Nutrient Salts, Inorganic and Organic Carbon Contents in the Waters of the Persian Gulf and the Gulf of Oman

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Abstract
Sea water samples were collected from 32 stations in the southern part of the Persian Gulf and the Gulf of Oman during winter of 1987. Surface water of the Persian Gulf exhibited wide range and higher values of salinity (37.15-43.95, mean 40.02%) compared with lower values and narrow range (36.58-36.95, mean 36.74%) in the Gulf of Oman.
Surface salinity did not reflect any significant relationship with nutrients and organic and inorganic carbon except, silicate which showed an increase in concentration with decreasing values of salinity (r= -0.65, p<0.01) in the Persian Gulf waters.
The Gulf of Oman exhibited higher levels of phosphate (0.08-1.65, mean 0.57 μ moles/L), nitrate (0.08-3.44, mean 0.78 μ moles/L) and silicate (2.49-22.47, mean 6.37 μ moles/L) than the surface water of the southern Persian Gulf, while inorganic carbon (7.5-22.6, mean 13.62 mg/L) and organic carbon (2.1-14.6, mean 6.37 mg/L) of the Gulf of Oman showed nearly comparable results with those of the Persian Gulf, respectively. Atomic ratio of the elements P:N:Si for the surface water showed similar values 1:2.2:11.1 and 1:2.7:11.8 for the Persian Gulf and the Gulf of Oman, respectively, indicating N is the limiting nutrient for this area.
The presence of a shallow Oxygen minimum in the Gulf of Oman (0.23-1.30 m/L) at depth 140-370 m and σt values (25.51-26.60) coincide with the layer of maximum PO4 (1.06-2.23 μ moles/L), NO3 (3.39-19.33 μ moles/L), SiO3 (12.54-29.51 μ moles/L) and PCO2 which could be resulted from mineralization of organic matter.
Water mass of Gulf origin was identified at 190-300 m in the Gulf of Oman that exhibit higher density levels 26.05-26.74 and medium concentrations of organic carbon.
The nutrients, inorganic and organic carbon budget in the Persian Gulf waters were evaluated as 42608, 20165, 227909, 3395×103 and 4943×103 Ton/year for phosphate, nitrate, silicate, organic and inorganic carbon, respectively, representing the net gain to the Persian Gulf water.

Keywords: Nutrient Salts, Inorganic and Carbon, Persian Gulf, Gulf of Oman

1. Introduction
The major micronutrient elements, Phosphorus, nitrogen and silicon have long been recognized as an index of potential fertility of seawater. In addition, these elements have been used for identifying different water masses in world oceans.
Although organic matter is only a minor component of sea water, it plays a major role in biological, geological and chemical processes (Cauwet, 1984). As such, great attention has been given to the study of organic matter in marine environment (Duursma, 1961; Berger et al., 1989).
Organic carbon is a small fraction of the dissolved inorganic carbon present mainly as bicarbonate.

While considerable information is available on such elements in the sea, little published work is known on hydrochemical conditions and in particular, organic (OC) and inorganic carbon (IC) contents of the Persian Gulf region (Kuronuma, 1974; Grashoff, 1976; Brewer and Dyrssen 1985; Emara et al., 1985; El-Samra, 1988; Anderson and Dyrssen 1993, Morrison et al, 1998 and Emara 1998).

The Persian Gulf itself is a shallow embayment of the northeastern Arabian Sea. It is separated from the Gulf of Oman by the Strait of Hormuz which is only 56 km wide. No sill or saddle in bathymetry constrains circulation and free exchange of water of the Persian Gulf and the Gulf of Oman occurs. The surface area of the Persian Gulf is approximately 2.39×10^5 km^2 and a mean depth of 36 m implies an average volume of 8.63×10^3 km^3 (Reynolds, 1993).

