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Review

The role of the exchanges through the Strait of Gibraltar on the budget of elements in the Western Mediterranean Sea: consequences of human-induced modifications

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Abstract

The role of the Strait of Gibraltar on the exchanges of substances between Mediterranean Sea and the Atlantic Ocean is reviewed. The previous estimations have been recalculated by using a similar water flux and compared with the river and atmospheric inputs to the Western Mediterranean Sea. The man-induced changes in the dimensions of the Strait of Gibraltar increasing (planning the sill) or reducing of the cross-section by a total or partial dam are discussed. A total dam will control the sea-level rise in the Mediterranean Sea, but an annual increase of major nutrient concentrations of 1–2% could be expected, lower than the rate of increase of the river and atmospheric inputs in the Western Mediterranean Sea. The increase of the cross-section of the Strait by increasing the depth (planning) at the sill could compensate the increase of the external nutrient inputs.

Keywords: Nutrient; Carbon; Trace metals; Radionuclides; Eutrophication; Global climate change; Gibraltar strait; Western Mediterranean Sea

1. Introduction

The Mediterranean Sea is undergoing a rapid alteration under the combined pressure of climate change and human impact (Jeftič et al., 1992; Turley, 1999). The Strait of Gibraltar, the only significant link between the Mediterranean Sea and the world's oceans (14 km width and less than 300 m depth at the sill), appears as a point of control of these exchanges and the modification of the biogeochemistry and circulation of the Mediterranean Sea and the North Atlantic Ocean.

The basic circulation in the Strait of Gibraltar consists in an upper layer of warm, fresh surface Atlantic water (SAW) and North Atlantic central water (NACW) inflowing into the Mediterranean Sea, and an opposite deep current of colder, salty Mediterranean outflowing water (MOW). As the evaporation exceeds over the sum of precipitation and river discharges in the Mediterranean Sea, the Atlantic inflow slightly exceeds around 4–5% the outflow of Mediterranean water to balance the net loss (Bryden et al., 1994).

The waters exchanges through the Strait have an influence on the formation of deep water (Reid, 1979; Baringer and Price, 1999), the surface circulation in the Atlantic Ocean (Ozgokmen et al., 2001) and in the biogeochemistry of the entire Mediterranean basin (Minas and Minas, 1993). Substances with higher concentrations in deep waters (nutrient-profile) present net loss through the Strait, experiencing a dilution in the Mediterranean Sea. The inverse estuarine circulation of the whole basin determinates a negative budget for the nutrients at the Gibraltar Strait, importing nutrient-poor surface waters from the Atlantic Ocean and exporting relatively nutrient-rich deep waters (Coste et al., 1988; Gómez et al., 2000b). On other hand, substances with higher concentration in the surface waters of the Gulf of Cádiz such as several trace metals will be concentrated in an evaporative basin as the Mediterranean Sea (Elbaz-Poulichet et al., 2001a,b).

In a dynamic and heterogeneous environment as the Strait, the strong spatial and temporal variability should be taken into account in the estimation of the exchanges of compounds (Gómez et al., 2000a,b, 2001). For elements such as trace metals or radionuclides that are not expected to change their concentrations during the transit through the Strait, the inputs can be estimated as

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the product of water fluxes and the concentration of the element of interest in each layer or water mass (e.g., Elbaz-Poulichet et al., 2001a,b). However for substances such as nutrients or carbon, with heterogeneous spatial and temporal distributions and changes of concentration during the passage through the Strait in the upper Atlantic current (Gómez et al., 2000b; Santana-Casiano et al., 2002), the results can present higher variability. This is especially evident in the plankton biomass, which changes in both relative contribution of taxa and abundance by more than one order of magnitude along the Strait (Gómez et al., 2000a).

The Strait is contemplated as a place to regulate the man-induced global climate change. Johnson (1997) predicted a dire chain of events and proposes that a dam across the Strait of Gibraltar could control the global climate by means of a reduction the outflow of the MOW, maintaining a mild climate in Northern Europe and preventing ice sheet formation in Canada.

In order to evaluate the influence of the exchanges on the budget of elements in the North Atlantic and the Western Mediterranean Sea, we need to know in what quantity these materials are exchanged between both basins. This study revises the advances on the role of the Strait in the biogeochemistry of the Mediterranean Sea and the possible consequences of human manipulation of the present could do.

2. Description of the approaches

Cognetti (2000) reported that a vast array of data are now available concerning pollution and eutrophication in the Mediterranean basin, but the data are often poorly comparable. Recent literature concerning the estimation of exchanges through the Strait of Gibraltar is available (e.g., Parrilla et al., 2002) (Figs. 1 and 2). One of the differences between the estimations of substances exchanged through the Strait is the water flux or transport (unit as Sverdrup, $1\ \mathrm{Sv} = 10^6\ \mathrm{m}^3\,\mathrm{s}^{-1}$) used for computation, where Atlantic fluxes (input) are positive and Mediterranean fluxes (output) are negative by definition.

