; Nair et al., 1989; Qasim, 1982; Wyrki, 1973]. As previously mentioned, the HK00 stoichiometry leads to the lowest DIC_{rem} concentrations ($135\text{--}169 \mu\text{mol L}^{-1}$) at 600 m and the RKR63 ratios to the highest numbers ($166\text{--}207 \mu\text{mol L}^{-1}$), whereas AS94 is in between. At the 3000-m depth range the concentrations of DIC_{rem} are generally lower than at the 600-m level because of both the input of low- DIC_{rem} deep waters from the south and the decrease in organic matter remineralization with depth. Nevertheless, the highest values of DIC_{rem} are still reached in the RKR63 configuration ($142\text{--}168 \mu\text{mol L}^{-1}$), followed by the concentrations derived from HK00 ($136\text{--}163 \mu\text{mol L}^{-1}$) and AS94 ($126\text{--}152 \mu\text{mol L}^{-1}$).

Two studies in the Arabian Sea [George et al., 1994; Mintrop et al., 1999] are chosen for a closer comparison of the DIC_{rem} results. In the first one the DIC_{rem} fraction was calculated from the AOU with reference to the $-\Delta O_2/\Delta C_{org}$ ratio of 141/106 [Kroopnick, 1985], an average for the world ocean, in the northern (20°N , 65°E) and central (10°N , 68°E) Arabian Sea (Figure 6a) [George et al., 1994, p. 248]. At 600 (3000) m the DIC_{rem} concentrations amount to ~ 205 (165) $\mu\text{mol L}^{-1}$ DIC_{rem} and 190 (140) $\mu\text{mol L}^{-1}$ DIC_{rem} for the northern and central parts, respectively. Considering the effect of denitrification, Mintrop et al. [1999] applied the classical $-\Delta O_2/\Delta C_{org}$ ratio of 138/106 [Redfield et al., 1963], yielding for both depth levels 210 (165) $\mu\text{mol L}^{-1}$ at 17°N , 62°E in the northern Arabian Sea and 170 (145) $\mu\text{mol L}^{-1}$ at 6°N , 65°E in the southern area (Figure 6a) [Mintrop et al., 1999, p. 328]. To convert the results of Mintrop et al. [1999] to $\mu\text{mol L}^{-1}$, the values were multiplied by an average density of 1.027 g cm^{-3} . The results of both local studies at selected stations are in fairly good agreement with the RKR63 configuration of this work. To conclude, the calculation of DIC_{rem} using the AOU with reference to the $-\Delta O_2/\Delta C_{org}$ ratios is dependent on the involved set of remineralization ratios (HK00, AS94, or RKR63), but the basin-wide gridded DIC_{rem} distributions are resolved well enough to reflect the results of local studies.

4.2. DIC_{rem} Inventories

The estimated DIC_{rem} inventories of the Arabian Sea between 500 and 4500 m for the three latitude belts are summarized in Table 3. At the time of the surveys (1995–1997) the investigation area contains a total inventory of 39.5 Gt C from organic matter remineralization employing the depth-dependent HK00 ratios. Applying the constant ratios of AS94 reveals an inventory of almost the same magnitude because the differences resulting from both sets of ratios are cancelled out by vertically integrating the mapped DIC_{rem} concentrations. This is because the AS94 ratios reveal higher values at inter-

Table 3. Estimated Water Column Inventory of Remineralized DIC (DIC_{rem}) in the Arabian Sea Between 500 and 4500 m Within the Time Period 1995–1997

| Latitude Belt, °N | Volume, 10^{15} m^3 | Inventory, Gt C | | | Specific Inventory, mol C m^{-2a} | | |
|-------------------|-------------------------------|-----------------|------|------|--|------|------|
| | | RKR63 | AS94 | HK00 | RKR63 | AS94 | HK00 |
| 17–25 | 2.6 | 5.0 | 4.4 | 4.4 | 488 | 437 | 431 |
| 9–17 | 8.4 | 16.2 | 14.5 | 14.6 | 461 | 413 | 408 |
| 0–9 | 12.4 | 22.6 | 20.3 | 20.5 | 429 | 384 | 379 |
| Total | 23.4 | 43.8 | 39.2 | 39.5 | | | |

