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Red Sea budgets of salinity, nutrients and carbon calculated in the Strait of Bab-El-Mandab during the summer and winter seasons

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ABSTRACT

Annual budgets of salinity, total inorganic carbon, total alkalinity, nitrates, phosphates and silicates are estimated through the Strait of Bab-el-Mandab. Two different methods that decouple the summer and winter periods are used.

A direct method uses the concentrations of these parameters, the velocity of currents, and the area of a cross section in the strait. The calculations for the fluxes and budgets during the summer period were based on data collected during two cruises made in July and September 1982 (MEROU 1 and 2).

An indirect method, based upon matrix inversion and the assumption of a steady-state balance of several properties over a period of one year, is used to calculate the winter and summer budgets of water, salinity, total inorganic carbon, total alkalinity, nitrates and phosphates.

The summer budgets obtained by the two different methods are positive for all the properties—a gain for the Red Sea—and are of the same order of magnitude for both methods. For the winter period, budgets are positive for total inorganic carbon and total alkalinity and negative for salinity and nutrients. This gain of total inorganic carbon and total alkalinity through the Strait of Bab-el-Mandab can be quantitatively explained by exchanges of CO_2 with the atmosphere and the processes of sedimentation in the basin.

1. Introduction

The study of the budgets for carbon and nutrients in the oceans needs information about both internal and external exchanges. The internal exchanges are due to dynamical transport (advective fluxes and mixing) and to biochemical processes (dissolution and consumption). The external exchanges are the gas fluxes (carbon dioxide, oxygen, nitrogen) through the air–sea interface, the losses by sedimentation and calcification and the exchanges at the domain boundaries (ocean–ocean) or the river inflows. For the Red Sea the Strait of Bal-el-Mandab is the hydrological boundary where most of the external exchanges for the basin take place. In this study we propose two methodologies for the quantification of the salinity, carbon, alkalinity

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and nutrients budgets at the Strait of Bal-el-Mandab, through which the Red Sea and the Gulf of Aden communicate.

Most of the determinations of carbon and nutrient fluxes in the strait reported in the literature (Grasshoff, 1969; Morcos, 1970) are based on winter data only. However, on the basis of data collected in summer 1982 in the Red Sea, the Strait of Bab-el-Mandab and the Gulf of Aden (Beauverger *et al.*, 1984), Poisson *et al.* (1984) suggested that, in order to calculate reliable budgets for salt and chemical species in the Red Sea, it is necessary to take into account the seasonal variation between summer and winter of the exchanges in the strait. Indeed these authors have pointed out that under the influence of the monsoon the current system in the strait and the concentrations of some properties in the inflowing properties intermediate water vary considerably between winter and summer. The aim of this paper is to evaluate the mean fluxes through the Strait of Bab-el-Mandab during the summer and the winter seasons for sea salt, total inorganic carbon (TCO_2), total alkalinity (TA), nitrates (NO_3) and phosphates (PO_4), and to infer the annual budgets for these properties.

2. Method

The reversal of wind in the southern part of the Red Sea between summer and winter implies a modification of the currents in the Strait of Bab-el-Mandab (Patzert, 1974a). More specifically, the two-layer system of winter (surface layer of low salinity inflowing into the Red Sea, and bottom layer of high salinity outflowing from the basin) is replaced in summer by a three layer system (outflowing surface and bottom layers and inflowing intermediate layer).

The chemical data from GEOSECS (Weiss *et al.*, 1983), together with the evaluations of water fluxes inflowing and outflowing from the basin given by Morcos (1984) have been considered here as representative of the winter system.

In summer, the NNE winds induce an upwelling along the northern coast of the Gulf of Aden, intensifying the primary production in surface water and increasing the nutrients' content in the intermediate layer of the gulf. As the chemical and the current data are almost nonexistent for this period of the year, two cruises covering the summer season were conducted: MEROU 1 in the beginning of July and MEROU 2 in the beginning of October 1982. All the stations located in the Gulf of Aden and the Strait of Bab-el-Mandab (Fig. 1) occupied during MEROU 1 were reoccupied during the MEROU 2 cruise. The velocity of the currents in the strait was measured at stations M1 and M2 (Fig. 1) from July to October and their variations due to the tides were observed during a 27-hour station (Maillard and Soliman, 1986). A bathymetric profile of the strait was recorded between Perim Island and the west coast of the strait (Fig. 2). The small (4 km wide) strait on the eastern side is not more than 26 m deep (Morcos, 1970) and, consequently, has not been taken into account here, its influence on the overall fluxes being small. Moreover it was forbidden to work in this area.