The transport used for the computation of the substances exchanges ranged from 0.69/−0.65 Sv (for inflow and outflow respectively) (used by Sarmiento et al., 1988) to 1.77/−1.73 Sv (used by Greze et al., 1985). The reasons for these differences could due to seasonal or inter-annual variations, the insufficient spatial or temporal coverage of the measurements, the omission of the interface movement, or inaccurate estimations of the difference of precipitation and evaporation over the Mediterranean Sea in indirect estimations based on budget models. The transports also depend on the position along the Strait where the fluxes are measured and the difference in the salinity considered as interface between the two opposite current system. At the Camarinal Sill, Tsimplis and Bryden (2000) reported transports of 0.78 and −0.67 Sv, whereas García Lafuente et al. (2000) reported 0.92 and −0.87 Sv on the eastern side of the Strait. These differences are compatible if we consider the return by mixing of part of the Mediterranean water to the Atlantic inflow (0.8–0.12 Sv) that takes place at the sill region (Wesson and Gregg, 1994).

As a consequence of the variability in the literature sources of the water fluxes, the input/output estimations can present differences by a factor of almost 3-fold for the similar concentration of a substance. The most ex-

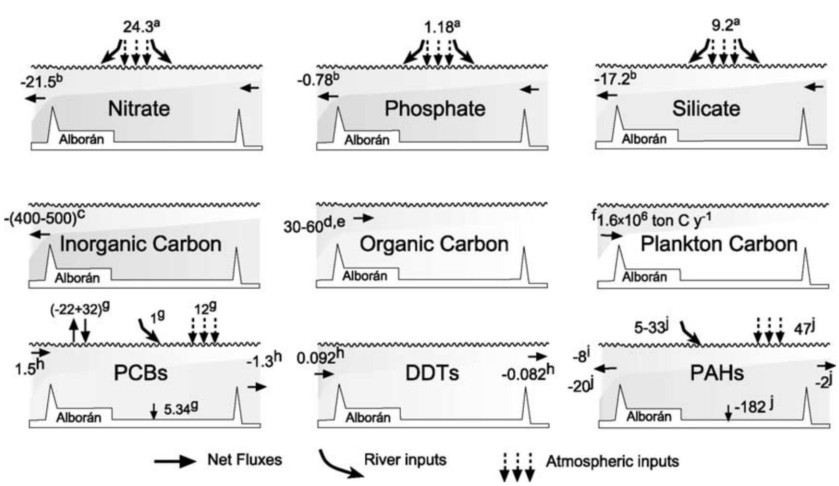

Fig. 1. Exchanges of nutrients and carbon through the Strait of Gibraltar and external inputs into the Western Mediterranean Sea based on literature sources (computed by using different water fluxes). Nutrient and carbon fluxes expressed as $\times 10^{10}$ mol year^{-1}. Plankton biomass and organic compounds are expressed as ton year^{-1}. Sources: [a]Béthoux et al. (2002), [b]Gómez et al. (2000b), [c]Santana-Casiano et al. (2002), [d]Dafner et al. (2001a), [e]Dafner et al. (2001b), [f]Reul et al. (2002), [g]Tolosa et al. (1997), [h]Dachs et al. (1997a), [i]Dachs et al. (1997b) and [j]Lipiatou et al. (1997) (only Ebro and Rhone rivers considered).