^a Mean values between 500 and 3000 m.

mediate waters, whereas the HK00 values are higher in the deep sea below 2000 m (Figure 4). Thus the vanishing of the differences is principally ascribed to the choice of the vertical integral. The highest inventory estimate of ~ 44 Gt C is supplied by the RKR63 ratio. It is very difficult to evaluate a reasonable estimate of the potential errors associated with the calculated inventories. Although some error contributions are difficult to assess (i.e., errors generated from the mapping routines and area calculations of the arrays), we believe that the variability in the DIC_{rem} inventories is caused mainly by uncertainties of the stoichiometric ratios and the AOU. We performed a sensitivity study for the HK00 $-\Delta\text{O}_2/\Delta\text{C}_{\text{org}}$ ratios with the standard deviations (Table 2) and an error for the AOU concentrations of $\pm 5 \mu\text{mol kg}^{-1}$. The latter consists of the uncertainty of oxygen measurements ($\pm 1 \mu\text{mol kg}^{-1}$) and the standard error of $\sim \pm 4 \mu\text{mol kg}^{-1}$ in determining the AOU from $-\Delta\text{O}_2$ (Figure 3). This scenario gives an uncertainty of total DIC_{rem} inventory estimate of ± 4 Gt C. Consequently, the errors of the inventories are of the order of at least 10%.

Recently, *Pahlow and Riebesell* [2000] estimated DIC_{rem} inventory for the North Pacific between 500 and 3000 m of ~ 300 Gt C by using the AS94 $-\Delta\text{O}_2/\Delta\text{C}_{\text{org}}$ ratio of 1.45. Like the Arabian Sea, this area is a major denitrification site with a thick oxygen minimum zone at intermediate depth [e.g., *Broecker and Peng*, 1982; *Boulaïdid and Minster*, 1989]. If one would adjust the fifteenfold greater area of the North Pacific ($75 \times 10^{12} \text{ m}^2$) to the dimensions of the Arabian Sea for the same depth interval ($5 \times 10^{12} \text{ m}^2$), the resulting inventory of 20 Gt C would be considerably lower than the estimate of ~ 30 Gt C for the Arabian Sea at the same depth range using the HK00 ratios. Potentially, the Arabian Sea contains more DIC_{rem} , owing to enhanced export fluxes of organic matter in the highly productive northern part, especially if one considers that the DIC_{rem} concentrations derived from AS94 are higher than the HK00 values at depths above 2000 m.

The inventories of the three latitude belts vary greatly, owing to the different volumes of these regions. The southern part contains roughly 50% of the total DIC_{rem} inventory. This is because more than 50% of the volume in the investigation area is located in the region between 0° and 9°N and is not due to a more effective biological pump in this latitude belt. To get a better representation of the regions where DIC_{rem} is accumulated, we look at the specific inventories, which are calculated by dividing the inventories by the surface area of the respective latitude belt. The distributions of the specific inventory for the depth range 500–3000 m are shown in Figure 7. Here the most productive areas in the northern Arabian Sea clearly reveal the highest values. Employing the HK00 ratios, we see that the specific inventory of DIC_{rem} increases from $\sim 370 \text{ mol C m}^{-2}$ at the equator to almost 440 mol C m^{-2} in the northernmost Arabian Sea. While the specific inventories derived from HK00 and AS94 are similar (Table 3), the values produced by RKR63 are up to 50 mol C m^{-2} higher. An illustration of the specific inventories down to 4500 m is omitted because of the data scarcity at this depth.

Two recent studies have exploited DIC_{rem} as an essential parameter while assessing anthropogenic CO_2 in the water column of the Arabian Sea [*Goyet et al.*, 1999; *Sabine et al.*, 1999]. *Sabine et al.* [1999] used the AS94 $-\Delta\text{O}_2/\Delta\text{C}_{\text{org}}$ ratio, which is considered in the present study for comparison (Table 3). The corresponding DIC_{rem} inventories should thus be comparable, although *Sabine et al.* [1999] did not explicitly report on those values. *Goyet et al.* [1999] used a $-\Delta\text{O}_2/\Delta\text{C}_{\text{org}}$ ratio