This paper is aimed at studying the major microelements PO_4, inorganic nitrogen species (NO_3, NO_2 and NH_4) and silicate as well as organic and inorganic carbon contents of the southern Persian Gulf and the Gulf of Oman; identifying the interaction between these elements and hydrochemical data of the two water bodies. Special attention is given to partial pressure of CO_2 (PCO_2) at some stations in both areas and in particular, to the layer of minimum oxygen.

2. Materials and Methods

Seawater samples were taken with Nansen bottles, equipped with reversing thermometers. The samples were collected from 32 stations at the standard depths from the surface down to 400 m in the southern Persian Gulf and the Gulf of Oman (Fig. 1) during the period (February-March, 1987) using R/V Muhktabar-Al-Behar.

Nutrient salts (PO_4, NO_3, NO_2 and NH_4) and silicate as well as Salinity hydrochemical parameters pH and dissolved oxygen were determined according to the methods described by Grasshoff (1976).

Organic and inorganic carbon were analyzed by Beckman Total Organic Carbon Analyzer model 915B. The method is based on the catalytic combustion process where all known carbonaceous materials are converted to CO_2. The two-channel instrument (total carbon and inorganic carbon analyzer) measures total organic carbon (TOC) by the difference method. The blank of total organic carbon was found to be 0.35 mg/L.

The carbon system calculation parameters in seawater are calculated by the CO2 program using pH and total alkalinity (TA). The units used for the variables in this program are μ moles/kg of seawater for concentration of TA, Dissolve Inorganic carbon (DIC) and carbonate alkalinity (CA). Dissolved CO_2 in (μ atm) for PCO_2 and FCO_2 and as ppm for the mole ratio of CO_2 in dry air, CO_3^-2 and HCO_3^-1 as μeq/kg^-1.

Density of seawater is calculated in purpose of unit conversions. For this calculation, temperature, salinity, pressure, abundances of other constituents, PO_4, SiO_3 and the relevant equilibrium constants were used. The pH total scale is used with apparent dissociation constants from Mehrbaach et al., (1973) refitted by Dickson and Millero (1987).

3. Results and Discussion

The physico-chemical characteristics of the Persian Gulf and the Gulf of Oman surface water are
given in Table 1. Surface water of the Persian Gulf exhibited wide range and higher values of salinity (37.15-43.95, mean 40.02) compared with lower values and narrow range (36.58-36.95, mean 36.70) in the Gulf of Oman reflecting a difference of 3.28 in salinity between the two water bodies. T-S diagram of the offshore stations (Fig. 2) showed surface water of lower salinity (36.65-37.15) and higher temperature (23.09-23.43°C) from the Gulf of Oman entering the Persian Gulf and flows northward, decreasing in temperature to (20.69-21.61°C) at the southern part of the Persian Gulf and being greatly modified in salinity to (40.62-40.72). The deep water of the Persian Gulf near the Strait of Hormuz exhibited higher salinity values (38.36-38.81) at 50 m depth than salinity values (36.59-36.92) at the same depth in the Gulf of Oman. In addition, the outflowing water from the Persian Gulf (Fig. 3) showed higher values of both salinity (40.80-40.94) and temperature 22.30-22.35°C at 75 m depth in the Persian Gulf and could be traced at a depth of 200-300 m in the Gulf of Oman (Table 2) with comparatively higher salinity (37.06-38.12) and temperature (20.10-20.85°C) values and lower oxygen and PO₄ contents. Reynolds (1993), summertime cross-section in the vicinity of the Strait of Hormuz reveal a similar picture of the water mass exchange. The tongue of Gulf water at 200 m is apparent a water mass with temperature of 20-21°C, salinity just above 37.5 and a thickness of almost 200m.