The following parameters were sampled at all the stations with either a rosette of 12

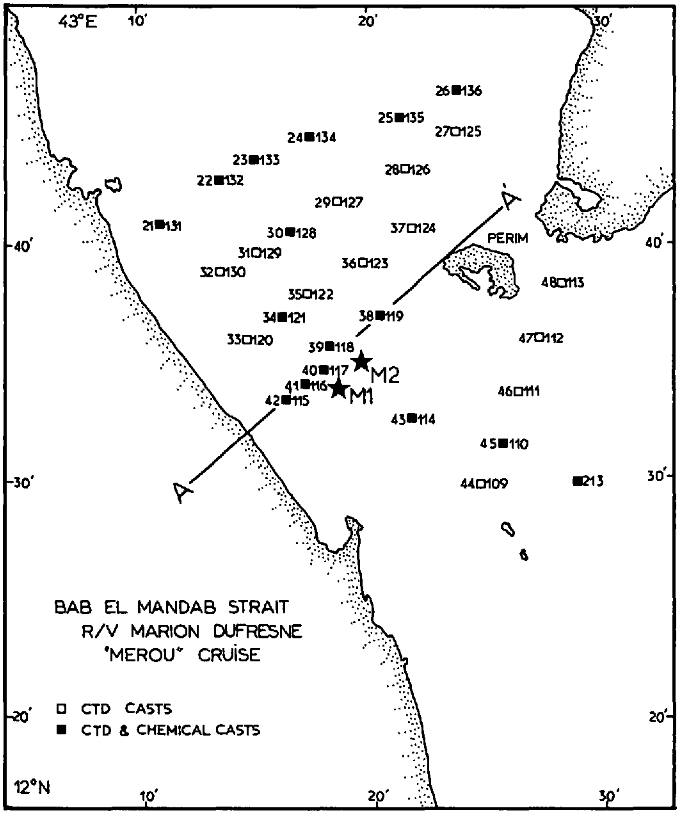

Figure 1. Stations occupied in the vicinity of the Bab-el-Mandab Strait during the MEROU-1 and MEROU-2 cruises. Stations 21 to 48 were occupied during the period from 30 June to 2 July 1982, while the stations 109 to 139 were retrieved in the period from 27 September to 1 October 1982.

liter Niskin bottles connected to a C.T.D. probe, or with 6 liter Niskin bottles fitted with reversing thermometers: TCO_2 and TA were measured by the potentiometric method developed by Dyrssen (1965) and modified by Bradshaw *et al.* (1981); salinity was obtained by a "Guildline autosal 8400" salinometer and nutrients by a Technicon autoanalyser II. All these data are presented in cruise reports (Beauverger *et al.*, 1984a, b; Maillard and Soliman, 1985).

3. Results

The summer budgets in the strait have been determined in two different ways: (1) a direct evaluation using the chemical data and the current velocity measured during the MEROU cruises for the section in the strait near Perim Island; and (2) an inverse calculation to establish the summer and winter budgets from an annual budget model of the fluxes in the strait.

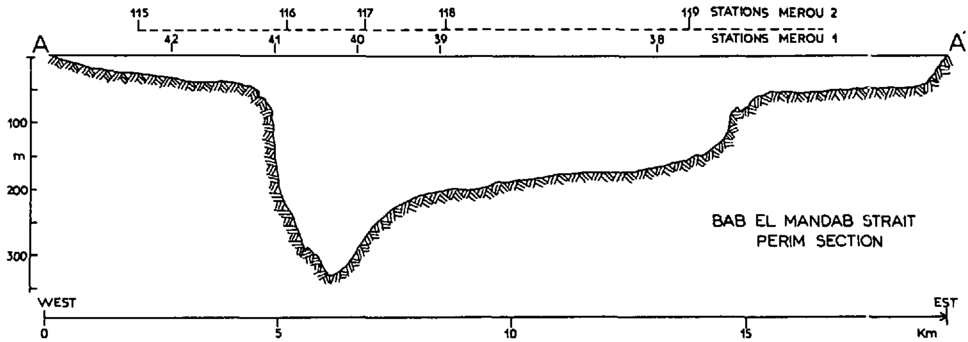

Figure 2. Sea bottom bathymetry obtained during a crossing of the strait at the height of Perim Island (AA′ on Fig. 1).

a. Direct determination of the summer budgets. The data of Maillard and Soliman (1986) show that the summer current system consists of three layers and that the depths of their interfaces vary from July to September. It is assumed in this calculation that the flux of water is the product of the area of the cross section of the water core multiplied by the corresponding mean velocity of the current. Due to technical problems, only the velocity of the intermediate current inflowing into the basin was recorded. Using the positive component of water flux through the Strait of Bab-el-Mandab proposed by Morcos (1959, 1984) the mean velocity of the outflowing current was calculated, considering this value as the mean velocity of both the surface and the bottom layers. The resulting mean velocities of the three currents in the strait and the corresponding water fluxes from the beginning of July to the end of September were calculated for 10 day periods (Table 1).

The budgets of the different parameters (p), were calculated using the following equations,

$$\sum_i r(i)q(p,i)\phi(i) = B(p) \tag{1}$$

where

i is the relevant water layer, $r(i)$ is the absolute density of seawater, $q(p, i)$ is the mean concentration of the constituent p in the layer i, and $\phi(i)$ is the water flux in the layer i, calculated by

$$\phi(i) = A(i)v(i) \tag{2}$$

where $A(i)$ is the area of the cross section in the strait corresponding to the water layer i (Table 1) and $v(i)$ is the mean velocity of the water of the layer i at this section in the strait; $B(p)$ is the loss or the gain for the Red Sea in the parameter p through the Strait of Bab-el-Mandab.