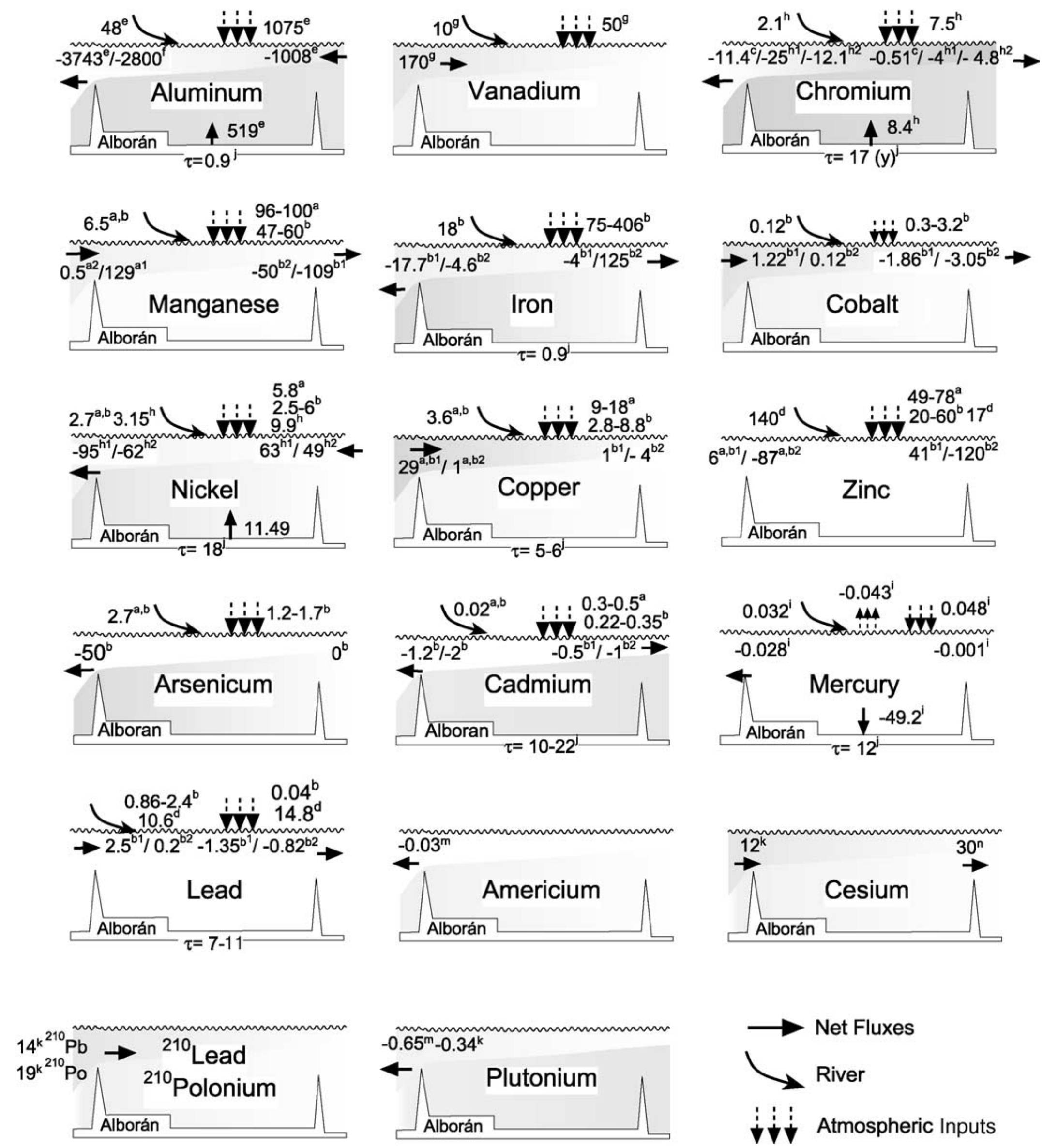

Fig. 2. Exchanges of trace metals and radionuclides through the Strait of Gibraltar and external inputs into the Western Mediterranean Sea based on literature sources (computed by using different water fluxes). Fluxes expressed as $\times 10^6$ mol year^{-1} for trace metals and TBq year^{-1} (10^{12} Becquerel) for radionuclides. Sources: [a]Elbaz-Poulichet et al. (2001b), [b]Elbaz-Poulichet et al. (2001a) based on atmospheric inputs by Ridame et al. (1999). The estimations by Elbaz-Poulichet et al. (2001a,b) include the influence of the SSW, [c]Ruiz-Pino et al. (1991), [d]Guerzoni et al. (1999), [e]Chou and Wollast (1997), [f]Measures and Edmond (1988), [g]Jeandel et al. (1987), [h]Achterberg and van den Berg (1997) [h_1, February 1992 and h_2, June 1993], [i]Cossa et al. (1997), [l]τ = residence time (year) reported by Martin et al. (1989), [k]Gascó et al. (2002), [m]León Vintró et al. (1999) and [n]Papucci and Delfanti (1999).

tended transport used for the computation of the exchanges are the indirect estimations by Béthoux (1980) that also proposed transports between the Mediterranean sub-basins and vertical fluxes. However these values (1.68/−1.60 Sv) are 2-folds the values of about 0.8 Sv obtained from direct measurements (Bryden et al., 1994; Tsimplis and Bryden, 2000).

Here the fluxes are re-calculated by using an average transport of 0.81 Sv for the Atlantic inflow and −0.76 for the Mediterranean outflow (Baschek et al., 2002) that implies a net input of 0.05 Sv (Table 1). The transports reported by Tsimplis and Bryden (2000) at the sill (0.78/−0.67 Sv) showed a net input of 0.11 Sv (difference between inflow and outflow) that is about 2-folds higher than most estimations.