Table 1- Concentration of physico-chemical parameters (ranges and average) of the Persian Gulf and the Gulf of Oman surface water.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Persian Gulf</th>
<th>Gulf of Oman</th>
</tr>
</thead>
<tbody>
<tr>
<td>S‰</td>
<td>37.15-43.95</td>
<td>36.58-36.95</td>
</tr>
<tr>
<td>O₂ (ml/L)</td>
<td>3.93±0.90</td>
<td>(36.74±0.13)</td>
</tr>
<tr>
<td>PO₄ (μ mole L⁻¹)</td>
<td>0.07±0.04 (0.37±0.28)</td>
<td>0.08-1.65 (0.57±0.6)</td>
</tr>
<tr>
<td>NO₃ (μ mole L⁻¹)</td>
<td>0.17-0.54 (0.29±0.11)</td>
<td>0.08-3.44 (0.78±0.9)</td>
</tr>
<tr>
<td>NH₄ (μ mole L⁻¹)</td>
<td>0.12-0.65 (0.25±0.16)</td>
<td>0.17-0.80 (0.39±0.17)</td>
</tr>
<tr>
<td>SiO₄ (μ mole L⁻¹)</td>
<td>0.14-0.45 (0.33±0.1)</td>
<td>0.25-0.58 (0.35±0.1)</td>
</tr>
<tr>
<td>Organic carbon (mg L⁻¹)</td>
<td>2.14-6.26 (4.20±1.1)</td>
<td>2.49-22.47 (6.37±5.8)</td>
</tr>
<tr>
<td>Inorganic carbon (mg L⁻¹)</td>
<td>1.8-11.8 (6.1±3.4)</td>
<td>2.1-14.6 (6.37±3.7)</td>
</tr>
<tr>
<td>PCO₂ (μ atm)</td>
<td>8.3-25.8 (14.03±5)</td>
<td>7.5-22.6 (13.62±4.6)</td>
</tr>
<tr>
<td>PCD (mg L⁻¹)</td>
<td>190-348 (232±43 μ atm)</td>
<td>68-347 (211±139)</td>
</tr>
</tbody>
</table>

Below this depth at 400 m, both salinity 36.17-
36.42 and temperature 16.16-16.97°C represent the real values of the Gulf of Oman. Hartman, Lange, Seibold and Walger (1971) give a salinity of 39.7‰ for the out flowing water, but waters of this salinity could not be recorded in this study, and the observed value being closer to 38.12.

The distribution of surface inorganic phosphate showed the presence of detectable concentrations at virtually all stations in the southern Persian Gulf (0.07-0.84, mean 0.37±0.3 μ moles/L) and the Gulf of Oman (0.08-1.65, mean 0.57±0.4 μ moles/L) indicating that phosphate is not a limiting factor (Emara, 1985). Nitrate showed also similar trend to that of PO₄, reflecting higher concentrations at the Gulf of Oman (0.08-3.44, mean 0.78±0.8 μ moles/L) compared with a lower one for the Persian Gulf (0.17-0.54, mean 0.29 ±0.11 μ moles/L).
Table 2- Physio-chemical characteristics of out flowing water from the Persian Gulf to the Gulf of Oman

<table>
<thead>
<tr>
<th>St. No</th>
<th>Depth m</th>
<th>Temp. °C</th>
<th>S‰</th>
<th>σ</th>
<th>O₂ ml/L</th>
<th>PO₄ μ moles/L</th>
<th>NO₃ μ moles/L</th>
<th>SiO₃ mg/L</th>
<th>IC mg/L</th>
<th>TOC mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>F4</td>
<td>300</td>
<td>20.85</td>
<td>37.58</td>
<td>26.51</td>
<td>2.09</td>
<td>1.02</td>
<td>0.35</td>
<td>9.17</td>
<td>15.75</td>
<td>4.2</td>
</tr>
<tr>
<td>F3</td>
<td>200</td>
<td>21.54</td>
<td>38.12</td>
<td>26.74</td>
<td>1.96</td>
<td>0.84</td>
<td>5.31</td>
<td>9.11</td>
<td>12.3</td>
<td>7.2</td>
</tr>
<tr>
<td>G4</td>
<td>300</td>
<td>20.10</td>
<td>37.06</td>
<td>26.33</td>
<td>1.40</td>
<td>1.62</td>
<td>4.82</td>
<td>16.11</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>G2</td>
<td>190</td>
<td>21.27</td>
<td>37.10</td>
<td>26.05</td>
<td>1.79</td>
<td>0.63</td>
<td>0.79</td>
<td>12.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>300</td>
<td>20.26</td>
<td>37.62</td>
<td>26.71</td>
<td>1.42</td>
<td>0.71</td>
<td>15.86</td>
<td>-</td>
<td>9.5</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3- Shallow oxygen minimum at some stations in the Gulf of Oman with nutrients concentrations (μ moles/L), oxygen content(ml/L), organic and inorganic carbon (mg/L) and partial pressure of CO₂ (μ atm.)