The mean concentrations of the three layers have been calculated by dividing the

Table 1. Ten-day averaged depth of the interfaces between surface and intermediate layers (Z_1) and between intermediate and bottom layers (Z_2). $A(i)$ are the averaged surfaces of the cross sections of the three layers. v_1 (Φ_1), v_2 (Φ_2) and v_3 (ϕ_3) are the mean velocity (mean flux) of the surface, intermediate and bottom layers. Positive value is a gain for the Red Sea.

Period	7/9–7/16	7/15–7/25	7/25–8/4	8/4–8/14	8/14–8/24	8/24–9/3	9/3–9/13	9/13–9/23
Z_1 (m)	40	41	45	45	45	47	43	46
Z_2 (m)	190	197	222	223	222	236	221	228
A_1 ($10^6 m^2$)	0.713	0.727	0.784	0.784	0.784	0.813	0.756	0.799
A_2 ($10^6 m^2$)	1.451	1.470	1.499	1.501	1.499	1.501	1.524	1.497
A_3 ($10^6 m^2$)	0.253	0.220	0.134	0.132	0.134	0.103	0.137	0.121
v_2 ($m.s^{-1}$)	0.172	0.170	0.240	0.226	0.213	0.206	0.138	0.127
$v_1 = v_3$ ($m.s^{-1}$)	−0.232	−0.237	−0.355	−0.322	−0.300	−0.286	−0.179	−0.152
Φ_1 ($10^6 m^3 s^{-1}$)	−0.165	−0.172	−0.278	−0.252	−0.235	−0.233	−0.135	−0.121
Φ_2 ($10^6 m^3 s^{-1}$)	0.249	0.250	0.360	0.339	0.319	0.309	0.210	0.190
Φ_3 ($10^6 m^3 s^{-1}$)	−0.059	−0.052	−0.048	−0.043	−0.040	−0.029	−0.025	−0.018

total section of the strait in rectangles and trapezoids (Souvermezoglou, 1985) and using the strait cross-section data of the two MEROU cruises (Table 2). The fluxes of the different parameters and the corresponding budgets are gathered in Table 3 for the beginning of July and the end of September 1982. The budgets for the ten-day periods of these three months reported in Table 4 were calculated using the area of each layer given in Table 1, and the mean concentrations for each period estimated by a linear interpolation between July and September 1982 (Table 2).

The gain in the Red Sea of the various constituents by the intermediate layer exceeds its loss by the surface and the bottom layers. The budgets of salinity, TCO_2, TA and nutrients are positive—a gain for the Red Sea—during all the periods from July 9 to September 23 with a maximum supply at the end of August (Table 4). The increased input in Total Inorganic Carbon and nutrients is correlated to the subsurface inflow of nutrient-rich waters from the Gulf of Aden when the establishment of the summer current regime takes place. Furthermore, the positive component of the water flux through the strait is also maximal (Morcos, 1959; 1984; Bogdanova, 1974) in late

Table 2. Averaged concentrations of the measured parameters in the three layers at the Strait of Bab-el-Mandab measured during the two MEROU cruises.

	Surface		Bottom		Intermediate	
Period	6/30–7/2	9/27–10/1	6/30–7/2	9/27–10/1	6/30–7/2	9/27–10/1
Salinity	36.55	36.57	38.85	38.57	36.28	35.92
σ_t	22.49	21.72	27.01	27.50	25.03	25.76
TA ($meq.kg^{-1}$)	2.39	2.40	2.43	2.40	2.35	2.35
TCO_2 ($mmol.kg^{-1}$)	1.97	1.99	2.12	2.21	2.11	2.21
NO_3 ($\mu gat.l^{-1}$)	0.4	0.9	13.4	26.3	15.7	23.4
PO_4 ($\mu gat.l^{-1}$)	0.2	0.3	1.0	1.9	1.4	1.9
SiO_4 ($\mu gat.l^{-1}$)	0.3	1.7	7.9	19.1	9.3	17.9

Table 3. Surface, intermediate, bottom fluxes and budgets of properties in the Strait of Bab-el-Mandab during the two MEROU cruises periods. Positive value is a gain for the Red Sea.

	Surface		Bottom		Intermediate		Budget	
Period	6/30–7/2	9/27–10/1	6/30–7/2	9/27–10/1	6/30–7/2	9/27–10/1	6/30–7/2	9/27–10/1
Salt ($10^9 g.s^{-1}$)	−6.18	−4.54	−2.34	−0.73	+9.28	+7.01	+0.76	+1.74
TA ($10^9 meq.s^{-1}$)	−0.403	−0.298	−0.147	−0.045	+0.600	+0.459	+0.050	+0.116
TCO_2 ($10^9 mmol.s^{-1}$)	−0.334	−0.247	−0.128	−0.042	+0.539	+0.431	+0.078	+0.142
NO_3 ($10^9 \mu gat.s^{-1}$)	−0.066	−0.104	−0.786	−0.483	+3.911	+4.452	+3.059	+3.865
PO_4 ($10^9 \mu gat.s^{-1}$)	−0.030	−0.034	−0.058	−0.035	+0.342	+0.359	+0.254	+0.290
SiO_4 ($10^9 \mu gat.s^{-1}$)	−0.051	−0.204	−0.462	−0.351	+2.328	+3.411	+1.815	+2.856

summer. The supply was minimal during the period of MEROU 1 cruise (9 to 16 July). During this period, summer circulation is not yet well established.