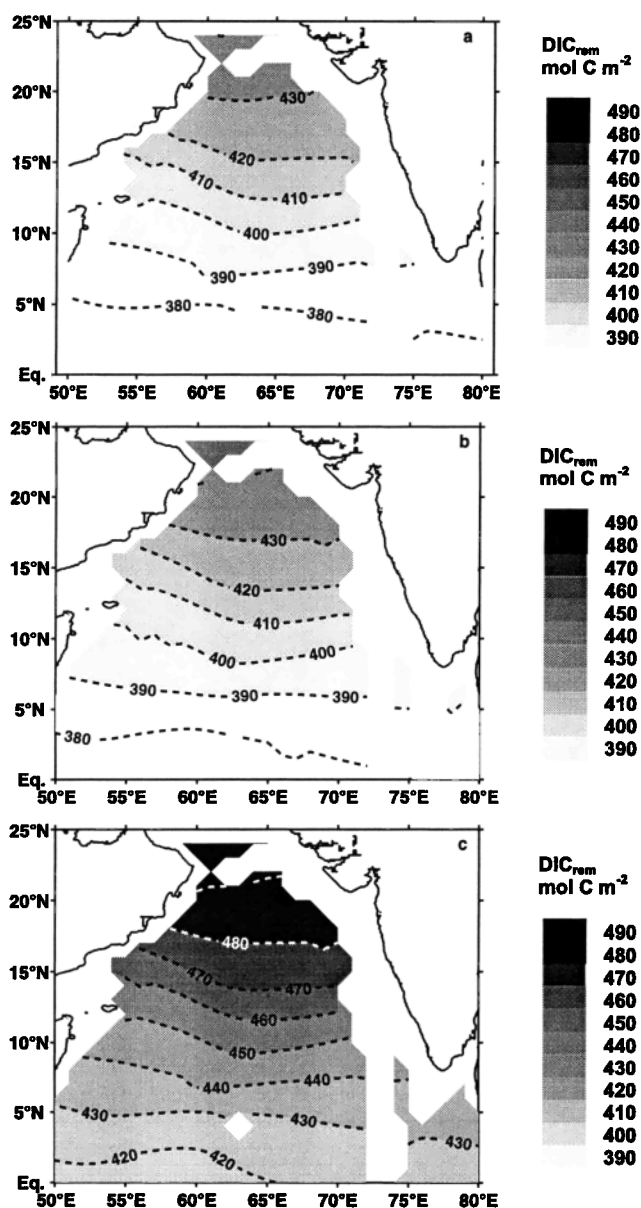


Figure 7. Specific inventory distributions of DIC_{rem} (mol C m^{-2}) between 500 and 3000 m for (a) HK00, (b) AS94, and (c) RKR63.

which was a mean value of RKR63 and AS94. The corresponding DIC_{rem} inventories should thus lie between the latter ones (Table 3). A comparison of specific inventories of DIC_{rem} and anthropogenic CO_2 in the three latitude belts of the Arabian Sea is illustrated in Figure 8. The specific anthropogenic CO_2 inventories for the year 1996 were extracted from a recent global study by *Thomas et al.* [2001], providing 18.7, 19, and $22.4 \text{ mol C m}^{-2}$ for the northern, central, and southern Arabian Sea, respectively. *Thomas et al.* [2001] have developed a method for anthropogenic CO_2 quantification which is independent of remineralization ratios. Figure 8 shows that the anthropogenic CO_2 inventory is only $\sim 5\%$ of the DIC_{rem} inventory between 500 and 4500 m. Keep in mind that if the upper 500 m were considered, the DIC_{rem} inventories would be even larger. Interestingly, the distributions of the specific inventories of DIC_{rem} and anthropogenic CO_2 reveal contrast-