<table>
<thead>
<tr>
<th>St. No</th>
<th>Depth of O₂ minimum</th>
<th>O₂</th>
<th>O₂%</th>
<th>σ</th>
<th>PO₄</th>
<th>NO₃</th>
<th>SiO₃</th>
<th>IC</th>
<th>TOC</th>
<th>PCO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>F4</td>
<td>370</td>
<td>0.38</td>
<td>6.1</td>
<td>26.60</td>
<td>1.02</td>
<td>1.16</td>
<td>17.91</td>
<td>25.10</td>
<td>11.7</td>
<td>1047.0</td>
</tr>
<tr>
<td>F3</td>
<td>150</td>
<td>0.76</td>
<td>14.8</td>
<td>25.86</td>
<td>1.31</td>
<td>11.00</td>
<td>14.10</td>
<td>10.95</td>
<td>21.0</td>
<td>878.3</td>
</tr>
<tr>
<td>6</td>
<td>150</td>
<td>0.79</td>
<td>15.2</td>
<td>25.86</td>
<td>1.06</td>
<td>2.95</td>
<td>15.37</td>
<td>28.10</td>
<td>6.40</td>
<td>-</td>
</tr>
<tr>
<td>G4</td>
<td>200</td>
<td>0.25</td>
<td>4.9</td>
<td>25.81</td>
<td>1.86</td>
<td>17.95</td>
<td>14.90</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>G3</td>
<td>150</td>
<td>1.30</td>
<td>25.7</td>
<td>25.51</td>
<td>1.42</td>
<td>13.86</td>
<td>12.54</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>G2</td>
<td>140</td>
<td>0.33</td>
<td>6.5</td>
<td>25.57</td>
<td>1.53</td>
<td>3.59</td>
<td>13.66</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>150</td>
<td>0.23</td>
<td>4.2</td>
<td>26.07</td>
<td>2.16</td>
<td>10.24</td>
<td>29.51</td>
<td>7.65</td>
<td>3.60</td>
<td>221.3</td>
</tr>
</tbody>
</table>

The distribution of NO₃ (Figs. 4 and 5) showed the penetration of surface water from the Gulf of Oman towards the Strait of Hormuz with higher concentrations towards the Persian Gulf area. Phosphate showed similar trend but at depth of 10 m (Fig. 6). NO₂ concentration was higher at the surface (1.6 times) for the Gulf of Oman than that for the Persian Gulf. In addition, no distinct secondary maximum was detected in the area, but subsurface maximum were recorded in the euphotic zone at a shallow depths (20-50 m) with values fluctuating from 0.6 to 1.52 μ moles/L.

This maximum probably arised from the intermediate formation of NO₂ in the nitrification process. Beneath this maximum, NO₂ concentrations fell rapidly to undetectable levels.

![Fig 4. Map of surface nitrate (μ moles/l) within the Persian Gulf](image)

![Fig 5. Vertical distribution of nitrate (μ moles/l) at the offshore stations in the Persian Gulf waters and the Gulf of Oman](image)

![Fig 6. Vertical distribution of phosphate (μ moles/l) at the offshore stations in the Persian Gulf waters and the Gulf of Oman](image)
The concentration of ammonia (0.14-0.45, mean 0.33±0.1 μ moles) was similar in both water bodies.