The major uncertainty in this calculation of the budget is in the water fluxes determinations, since only the velocity of the intermediate layer was recorded. Therefore, we have tested our direct computation by using the mean velocity given by Patzert (1974b) for the surface layer, which was derived from the ship's drifts. The Patzert estimate for flux of water in the bottom layer is 0.11 10^6 m^3/s in July. This is about twice our estimate of 0.059 10^6 m^3/s. Because the loss by the bottom layer is doubled, the corresponding budgets (Table 5) decrease for all the parameters, but they remain positive.

b. Indirect determination of summer and winter budgets. Following the classical budget calculation in a strait for water and salinity and to confirm the summer budgets computed with the direct method, we have constructed an indirect method where the summer and the winter budgets are calculated using the hypothesis of the annual steady-state balance for the same parameters (salt, TCO_2, TA, NO_3 and PO_4). The durations of summer and winter have been taken equal to five and seven months respectively. The system of currents in the strait in summer keeps the same distribution as in the direct method of determination and consists of three layers, with the interfaces at 40 and 200 m. In winter, the two-layer system, with the interface at 100 m, is divided for the computation in four layers, in the same manner as the three

Table 4. Averaged ten-day budgets in the Strait of Bal-el-Mandab during the summer period calculated using the parameters measured during the MEROU cruises.

Period	7/9–7/16	7/15–7/25	7/25–8/4	8/4–8/14	8/14–8/24	8/24–9/3	9/3–9/13	9/13–9/23
Salt ($10^9 g.s^{-1}$)	+0.758	+0.765	+1.049	+1.442	+1.425	+1.566	+1.731	+1.738
TA ($10^9 meq.s^{-1}$)	+0.050	+0.051	+0.068	+0.094	+0.118	+0.103	+0.115	+0.116
TCO_2 ($10^9 mmol.s^{-1}$)	+0.078	+0.082	+0.121	+0.143	+0.143	+0.154	+0.143	+0.142
NO_3 ($10^9 \mu gat.s^{-1}$)	+3.06	+3.32	+5.47	+5.49	+5.43	+5.72	+3.99	+3.86
PO_4 ($10^9 \mu gat.s^{-1}$)	+0.25	+0.27	+0.43	+0.42	+0.42	+0.43	+0.30	+0.29
SiO_4 ($10^9 \mu gat.s^{-1}$)	+1.81	+2.06	+3.52	+3.65	+3.72	+4.02	+2.88	+2.86

Table 5. Surface, intermediate, bottom fluxes and budgets of properties in the Strait of Bab-el-Mandab during the 6/30–7/02 period using the mean speed of surface current determined by Patzert (1974b). Positive value is a gain for the Red Sea.

	Surface	Bottom	Intermediate	Budget
Salt ($10^9 g.s^{-1}$)	−4.26	−4.44	+9.28	+0.58
TA ($10^9 meq.s^{-1}$)	−0.278	−0.278	+0.600	+0.044
TCO_2 ($10^9 mmol.s^{-1}$)	−0.230	−0.242	+0.539	+0.067
NO_3 ($10^9 \mu gat.s^{-1}$)	−0.046	−1.490	+3.911	+2.375
PO_4 ($10^9 \mu gat.s^{-1}$)	−0.021	−0.110	+0.342	+0.211
SiO_4 ($10^9 \mu gat.s^{-1}$)	−0.035	−0.876	+2.328	+1.417

layers system in summer, with interfaces at 40, 100 and 200 m (Fig. 3). To preserve the contrast between outflowing and inflowing properties, we have applied the indirect method to the data located on both sides of the strait (Table 6), collected during MEROU 2 cruise (summer data) and at GEOSECS stations 408 and 409 (winter data). In order to compare the data used in both methods, we have reported in Table 6 the summer data computed (used for the direct method) in the strait for the period 9/27 to 10/1, when the summer regime (three layers) is well-established.

The annual budget of the parameter p is given by the equation

$$\sum_{is} r(is)q(p, is)\phi(is)Ts + \sum_{iw} r(iw)q(p, iw)\phi(iw)Tw + B(p) = 0 \qquad (3)$$

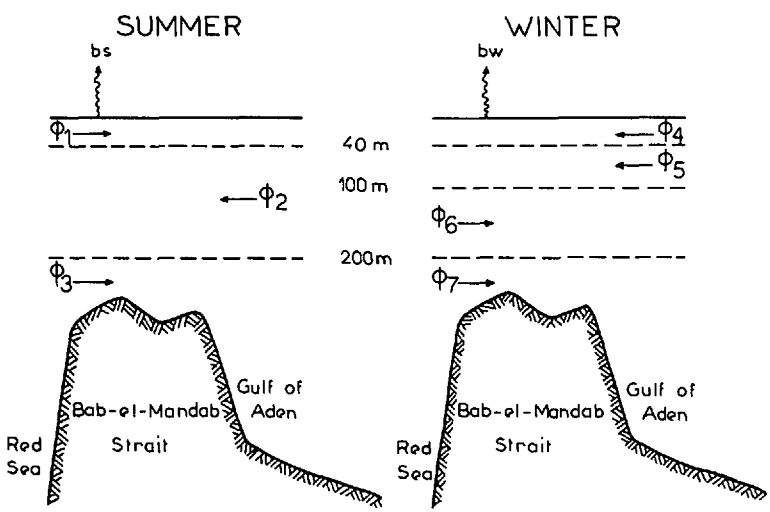

Figure 3. Discretization of the water column in the Strait of Bab-el-Mandab for summer (three layers) and winter (four layers) used in the indirect method. $\phi 1$, $\phi 2$, . . . , $\phi 7$ are the water fluxes of the layers. Water losses by evaporation in the Red Sea basin are represented by *bs* and *bw* (Eqs. 4 and 5).