3. Exchange of elements and pollutants

3.1. Nutrients

The Mediterranean Sea is characterised by low nutrient concentrations. The oligotrophy is generally considered as a consequence of the negative budget for the

Table 1
Re-calculated exchanges of elements through the Strait of Gibraltar by using an inflow of 0.81 and outflow of −0.76 Sv

Element	AW mM	MOW mM	Input 10^{10} mol year^{-1}	Output 10^{10} mol year^{-1}	Input/output %	Budget AW–MOW	Atm. + river input 10^{10} mol year^{-1}
NO_3^-	2	9.9[a]	5.11	−23.7	21	−18.6	24.3[b]
PO_4^{3-}	0.17	0.47[a]	0.43	−1.13	38	−0.7	1.18[b]
SiO_2	1.3	7.6[a]	3.32	−18.2	18	−14.9	24.3[b]
IC	2129	2310[c]	5438	−5536	98	−98	
TOC	59	46[d]	150	−110	136	40	
TOC	90	67[c]	229	−160	143	69	
	pg l^{-1}	pg l^{-1}	kg year^{-1}	kg year^{-1}	%	kg year^{-1}	
PCBs	35	7[e]	894	−168	533	726	
DDTs	3.5	1.75[e]	89	−42	213	47	
PAHs	622	1060[g]	15888	−25405	63	−9517	
	nM	nM	10^6 mol year^{-1}	10^6 mol year^{-1}	%	10^6 mol year^{-1}	10^6 mol year^{-1}
Al	16	86[h]	408	−2062	20	−1653	1123[h]
Cr	2.76	3.27[h]	70.5	−78.4	90	−7.91	9.6[i]
Mn	6.12	1[i]	156.3	−24	652	132.35	
Fe	1.503	0.754[j]	38.4	−18.1	212	20.31	80–400[j]
Co	0.11	0.056[j]	2.8	−1.3	209	1.47	0.4–3.3[j]
Ni	1.78	3[i]	45.4	−71.9	63	−26.47	5–10[j]
Ni	2.27	3.99[h]	58	−95.6	60	−37.69	5–10[j]
Cu	2.24	1[i]	57.2	−24	238	33.24	5–18[j]
Zn	5	5[i]	127.7	−119.9	106	7.83	200[j,i]
Cd	0.054	0.075[i]	1.4	−1.8	77	−0.42	0.3–0.5[i]
As	17.82	21[i]	455.2	−503.5	90	−48.35	
Hg	0.0016	0.0022[i]	0.04	−0.05	76	−0.01	0.07[l]
Pb	0.155	0.05[j]	3.9	−1.2	330	2.76	1– 2.5[j]
	Bq m^{-3}	Bq m^{-3}	10^{12} Bq year^{-1}	10^{12} Bq year^{-1}	%	TBq year^{-1}	
^{137}Ce	2.52	2.14[m]	64.4	−51.3	125	13.16	
$^{238/239}$Pu	0.0099	0.022[m]	0.25	−0.53	48	−0.27	
^{210}Po	1.53	0.84[m]	39	−20	194	19	
^{210}Pb	1.16	0.66[m]	29.7	−15.8	187	13.8	

The concentration in the Atlantic inflowing waters (AW), Mediterranean outflowing waters (MOW) and external inputs (atmosphere and rivers) were obtained from [a]Gómez et al., 2000b, [b]Béthoux et al., 2002, [c]Dafner et al., 2001a, [d]Dafner et al., 2001b, [e]Dachs et al., 1997a, [f]Tolosa et al., 1997, [g]Lipiatou et al., 1997, [h]Chou and Wollast, 1997, [i]Elbaz-Poulichet et al., 2001b, [j]Elbaz-Poulichet et al., 2001a, [k]Guerzoni et al., 1999, [l]Cossa et al., 1997 and [m]Gascó et al., 2002. IC = inorganic carbon, TOC = total organic carbon.

nutrients at the Gibraltar Strait (Coste et al., 1988; Gómez et al., 2000b). However Crispi et al. (2001) based on numerical simulations concluded that inverse estuarine circulation is not sufficient to explain the oligotrophic regime. Conversely, it appears that the downward fluxes of organic matter play a major role in sustaining and stabilising the oligotrophy (Crispi et al., 2001).

The Mediterranean waters are also characterised by a peculiar nitrate/phosphate ratio (N/P ∼ 20–27) different from that in the world ocean close to the Redfield ratio (N/P = 16). It has been hypothesised that this ratio might results from one or a combination of a high rate of biological nitrogen fixation (Béthoux and Copin-Montégut, 1986), preferential deposition of phosphate in dust particles (Krom et al., 1991) and the high N/P ratio of atmospheric input from the Sahara desert (Herut et al., 2002). Béthoux et al. (2002) reported an average N/P ratio of 21 for the input from the atmosphere and rivers.