As far as silicate is concerned, low concentrations 3-5 μ moles/L were recorded at the surface water of the Persian Gulf (Fig. 7) compared with higher values>20 μ moles/L for the Gulf of Oman, and the deeper water reflected higher values exceeding 26 μ moles/L.

Fig 7. Map of surface silicate (μ moles/l) within the Persian Gulf

Nutrient rich waters from the Gulf of Oman penetrate into the southern Persian Gulf through the Strait of Hormuz at 10-50 m depth. Sources of this nutrient rich water are the layers just below the thermocline in the Gulf of Oman. According to Grasshoff (1965) special attention should be given to the dynamics of silicate circulation and he considered that silicate was the limiting nutrient. Our results do not confirm this; the atomic ratio of the elements P:N:Si was estimated as 1:2.2:11.1 and 1:2.7:11.8 for the surface water of the Persian Gulf and the Gulf of Oman, respectively, reflecting nitrogen was the limiting factor for the Persian Gulf. This finding is supported by findings of Brewere and Dyrssen (1985) and Emara, (1985). Inorganic nitrogen/phosphate ratio were lower than the standard Redfield ratio of 15/1 (by atoms) suggesting N was more important than phosphate for phytoplankton growth as a limiting nutrient, and that the effects of denitrification dominated the effects of N-fixation (Morrison et al. 1998). The occurrence of a permanent thermocline and high primary production in the euphotic zone resulted in the depletion of nutrient above the thermocline. Nitrate is generally present at very low levels, but some phosphate was always available in the euphotic zone which indicated NO₃ might have been the limiting nutrient for primary production (Sen Gupta et al, 1976).

3.1 Shallow Oxygen minimum and maximum nutrients

Oxygen consumption within the Persian Gulf is not large, the short residence time of water and the deep outflow of nutrients results in little oxygen depletion or nutrient building and thus, the lowest oxygen value found within the Persian Gulf was 2.72 ml/l corresponding to 57.5% of saturation. In the Gulf of Oman (Table 3), the shallow oxygen minimum (0.23-1.30 ml/l corresponding to 4.2-25.7% saturation) lied at a depth of 140-200 m and at σt values (25.51-26.07), exhibiting high concentrations of nutrients and moderate values of organic and inorganic carbon content.

The relationship between nutrient salts and dissolved oxygen for the whole column from the surface down to 400 m depth showed significant negative correlations, revealing that the concentrations of PO₄, NO₃ and SiO₃ increased by decreasing the values of oxygen according to the following equations:

\[
\text{PO}_4 \text{ concentration} = 1.57 - 0.20 \text{O}_2 \quad r = -0.52, \quad P< 0.001
\]

\[
\text{NO}_3 \text{ concentration} = 10.5 - 2.25 \text{O}_2 \quad r = -0.62, \quad P< 0.001
\]

\[
\text{SiO}_3 \text{ concentration} = 19.3 - 3.59 \text{O}_2 \quad r = -0.77, \quad P< 0.01
\]

According to Richards (1965), below the photosynthetic zone, in situ processes such as the oxidation of organic matter, tend to reduce the oxygen content. In tropical N. Pacific, where the organic content is high and/or the water are warmer (thus speeding up the rates of oxidation), the decrease could be as much as 5 ml/l per 100 m and, where it is lower and the water colder as in the
Antarctic Convergence, the decrease could even be less than 1 ml/l per 100 m. In the present study, the decrease of oxygen was found to be 3.5-4.8 ml/l per 100 m reflecting nearly similar conditions to the tropical N. Pacific. This decrease in oxygen was equivalent to the oxidation of approximately 1.4-1.8 mg/l, using an oxidative ratio of 2.6:1 (O:C) by atoms (Redfield et al., 1963).