Table 6. Averaged concentrations of the measured parameters, in the three layers of summer (MEROU 2) and the four layers of winter (GEOSECS) on both sides of the Strait of Bab-el-Mandab (used for the indirect method). For each parameter the upper line corresponds to the surface layer, the second line to the intermediate one, and the third and fourth lines to the bottom ones. For comparison the computed concentrations in the strait for the summer period used for the direct method are reported in the first column.

	Summer (MEROU 2)			Winter (GEOSECS)	
	Direct Method	Indirect Method		Indirect Method	
	Strait	Red Sea Out	Aden In	Red Sea Out	Aden In
	36.57	37.336			36.452
S	35.92		35.877		35.952
				40.274	
	38.57	40.520		40.520	
	21.72	23.25			23.97
σ_t	25.76		25.80		24.89
				24.39	
	27.50	28.48		28.39	
	2.40	2.391			2.350
TA($meq.kg^{-1}$)	2.35		2.337		2.325
				2.446	
	2.40	2.441		2.441	
	1.99	1.997			2.025
TCO_2($mmol.kg^{-1}$)	2.21		2.170		2.160
				2.170	
	2.21	2.188		2.210	
	0.9	2.00			3.00
NO_3($\mu gat.kg^{-1}$)	23.4		20.39		16.00
				14.60	
	26.3	16.69		18.00	
	0.3	0.37			0.37
PO_4($\mu gat.kg^{-1}$)	1.9		1.30		1.14
				1.06	
	1.9	1.21		1.14	

where is (or iw) is the number of the water layer in summer (or winter), Ts (or Tw) is the duration of the summer (or winter), $\phi(is)$ or $\phi(iw)$ is the water flux in the layer i in summer (or winter), $r(is)$ or $r(iw)$ is the mean absolute density of layer i in summer (or winter), $q(p, is)$ or $q(p, iw)$ is the average concentration of the constituent p in the layer i in summer or in winter, $B(p)$ is the annual residual term of parameter p; a positive $B(p)$ corresponds to a gain for the Red Sea and a negative one is a loss for the basin.

The steady-state equation for the water is divided in two seasonal balances (Fig. 3):

$$\sum_{is} r(is)\phi(is) = bs(m) \quad (4)$$

$$\sum_{iw} r(iw)\phi(iw) = bw(m) \quad (5)$$

where $bs(m)$ and $bw(m)$ are respectively the evaporation during summer and winter. Eqs. 3, 4 and 5 form a linear system which can be formulated in matrix form,

$$Ax = b \quad (6)$$

where the unknowns are $\phi(is)$, $\phi(iw)$ and $B(p)$. Eq. (3) characterizes the advective processes relative to the other effects included in the term $B(p)$, i.e. ocean-atmosphere exchanges, production and consumption, sedimentation, formation of corals, etc.

The values for evaporation found in the literature (e.g. Morcos, 1970) vary between 1.56 m/year (0.023 10^6 m^3/s) to 2.40 m/year (0.035 10^6 m^3/s). The evaporation terms in Eqs. (4) and (5) have been taken representative of summer and winter, respectively 0.035 10^6 m^3/s and 0.025 10^6 m^3/s.

Several constraints are imposed to the system (6): the values of the fluxes of water in the Strait of Bab-el-Mandab in summer must lie between the values of the fluxes deduced from the direct measurements of the velocity of currents made by Maillard and Soliman (1985) during the MEROU cruises. The ranges of these fluxes (in 10^6 m^3/s) are respectively

$0.10 \leq \phi 1 \leq 0.15$ for the surface current,

$0.15 \leq \phi 2 \leq 0.25$ for the intermediate current,

$0.00 \leq \phi 3 \leq 0.06$ for the deep current.

In winter the values of the fluxes of water in the strait must lie between the lower limit values of the fluxes proposed by Grasshoff (1969) and the higher ones determined by Siedler (1968). These fluxes (in 10^6 m^3/s) are $\phi 4$ from surface to 40 m, $\phi 5$ from 40 to 100 m, $\phi 6$ from 100 to 200 m and $\phi 7$ from 200 m to the bottom. The constraints are the following:

$$0.29 \leq \phi 4 + \phi 5 \leq 0.59$$

$$0.26 \leq \phi 6 + \phi 7 \leq 0.43$$

$$0.00 \leq \phi 5 \leq 0.50$$

$$0.00 \leq \phi 7 \leq 0.06$$

$$0.00 \leq \phi 6$$

$$\phi 5 \leq \phi 4$$

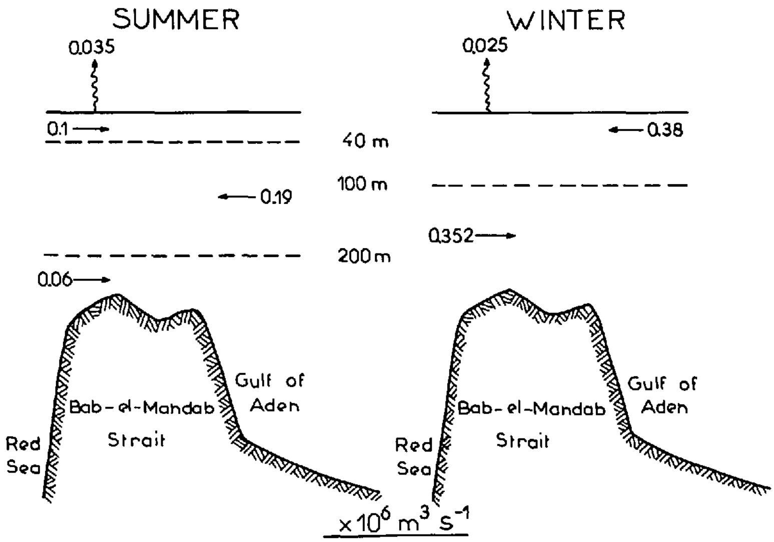

Figure 4. Water fluxes for the various layers through the Strait of Bab-el-Mandab for summer and winter seasons calculated by indirect method. Fluxes are in $10^6\ m^3 \cdot s^{-1}$

All of the constraints can be combined into a system of inequalities,

$$Gx \geq h. \tag{7}$$

In order to know the sensitivity of the method and deviations on solutions, a perturbation scheme has been applied on data (matrix A) and evaporation terms (vector **b**). The error imposed on data is of the order of the measurements precisions. Perturbation on evaporation has been taken equal to 10%. The solution of the system of Eqs. (6) and (7) is obtained by solving a least squares with a linear inequality constraint problem using the Algorithm developed by Lawson and Hanson (1974).

The solutions of water fluxes $\phi(is)$ and $\phi(iw)$ are presented in Figure 4; for the summer season, the model gives $-0.10\ 10^6\ m^3/s$ for the surface layer (minimum constraint), 0.19 (± 0.02) $10^6\ m^3/s$ for the intermediate layer and 0.06 $10^6\ m^3/s$ for the bottom layer (the corresponding experimental values are -0.121, 0.190 and -0.018 $10^6\ m^3/s$; Table 1, period 9/13–9/23). The fluxes obtained for the two layers in winter are 0.38 (± 0.01) $10^6\ m^3/s$ for the upper layer and -0.352 (± 0.005) $10^6\ m^3/s$ for the bottom layer. The model tends toward the maximum constraint for the outflowing water flux of the bottom layer, as well as the inflowing intermediate layer from the subsurface water of the Gulf of Aden. The intermediate fluxes are centered with regard to the minimum and maximum expected.

The budgets obtained with this method for the two seasonal regimes and annual sum are shown in Table 7. All the budgets of the chemical parameters are positive, a gain for the Red Sea, in summer. The winter budgets indicate a loss of salt, NO_3 and PO_4

Table 7. Seasonal (summer and winter) and annual budgets of properties deduced from the indirect method (positive value is a gain for the Red Sea).

		Summer	Winter	Annual budget
Salt	10^9 g.s^{-1}	0.74 (±0.09)	−0.40 (±0.06)	
	10^{15} g/period	9.76 (±1.18)	−7.34 (±0.90)	2.4 (±1.48)
TA	10^9 meq.s^{-1}	0.064 (±0.005)	0.04 (±0.01)	
	10^{15} meq/period	0.84 (±0.09)	0.77 (±0.14)	1.61 (±0.17)
TCO_2	10^9 mmol.s^{-1}	0.087 (±0.005)	0.042 (±0.008)	
	10^{15} mmol/period	1.147 (±0.09)	0.77 (±0.15)	1.92 (±0.17)
NO_3	10^9 μgat.s^{-1}	2.78 (±0.06)	−1.75 (±0.07)	
	10^{15} μgat/period	36.8 (±0.8)	−32.0 (±0.6)	4.79 (±1.)
PO_4	10^9 μgat.s^{-1}	0.144 (±0.005)	−0.091 (±0.003)	
	10^{15} μgat/period	1.90 (±0.10)	−1.66 (±0.15)	0.23 (±0.18)

and a gain in TCO_2 and TA. On an annual basis, the budget of salinity, NO_3, PO_4 are close to the zero balance; the TCO_2 and TA budgets are positive. The budgets calculated (Table 7) with the indirect method (which seeks to minimize the seasonal mass budget) are of the same sign and the same order of magnitude as those calculated with the direct method (Table 5) by using mean velocity given by Patzert (1974b); but they are smaller (by a factor of 2) than summer budgets calculated with current measurements during the period (9/27–10/1) when summer regime is well established (Table 8). Figure 5 presents a comparative sketch of budgets for salinity, TA, TCO_2, NO_3 and PO_4 using direct (two computations) and indirect (summer and winter) methods.