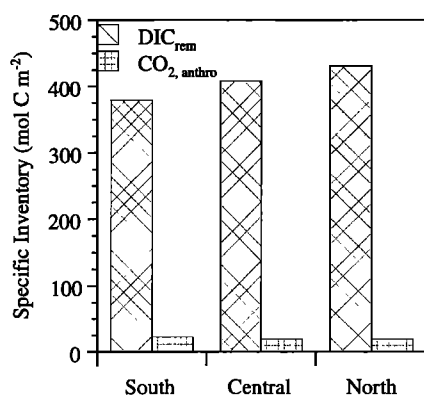


Figure 8. Specific inventories of DIC_{rem} in the latitude belts estimated from HK00 (cross hatching) in comparison with the corresponding vertically integrated anthropogenic CO₂ inventories for the year 1996 of the Arabian Sea (square hatching) [Thomas et al., 2001].

ing patterns. The specific DIC_{rem} inventories increase northward because of the higher biological production in the north. In contrast, anthropogenic CO₂ shows the highest inventories in the southern Arabian Sea since the deeper Arabian Sea is largely ventilated from the south. The younger, more recently ventilated waters which contain higher anthropogenic CO₂ concentrations are thus found in the southern Arabian Sea.

5. Summary and Conclusions

The current study has focused on a first assessment of the DIC_{rem} inventory in the Arabian Sea. DIC_{rem} concentrations have been obtained with reference to different $-\Delta\text{O}_2/\Delta\text{C}_{\text{org}}$ remineralization ratios and AOU. The DIC_{rem} water column inventories at the time of the surveys (1995–1997) have been estimated in order to quantify the biological carbon pump in the Arabian Sea between 500 and 4500 m. The scope of this study is to investigate the differences of the estimates resulting from applying variable (HK00) and constant (AS94 and RKR63) $-\Delta\text{O}_2/\Delta\text{C}_{\text{org}}$ ratios with depth. We find a significant impact of the different sets of ratios on the DIC_{rem} concentrations at specific depth horizons. The highest concentrations throughout the water column are achieved by using the classical Redfield ratio. The depth-dependent HK00 ratios lead to lower DIC_{rem} values compared with the AS94 ratio above 2000 m and vice versa in the deep ocean below this depth. By vertically integrating the calculated DIC_{rem} concentrations, the opposing influences of the involved remineralization ratios in intermediate and deep waters (partly) cancelled out due to the actual choice of the depth integral. The Arabian Sea stores at depths from 500 to 4500 m 39 or 44 Gt C from organic matter remineralization by applying the HK00/AS94 or RKR63 ratios, respectively. These values should be understood as the lower bound because the upper 500 m where most of the particulate organic matter is remineralized had to be excluded in this study.

Considering an uncertainty of at least ± 4 Gt C, the influence of the remineralization ratios on the inventory estimates seems marginal but is in any case significant on the DIC_{rem} concentrations at specific depth horizons. The choice of remineralization ratios is thus important in determining the anthropogenic CO₂ signal in the ocean. In the upper 1500 m, where

most of the anthropogenic CO₂ is accumulated, the DIC_{rem} values diverge up to 40 $\mu\text{mol L}^{-1}$ depending on the applied ratio. As the DIC_{rem} concentrations are subtracted from the observed DIC, whatever method is applied to estimate the amount of anthropogenic CO₂, the differences stemming from the remineralization ratios have to be reflected in the calculated anthropogenic CO₂ [e.g., Wanninkhof et al., 1999]. A ratio-based difference of 40 $\mu\text{mol L}^{-1}$ is even higher than the anthropogenic CO₂ concentration itself in the Arabian Sea at intermediate depth [Sabine et al., 1999; Goyet et al., 1999; Thomas et al., 2001]. Thus more studies have to be carried out to estimate more reliable global remineralization ratios to reduce the uncertainties associated with these ratios in many fields of biological and chemical oceanography.

The depth-dependent remineralization ratios should have an even greater impact on estimating the budget of DIC_{rem} by accounting for the water mass ages to calculate the residence times of the remineralization products in the deeper Arabian Sea. The preferential remineralization of nutrients with depth, also proposed by many other studies [e.g., Shaffer, 1996; Shaffer et al., 1999; Thomas et al., 1999], should lead to a more efficient biological carbon pump compared with a constant remineralization of carbon and nutrients. The water mass ages in the Arabian Sea could be assessed by combining OMP analysis with a mixing analysis of the transient tracer CFCs [Karstensen and Tomczak, 1998]. However, this technique is not applicable here because CFCs are missing in the current data set except for M32/4.

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