### 3.2 Apparent oxygen utilization (AOU), water density $\sigma_t$, salinity- Nutrients relationships

Redfield et al. (1963) has used the AOU to calculate the amount of NO$_3$ and PO$_4$ regenerated in bodies of water which have left the surface and sunk below the euphotic zone. The relationship AOU-Nutrients for the Gulf of Oman showed significant negative correlation indicating that with decreasing the values of AOU, the concentration of PO$_4$ ($r=-0.59$), NO$_3$ ($r=-0.66$) and SiO$_3$ ($r=-0.62$) increased.

The estimated atomic ratio of the elements were as follows:

\[
\text{AOU} : \text{P} : \text{N} : \text{Si} \\
183 : 1 : 2.9 : 12.7 \quad \text{Southern Persian Gulf} \\
183 : 1 : 4.9 : 10.9 \quad \text{Gulf of Oman}
\]

This indicated that nitrogen was the limiting nutrient for both areas; in addition, AOU and Si were lower by 34% and 15-27% than the theoretical ratio of Richards (1965).

The waters of the oceans are chemically identifiable on the basis of their silicate to nitrate and, even more spectacularly their silicate/phosphate ratios (Table 4).

<table>
<thead>
<tr>
<th>Oceans</th>
<th>Silicate/ phosphate</th>
<th>Silicate/ Nitrate</th>
<th>Nitrate/ Phosphate</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.E. Pacific</td>
<td>55-65</td>
<td>3-5</td>
<td>13-14</td>
</tr>
<tr>
<td>Equatorial Indian</td>
<td>40-50</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>N. Atlantic</td>
<td>20-40</td>
<td>1.2</td>
<td>12-16</td>
</tr>
<tr>
<td>Present study</td>
<td>15.4</td>
<td>2</td>
<td>7.8</td>
</tr>
<tr>
<td>Gulf of Oman</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Comparing our data (depths 200-400 m) with those from other regions, it is obvious that the ratios for all parameters obtained in the present study were lower than those of other water bodies except for SiO$_3$/NO$_3$ which showed comparable results.

On the other hand, the effect of salinity on the distribution of nutrient, organic and inorganic carbon contents did not reflect any significant relationship except for silicate which showed an increase in concentration with decreasing values of surface salinity in the Persian Gulf waters (Fig. 8a) according to the following equation:

\[
\text{Silicate concentration} = 19.65-0.385 \text{ S‰} \\
r=-0.645, p <0.01
\]

![Fig 8a. Relationship between Salinity (‰) and silicate (μ moles/l) in Southern Gulf and Gulf of Oman](image1)

![Fig 8b. Relationship between $\sigma_t$ and phosphate (μ moles/l) in Southern Gulf and Gulf of Oman](image2)
On the other hand, the present study showed the presence of significant correlations between σt and Nutrients for both areas, except that of σt-PO4 for the Gulf of Oman. The PO4-σt, NO3-σt and SiO3-σt plots (Figs. 8a, b and c) showed a marked break at entrance of the Persian Gulf in the Strait of Hormuz and thereafter a linear regression equation was estimated. Rajendran et al. (1980) reported that water density (σt) and Nutrients relationship, in particular silicate, was useful for the identification of water masses in the Indian Ocean.

3.3 Organic and inorganic carbon contents

Surface distribution of total organic carbon TOC (2.1-14.6 mean 6.37±3.7 mg/l) showed nearly comparable values in both study areas (Figs. 9, 10), revealing higher surface concentration for the Gulf of Oman than the deeper water. In addition, the distribution showed an increase in concentration from the southern part of the Persian Gulf towards the Strait of Hormuz with an estimated rate of 2.5 mg/l per 100 km (Fig. 9).

Reported values of TOC (Emara, 1998) for the United Arab Emirates (UAE) and Qatar of the Persian Gulf water during April 1986 were found to be (0.8-3.9) and (0.5-3.6) mg/l respectively, revealing higher concentration at UAE than that of Qatar for both surface and bottom water. Surface distribution of TOC (Fig. 10) showed higher concentration at the coastal area of UAE and the values decrease in a seaward direction.