In order to understand the positive value for annual budget of carbon, one can compute the corresponding value in terms of sinks for the basin. We must consider both exchanges with the atmosphere and the sedimentation processes because these are the main processes occurring in concentration basins like the Red Sea. During the summer, we have measured partial pressure of CO_2 (pCO_2) in the sea and in the air (Beauverger *et al.*, 1984a). From data of TCO_2, TA, temperature of MEROU 2

Table 8. Comparison of summer budgets calculated by the two methods.

	Direct Method	Indirect Method
S (10^9g.s^{-1})	1.74	0.737 (±0.086)
TA (10^9meq.s^{-1})	0.12	0.064 (±0.005)
TCO_2 (10^9mmol.s^{-1})	0.14	0.087 (±0.005)
NO_3 ($10^9$$\mu$gat.s^{-1})	3.9	2.78 (±0.06)
PO_4 ($10^9$$\mu$gat.s^{-1})	0.29	0.144 (±0.005)

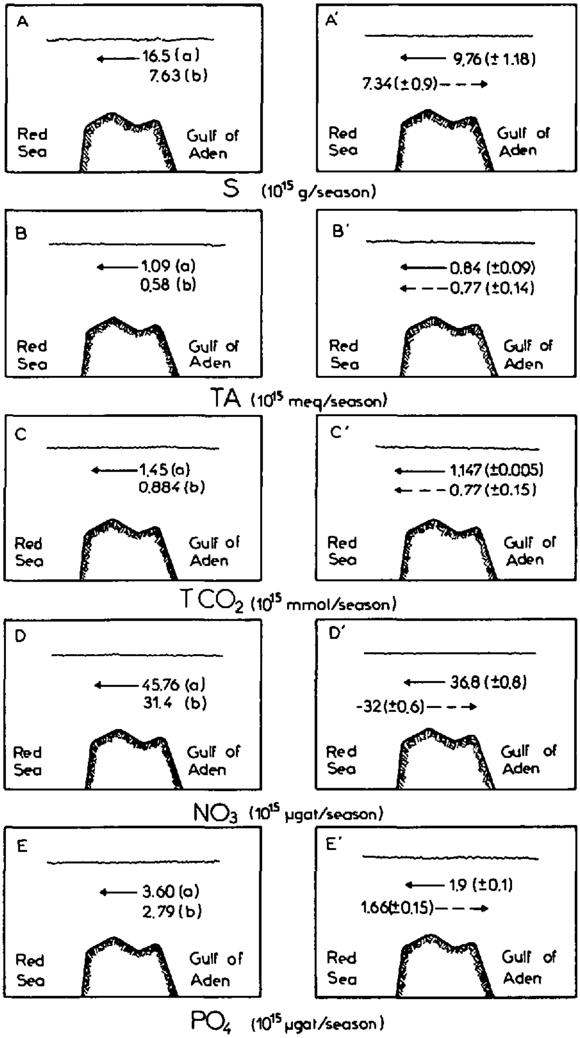

Figure 5. Budgets of salinity (A), total alkalinity (B), total inorganic carbon (C), nitrates (D) and phosphates (E); Units are given for each property below the picture. Results of *direct method* (on left): (a) = mean budgets of the two observations periods (see Table 3); (b) = summer budgets calculated by using mean velocities given by Patzert (1974b). Results of *indirect method* (on right) for summer (→) and winter (- - →).

(Beauverger *et al.*, 1984a) and GEOSECS (Weiss *et al.*, 1983) expeditions, one can compute pCO_2 in the sea. During both seasons, the gradient pCO_2(sea)–pCO_2(atm) is positive: the flux of CO_2 is directed from the sea to the atmosphere. This gradient corresponds to a flux of 0.4 (±0.1) 10^{15} mmol/year from the Red Sea to the atmosphere. This is not enough to compensate the budget, 1.92 (±0.17) 10^{15}

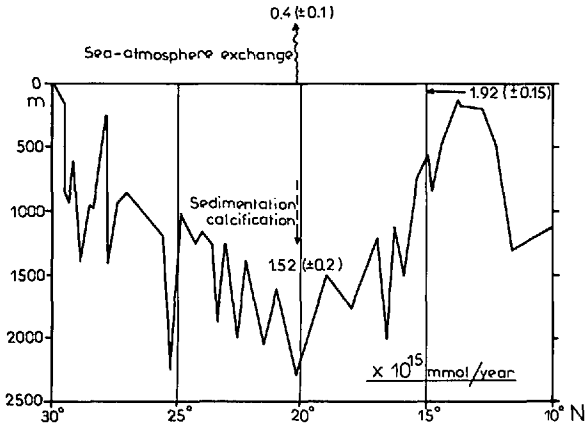

Figure 6. Red Sea TCO_2 annual fluxes (in 10^{15} mmol/year) calculated from indirect method (through the strait) and air-sea exchange evaluation. Sedimentation-calcification flux is deduced from previous estimations (see text).

mmol/year, computed with the indirect method (Table 7) but it reduces it to 1.52 (±0.2) 10^{15} mmol/year.