In the deep Western Mediterranean waters for the year 2000, Béthoux et al. (2002) reported average values of 9.3, 0.43 and 8.4 μM for nitrate, phosphate and silicate respectively, that implies a ratio N/P = 22. The average ratio of the entering Atlantic waters shows high variability due to biological uptake ranging from 11–12 (Gómez et al., 2000b) to 17 (Coste et al., 1988). In the Gulf of Cádiz, Ambar et al. (2002) reported in the MOW values 7.9, 0.64 and 6.7 μM for NO_3, PO_4 and SiO_2 in summer and 8.4, 0.44 and 6.0 μM in winter (N/P ratios of 12 and 19 for summer and winter respectively). The mixing just in the Strait of Gibraltar and along the Gulf of Cádiz could be the responsible of the fast lost of the characteristics of the MOW (Price et al., 1993).

In the case of the nitrate, Béthoux et al. (2002) reported that in the Western Basin for the year 2000, the total atmospheric and terrestrial sources amounted to 24.3×10^{10} mol year^{-1} NO_3^-. These inputs are compensated by a similar net lost through the Strait of -21.5×10^{10} mol year^{-1} (Gómez et al., 2000b) (Fig. 1). Considering an area of the Western Mediterranean Sea of 0.854×10^{12} m^2 (average depth 1433 m) results in 1.22×10^{15} m^3, that corresponds to 0.17- and 1.05×10^{15} m^3 for surface waters (0–200 m) and deeper waters respectively. By using an average value of 9.3 μM for Western Mediterranean deep waters (Béthoux et al., 2002) and 2 μM for surface waters, results in approximately 1000×10^{10} mol NO_3^- in the Western Mediterranean Sea. After re-calculating the values reported by Gómez et al. (2000b), the annual net loss through the Strait represents around −1.86% of the total stock (Tables 1 and 2). Consequently, the interruption of the exchanges (i.e., total dam) will be supposed to increase annually the stock in the Western Mediterranean Sea in the same proportion.

The phosphate is considered the limitant nutrient for primary production in the Mediterranean Sea, especially in the eastern basin (Krom et al., 1991). In the Western Basin, the atmospheric and terrestrial inputs was estimated as 1.18×10^{10} mol year^{-1} (Béthoux et al., 2002), higher than the net lost through the Strait of -0.78×10^{10} mol year^{-1} (Gómez et al., 2000b) (Fig. 1). Using the same approach than for nitrate [surface waters: 0.2 μM and deep waters: 0.43 μM (Béthoux et al., 2002)], results in approximately 50×10^{10} mol PO_4^{3-} in the Western Mediterranean stock. The re-calculated annual net loss through the Strait could represent around −1.38% of this stock. The same annual increase could be expected as a consequence of the interruption of the exchanges through the Strait (Tables 1 and 2).

Whereas the nitrate and phosphate concentrations are progressively increasing in the Mediterranean deep waters, the temporal evolution of the concentration of silicate seems to be stationary due to the reduction of the freshwater inputs (Béthoux et al., 1998, 2002). Béthoux et al. (2002) reported that in the Western Basin the total atmospheric and terrestrial source amounted to 9.2×10^{10} mol year^{-1}. The net lost through the Strait of -17.19×10^{10} mol year^{-1} (Gómez et al., 2000b) constitutes approximately 2-folds the atmospheric and terrestrial inputs (Fig. 1). Considering an average concentration of 2 μM in surface waters and 8.4 μM in deep waters (Béthoux et al., 2002) results in a stock of 915×10^{10} mol in the Western Mediterranean Sea. The annual net loss through the Strait represents around −1.63% of the total stock (Table 2).

The contribution of the dissolved organic nitrogen and phosphorus to the budget through the Strait has been scarcely investigated (Béthoux and Copin-Montégut, 1986; Coste et al., 1988). According to Coste et al. (1988) the inclusion of all the forms of nitrogen and phosphorus is crucial for estimating correctly the budget, where the net loss previously calculated for inorganic nutrients appeared to be balanced (Coste et al., 1988). The values of organic nutrients reported by these authors were obtained in a station located at the NW Alborán Sea that did not represent the characteristics of the Strait. More studies will be convenient in order to evaluate the role of the organic nutrient fractions on the exchanges.