In the Gulf of Oman, the offshore stations F3 and F4 showed higher concentrations of TOC exceeding 14.6 mg/l which could be attributed to upwelling process in this area.

Inorganic carbon contents (Fig. 11) showed also similar trend revealing high concentrations (22.8-26.6 mg/l) in this area with a decreasing order towards both, the southern part of the Gulf of Oman and the Strain of Hormuz. The offshore stations of UAE in the Persian Gulf showed high IC content exceeding 24 mg/l.

At subsurface levels, (Fig. 12), IC showed higher
levels (25-35 mg/L) in the outflowing water from the Persian Gulf to the Gulf of Oman at a depth of 75 m. Previous study conducted by Emara (1998) showed variations for IC from 22 to 26 mg/l with similar values at the surface and bottom water of the Persian Gulf.

On an average scale, the concentrations of total organic carbon TOC (7.4±4.2 mg/L), inorganic carbon IC (19.05±8.7 mg/l) and total carbon contents TC (26.5±12.5 mg/L) of the Persian Gulf were higher than that of the Gulf of Oman by 0.9, 4.03 and 5 mg/L for TOC, IC and TC, respectively. The ratios of TOC/TC and IC/TC were found to be 28%, 72% for the Persian Gulf and 30%, 70% for the Gulf of Oman, respectively.

Physical factors (S‰ and $\delta^{18}O$) showed insignificant relationship with organic and inorganic carbon contents except that of $\sigma$-IC which showed significant relationship for the Persian Gulf (Fig. 13) and the relation is given by the equation as follows:

\[ \text{IC Concentration} = 129.8 - 3.9 \sigma \quad r = -0.47, \quad P<0.05. \]

Fig 11. Map of surface inorganic carbon contents IC (mg/l) within the Persian Gulf

Fig 12. Vertical distribution of inorganic carbon contents IC (mg/l) at the offshore stations in the Persian Gulf waters and the Gulf of Oman

Fig 13. Vertical profile of salinity (‰), oxygen (ml/l), nitrate (μ mols/l) and partial pressure of carbon dioxide (μ atm) station (F4) in the Gulf of Oman

3.4 Partial pressure of carbon dioxide $\text{PCO}_2$

Distribution of $\text{PCO}_2$ in both study areas showed the surface values ranged from 190 to 347 μ atm and from 68 to 347 μ atm for the Persian Gulf and the Gulf of Oman, respectively. Maximum $\text{PCO}_2$ was detected at the intermediate depths 200-300 m where values >1047 μ atm occurred in the Gulf of Oman within the Oxygen minimum layer (Fig. 14). This is supported by the studies of Ivanekov (1964) in the Indian Ocean. Anderson and Dyrssen (1994) reported that the depth profile of specific alkalinity showed low values below the euphotic zone due to decomposition of organic carbon. Dissolved inorganic carbon (DIC) calculated from alkalinity and pH, showed almost perfect correlation with inorganic carbon determined by organic carbon analyzer. The relationship is given by the equation:

\[ \text{IC Concentration} = -0.064 + 0.8 \text{DIC} \quad r = 0.90, \quad P<0.001 \]
The relationship $\sigma$–PCO$_2$ did not show any significant correlation for both areas, but PCO$_2$ revealed good relation with dissolved oxygen and water temperature for the Gulf of Oman; These relationships are represented by the following equations indicating that PCO$_2$ increases correlated with decreasing both dissolved oxygen and water temperature:

\[
\text{PCO}_2 \text{ concentration} = 496.2 - 57.3 \text{ O}_2 \quad r = -0.43, P<0.05 \\
\text{PCO}_2 \text{ concentration} = 1395 - 48.8 \text{ Temp. (°C)} \\
r = -0.52, \ P<0.02
\]