With this value, and assuming that proportion of sedimentation is a quarter of calcium carbonate ($CaCO_3$) flux and three quarters of organic material (Brun-Cottan, 1986), we can evaluate the losses of $CaCO_3$ necessary to balance the input of dissolved inorganic carbon at the strait. The Red Sea area is about 0.44 10^{12} m^2 (Morcos, 1970). One mole of $CaCO_3$ weighs almost exactly 100 g. The $CaCO_3$ sedimentation corresponding to 1.52 (±0.2) 10^{15} mmol/year is 8.6 (±1.1) mg · cm^{-2}/year in the Red Sea. This value is greater than the estimation of 0.3 to 2 mg · cm^{-2}/year proposed by Brun-Cottan (Beauverger *et al.*, 1984a), but these measurements did not include particles greater than 40 μm. Vertical flux of material is due to large but rare particles. Taking into account the mean proportion of particles greater than 40 μm in the open ocean (Brun-Cottan, 1986), these measurements must be multiplied by a factor of 2 to 4. Thus, the evaluation of 8.6 (±1.1) mg · cm^{-2}/year for the $CaCO_3$ sedimentation flux made above is in agreement with measurements. In order to compare this estimation, we have translated the computed value in terms of sedimentation rate. Given the molar density of $CaCO_3$ of 0.015 mole · cm^{-3}, we found a rate of 5.8 (±0.8) cm/1000 years. This result is three times larger than the rate of sedimentation, 2 cm/1000 years, proposed by Grasshoff (1969) for $CaCO_3$ in the Red Sea, and it is inside the range of rates of sedimentation of biogenic (calcareous ooze) sediments in the oceans, 0.3 to 6 cm/1000 years (Berger, 1974, cited by Lerman, 1979). It is important to notice that the Red Sea is not a very deep basin, below 500 m potential temperature is higher than 21.5°C, pH is higher than 8 almost everywhere for MEROU and GEOSECS expeditions, and that the lysocline does not exist (CO_3^{2-} *in* *situ* > CO_3^{2-} saturation). These points explain why carbonate sedimentation is relatively high (especially for the larger particles) or equivalently that the dissolution is not as active as in the open ocean. Thus, a loss of inorganic carbon of 1.52 (±0.2) 10^{15} mmol/year by sedimentation and calcification processes is reasonable with regard to the chemical environment in the Red Sea, and it could balance exchanges through the strait and with atmosphere (Fig. 6). This simple evaluation confirms our previous quantitative estimations (indirect method) of a positive annual budget of TCO_2, as for TA, through the Bab-el-Mandab Strait.

Moreover, we have only considered exchange processes for the atmosphere and sediment to improve the carbon budget. The positive, but small, budgets for salt and nutrients confirm the existence of other processes, as formation of corals, salt domes, or organic sedimentation, which must participate in the annual exchanges. The quantification of the coral formation in terms of carbon or salt losses is difficult, and is not the aim of this study. Quantitatively, it would reduce the rate of sedimentation that we assume here.

4. Conclusions

The direct method of the determination of the summer budgets for the chemical parameters, both nutrients and carbon, are based on direct chemical and current velocity measurements made in the strait at the beginning and at the end of the SSW monsoon period. The calculated mean values of the concentrations are not representative of the "true" mean concentrations, because of the spatial and temporal variability of the currents over the sill of the strait. The same complication results for the mean velocities of the various layers of water in the strait which were deduced from discrete measurements at several depths and at only two stations. Consequently we checked this method relative to an indirect method which is based on several parameters measured in summer during the MEROU cruises, as well as other data from the literature. Moreover, this second method has the advantage of being based also on annual steady-state budgets of all the studied parameters. Although the two methodologies are different, the budgets obtained have the same sign. The indirect method, which minimizes overall annual budgets, leads to summer budgets which are close to results computed by using mean summer velocities through the strait, whereas they are about half of the results deduced from specific summer (1982) current measurements.

Monthly budgets of phosphates in the Strait of Bab-el-Mandab have been proposed by Khimitsa and Bibik (1979). In September they found a phosphate budget of 0.3 10^9 μgat/s, which is very close to our results (Tables 4 and 8).

Naqvi *et al.* (1986) established an annual nitrate budget using the relationship between nitrates and phosphates (METEOR data from the south of the strait, Grasshoff, 1969) and the water budgets computed by Morcos (1970). They estimated an annual loss of nitrates of −0.74 10^{12} gN/year. This result, representative of the winter conditions (Morcos, 1970, page 157, uses the temperature, salinity and density characteristics of the winter season), is larger than our result, -32.0 (± 0.6) 10^{15} μgat/winter (or equivalently, -0.45 (± 0.01) 10^{12} gN/winter), obtained for NO_3 budget by using the indirect method. This negative winter budget is compensated by a gain of nitrates by the Red Sea in summer (Table 7).

This work clearly demonstrates that the influence of the reversal of the currents in the Strait of Bab-el-Mandeb and the variation of the concentrations of the nutrients and carbon species between winter and summer must be taken into account when estimating their annual budgets in the Red Sea. The budgets of nutrients are positive in summer and negative in winter, yielding an annual budget that is approximately null. The budgets of TA and TCO_2 are positive all the year round. This can be explained by the carbonate sedimentation and, to a small extent by the flux of CO_2 through the air-sea interface from the ocean to the atmosphere. Other processes like the formation of corals or salt domes, must participate in Red Sea TCO_2 budgets, but these sinks are difficult to quantify.

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