Table 2
Percentage of the annual variation of the stock of several compounds in the Western Mediterranean Sea due to the net flux through the Strait of Gibraltar

Element	Budget 10^{10} mol year^{-1}	W Med stock 10^{10} mol	Annual % stock
Nitrate	−18.62	1000[a]	−1.86
Phosphate	−0.69	50[a]	−1.38
Silicate	−14.89	915[a]	−1.63
	kg year^{-1}	kg	
PCBs	726	16514[b]	4.40
DDTs	47	996[b]	4.77
PAHs	−9517	707,000[c]	−1.35
	10^6 mol year^{-1}	10^6 mol	
Aluminium	−1653	155,662[d]	−1.06
Iron	20.3	1820[e]	1.12
Nickel	−26.5	5460[e]	−0.48
Nickel	−37.7	5460[e]	−0.69
Copper	33	2240[e]	1.48
Zinc	7.8	7140[e]	0.11
Cadmium	−0.42	1370[e]	−0.03
Mercury	−0.01	3.14[f]	−0.41
Lead	2.76	160[e]	1.73
	10^{12} Bq year^{-1}	10^{12} Bq	
^{238,239}Pu	−0.27	24.8[g]	−1.11

Budgets from the Table 1. Sources: [a]This study, [b]Dachs et al. (1997a), [c]Dachs et al. (1997b), [d]Chou and Wollast (1997), [e]Yoon et al. (1999), [f]Cossa et al. (1997) and [g]León Vintró et al. (1999).

3.2. Carbon

The Mediterranean Sea acts as a basin of active remineralization of organic material, sink of organic carbon and source of inorganic carbon into the Atlantic Ocean (Copin-Montégut, 1993). Dafner et al. (2001a) estimated a net loss of inorganic carbon of −4 to 5×10^{12} mol year^{-1} and Santana-Casiano et al. (2002) reported a net alkalinity outflow of -1.9×10^{12} mol year^{-1} through the Strait.

For total organic carbon (TOC), Dafner et al. (2001a,b) estimated a net input ranging from 0.3 to 0.6×10^{12} mol year^{-1}. Considering an entire Mediterranean stock of TOC of 247×10^{12} mol (Sempéré et al., 2000), the annual input through the Strait only represents an increase about 0.2% of the total stock in the entire basin. For plankton biomass, Reul et al. (2002) estimated on the eastern side of the Strait an annual input of 1.6×10^6 ton C year^{-1} (0.13×10^{12} mol C year^{-1}). This value should be considered cautiously due to the large variability associated with biomass and the strong heterogeneity and the biomass changes along the transit through the Strait, together to a re-circulation of the biomass associated with the bi-layer opposite current system in the Strait (Gómez et al., 2000a).

3.3. Hydrocarbons and organochlorine compounds

The Mediterranean is heavily used by shipping and oil transport, being one of the most chronically world polluted regions. Ancient estimations give an input of petroleum hydrocarbons (natural, accidental or controlled) to the Mediterranean Sea of 1–0.88×10^6 ton year^{-1} (Burns and Saliot, 1986). This represented about 20% of the global oceanic oil pollution in a sea that only represents the 0.82% of the world ocean surface area. Remote sensing reveals that the pollution occurred along the main shipping routes (as the Strait of Gibraltar) and the oil spills occurs during the night-time (Gade and Alpers, 1999).

The partial combustion of fossil combustibles produces a mixture of polycyclic aromatic hydrocarbons (PAHs). Dachs et al. (1997b) estimated that the total budget in the dissolved and particulate in the Western Mediterranean Sea amounts to 335 and 372 tons respectively. Lipiatou et al. (1997) estimated a net outflow through the Strait of 20 ton year^{-1} PAHs. Considering a stock of 707 tons and a corrected net output of −9.5 ton year^{-1} from Lipiatou et al. (1997) values, the net loss through the Strait could represent an annual decrease of −1.3% of the stock (Table 2).

Other organochlorine compounds such as poly-chlorinated byphenyls (PCBs) and DDTs [Trichloro-2,2-bis-(4′-chlorophenyl) ethane] are declining concentration in the last decades in the Western Mediterranean Sea as a consequence of the international regulations, being the larger budget of PCBs than DDTs consistent with an earlier banning of DDTs (Tolosa et al., 1997). Dachs et al. (1997b) reported a net input of PCBs and DDTs through the Strait of Gibraltar even though concentration of organochlorine compounds in the Western Mediterranean Sea are higher than in the Atlantic Ocean. Tolosa et al. (1997) estimated a stock of 140–420 ton PCBs for the 1990s. Dachs et al. (1997a) estimated a stock of 16.5 and 0.9 tons of PCBs and DDTs respectively in the Western Mediterranean Sea. Based on these values and a re-calculated net input of 0.72 and 0.047 ton year^{-1} of PCBs and DDTs respectively (values from Dachs et al., 1997a), the exchange through the Strait contributes to annual increase of 4.4% and 4.7% for PCBs and DDTs respectively of the stock in the Western Basin (Table 2).