3.5 Oxidation of organic matter

In oxygenated water, the normal oxidation of organic matter is represented by the following equation (Richards, 1965):

\[
(\text{CH}_2\text{O})_{106} (\text{NH}_3)_{16} \text{ H}_3\text{PO}_4 + 138 \text{ O}_2 \rightarrow 106 \text{ CO}_2 + 122 \text{ H}_2\text{O} + 16 \text{ HNO}_3 + \text{ H}_3\text{PO}_4
\]

This equation enabled us to calculate the amount of oxygen necessary for complete oxidation of organic matter in the Persian Gulf, Gulf of Oman and within the oxygen minimum layer. Accordingly, the amount of oxygen present after complete oxidation of organic matter (Table 5 was found to be 26%, 29% and 4% for the Persian Gulf water, Gulf of Oman and within the layer of minimum O$_2$. The average % saturation of oxygen within the layer of minimum oxygen layer (excluding Station No. G3) was found to be 8.6% (Table 2).

<table>
<thead>
<tr>
<th>Item</th>
<th>Organic carbon (mg/l)</th>
<th>Organic matter (mg/l)</th>
<th>O$_2$ present (mg/l)</th>
<th>O$_2$ necessary for oxidation of O.M. (mg/l)</th>
<th>Original O$_2$ mg/l</th>
<th>O$_2$ present after oxidation of V.M. mg/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>Persian Gulf</td>
<td>7.40</td>
<td>13.32</td>
<td>5.84</td>
<td>16.57</td>
<td>22.41</td>
<td>26.0%</td>
</tr>
<tr>
<td>Gulf of Oman</td>
<td>6.20</td>
<td>11.16</td>
<td>4.10</td>
<td>13.88</td>
<td>17.98</td>
<td>29.0%</td>
</tr>
<tr>
<td>O$_2$ minimum</td>
<td>7.17</td>
<td>12.91</td>
<td>0.63</td>
<td>16.06</td>
<td>16.69</td>
<td>4.0%</td>
</tr>
</tbody>
</table>

Table 6- Nutrients salts, organic and inorganic carbon budget (T. yr$^{-1}$) in the Persian Gulf and the Gulf of Oman

<table>
<thead>
<tr>
<th>Type of waters</th>
<th>Volume of water (km$^3$ y$^{-1}$)</th>
<th>Concentrations (μ moles/l)</th>
<th>PO$_4$</th>
<th>NO$_3$</th>
<th>SiO$_3$</th>
<th>TOC</th>
<th>IC (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflowing water</td>
<td>3365</td>
<td></td>
<td>0.76</td>
<td>0.77</td>
<td>6.45</td>
<td>7.58</td>
<td>14.87</td>
</tr>
<tr>
<td>Outflowing water</td>
<td>3110</td>
<td></td>
<td>0.38</td>
<td>0.37</td>
<td>4.37</td>
<td>7.11</td>
<td>14.50</td>
</tr>
<tr>
<td>Net gain</td>
<td>255</td>
<td></td>
<td>0.38</td>
<td>0.40</td>
<td>2.08</td>
<td>0.47</td>
<td>0.37</td>
</tr>
<tr>
<td>Amount transported</td>
<td>42608</td>
<td></td>
<td>20165</td>
<td>227909</td>
<td>3395×10$^5$</td>
<td>4943×10$^3$</td>
<td></td>
</tr>
</tbody>
</table>

3.6 Nutrient salts, organic and inorganic carbon budget

The volume of inflowing and outflowing water throughout the Strait of Hormuz was given by Hartman et al. (1971) as 3365 and 3110 km$^3$ yr$^{-1}$, respectively. The average concentrations of Nutrient, organic and inorganic carbon contents are given in Table 6. These data make it possible to evaluate a first order nutrients, organic and inorganic carbon budget for the Persian Gulf. Respective values for phosphate, nitrate, silicate, organic and inorganic carbon content (42.6, 20.2, 227.9, 3395 and 4943 10$^3$.T/yr) reflect a net gain to the Persian Gulf water.
4. Acknowledgment

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References