3.4. Trace metals

Trace metal concentrations are relatively high in Mediterranean waters compared to the open ocean (Boyle et al., 1985). The enrichments of Cu, Ni, Cd and Zn in the Atlantic inflowing waters have been related to the flow of Spanish shelf water (SSW) (van Geen et al., 1988), enriched in trace metals due to the drainage of mineralisation and mining activity in the Iberian Pyrite Belt (SW Spain). Consequently the inflow through the Strait of Gibraltar constitutes the main source of dissolved metals into the Western Mediterranean basin and the presence of SSW in the Atlantic current increases the metal flux to the Mediterranean Sea by a factor of 2.3, 2.4, 3 and 7 for Cu, Cd, Zn and Mn respectively, but it does not modify significantly As and Ni fluxes (Elbaz-Poulichet et al., 2001a,b). At a basin scale, the second source of metals in the Mediterranean is the atmosphere and the rivers represent a minor source. It is apparent that the overall import and export fluxes are near equilibrium, outputs balance inputs, except for Fe which sediments in the basin and subject to other processes in the water column (Sarthou and Jeandel, 2001). Due to the rapid exchange of water masses, the Western Mediterranean may have the ability to assimilate the increased external inputs for some trace metals such as Cu, Cd, Ni and Zn, but the external inputs for Pb and Fe where the effects of the atmospheric inputs are more pronounced than for the other metals exceed the removal capacity of the Western Mediterranean and these elements may accumulate in the water column (Yoon et al., 1999).

From the stock of trace metals reported by Yoon et al. (1999) in the Western Basin, the contribution of the net flux through the Strait reveals an annual decrease of the stock of Al (−1.06%), Ni (−0.68/−0.48%), scarce incidence in elements such as Zn (0.11%), Cd (−0.03%) and an increase in Cu (1.48%), Fe (1.12%) and Pb (1.73%) in the stock of the Western Mediterranean Sea (Table 2).

3.5. Radionuclides

Anthropogenic radionuclides such as ^{137}Cs and ^{239,240}Pu show a clear decline in both the Atlantic Ocean and the Mediterranean Sea as a result of reductions in atmospheric input, radioactive decay and vertical diffusion/convection processes. Gascó et al. (2002) reported that the Mediterranean basin experiences a net annual loss of −0.34 TBq (1 TBq = 10^{12} Becquerel) of ^{239,240}Pu through the Strait. León Vintró et al. (1999) estimated an inventory of 24.8 TBq of ^{239,240}Pu in the Western Mediterranean Sea and an annual net lost of −0.65 TBq ^{239,240}Pu through the Strait that represents the lost −2.6% of the total stock. A re-evaluation by using the values reported by Gascó et al. (2002) results in a net loss of −1.1% of the Western Mediterranean stock through the Strait. Nowadays for ^{137}Cs input and output fluxes appear to be balanced according to Gascó et al. (2002).

Natural radionuclides such as ^{210}Pb and its descendant ^{210}Po experience a net annual input of 14 TBq of ^{210}Pb and 19 TBq of ^{210}Po (Gascó et al., 2002). The mining activity in the Iberian Pyrite Belt (SW Spain) also contributed to an extra input of natural radionuclides through the Strait (Martínez-Aguirre et al., 1996).

4. Discussion

The Strait of Gibraltar could be considered the key in the control of the biogeochemistry of the entire Mediterranean Sea and the circulation and climate in the Atlantic Ocean. A modification of the exchanges would be possible by a macro-engineer project as a high dam (Petroski, 1997). These possible man-induced change options will consist in (1) reduction of the fluxes with lower or null exchanges values by reducing of the cross-section, reducing the depth at the sill or by a total or partial dam or (2) increasing the cross-section by planning the sill (removing the material from the sill bottom). A partial dam implies that the top would be below the sea surface, to allow fresh Atlantic water enter in response to the lower sea-level of the Mediterranean basin. With a total dam, hydro-electrical energy production is possible if enough difference of sea-level is maintained. If the Mediterranean Sea is isolated from the Atlantic Ocean, the water deficit due to the balance evaporation/freshwater inputs implies an annual loss of approximately ~1 m of sea-level (Bryden et al., 1994).

4.1. Beneficies associated with the reduction of the water exchanges

Along this century an accelerated global sea-level rise is expected. Mediterranean surface temperature trends were strongly correlated to sea-level trends, indicating that at least part of the observed sea-level change has a thermal origin (Cazenave et al., 2001). A global rise in sea-level ranging from about 0.2–0.9 m by the year 2100 (Wigley and Raper, 1992) could imply an increase of the coastal erosion, inundation (as in Venice), risk of flooding and impeded drainage or salinity intrusion into freshwaters supplies (Nicholls and Hoozemans, 1996). By year 2025, Mediterranean coastal population is predicted to increase to 200–220 million (Baric and Gasparovic, 1992). Coastal tourism, rising to a projected 173–341 millions tourists in 2025, is a major and sometimes the only industry in many Mediterranean areas. Developed sandy coasts for both recreation and protective purposes may also be vulnerable (Nicholls and Hoozemans, 1996).

At a first sight a dam could control the consequences of the sea-level rise. Mediterranean countries should agree on the sea-level of the Mediterranean after the completion of the dam. A dam could produce almost cost-free renewable energy, but hydroelectric power required a difference of level at both sides of the Strait. A scarce difference of level (~1 m) will maintain a control of sea-level rise, but could not provide hydroelectric power. Several meters of Atlantic-Mediterranean sea-level difference will substantially modify the present day configuration of the coast in many areas.

4.2. Negative effects associated with the reduction of the water exchanges

Phosphate concentration in Western Mediterranean deep waters are increasing about 0.5% per year and the atmospheric and terrestrial inputs of phosphate and nitrate of about 3% per year (Béthoux et al., 1998). As a consequence of the interruption of the exchanges through the Strait, the nutrient concentrations will increase around annually of about 1–2% per year in the Western Mediterranean Sea (Table 2). Therefore the rate of increase of the nutrient concentrations due to the external inputs (rivers + atmosphere) is higher than the increase due to the lack of the net loss through the Strait.

An increase of nutrient concentration can produce episodes of anoxia as occur in other semi-enclosed basins such as the Black and Baltic Seas. Béthoux (1989) prognosticated that the first episodes of anoxia would appear in the Mediterranean Sea in this century. However the predictions by Roether and Well (2001) do not support imminent anoxia in the deep waters of the Eastern Mediterranean that could tolerate a 3.5-fold increase in nutrient supply before anoxia. Sarmiento et al. (1988), dealing with occurrences of anoxia in past climates, pointed out that the present Mediterranean differed from the world ocean in that nutrient levels are low in comparison, such that oxygen input by deep-water formation should by far exceed the deep oxygen demand. According to the model by Sarmiento et al. (1988) the phosphate concentrations would have to increase to 1.37 μM, with the appropriate amounts of nitrate, in order to obtain anoxia.

Observed changes in nutrient concentrations and ratios in the deep waters of the Western Mediterranean, suggest changes on the phytoplankton composition over the whole sea. A shift from a diatom-dominated ecosystem to a non-siliceous one could be associated with an increase of the algae massive blooms by red tides species (Turley, 1999; Garcés et al., 2000; Béthoux et al., 2002). Over the last few decades, the Mediterranean ecosystem has experienced changes in biodiversity due to climatic and environmental change or to accidental inputs of exotic species (Bianchi and Morri, 2000; Boudouresque and Verlaque, 2002; Occhipinti-Ambrogi and Savini, 2003). In the Mediterranean Sea that represents only the 0.82% in surface area and 0.32% in volume of the world oceans, marine macroscopic organisms in the Mediterranean basin represents an average value of 6.3% (4–18%) of the world marine species (Bianchi and Morri, 2000). As a consequence of the disconnection with the Atlantic Ocean, waters will warm and saline, purging the alien and native flora and fauna.

Fisheries in the Mediterranean Sea are not important in comparison to oceanic areas due to the oligotrophy. A total dam at the Strait will finish with the fisheries of migrants through the Strait such as tuna (Rey, 1996). Despite the general high exploitation rates, the overall Mediterranean landings are increasing (especially in the Adriatic Sea and also in the Black Sea), being only explicable due to the nutrient enrichment where productivity was limited by low nutrient concentrations (Caddy et al., 1995). Initially, it could be expected an increase of fisheries in a more eutrophic Mediterranean Sea, but changes of the composition could derived on less valuable species.

As the Strait of Gibraltar is a major maritime route (with more than 80,000 vessels transiting the Strait each year) a dam should be furnished with ship-locks. The dam will restrict the "secret" military traffic (i.e., submarines) in one of the most strategical areas in the world. This could lead to political or military conflicts in the complex Mediterranean geo-political relationships (Suárez de Vivero and Rodríguez Mateos, 2002) that would increase the difficulty of organising the broad international effort needed to carry out the project.

4.3. Ocean circulation changes associated with the reduction of the water exchanges

The restriction of an outflow of approximated 1 Sverdrup (10^6 $m^3\,s^{-1}$) of salty Mediterranean water has an influence on the circulation of the Atlantic Ocean. Reid (1979) and Rahmstorf (1998) argued from different viewpoints that Mediterranean Outflow Waters (MOW) entering into the Atlantic Ocean via the Strait, was of importance for promoting the formation of North Atlantic Deep Water, and hence for stabilising the present thermohaline circulation. Johnson (1997) goes further and proposes that a dam in the Strait of Gibraltar would control the climate change. Rahmstorf (1998) modelled the thermohaline circulation in the Atlantic Ocean and concluded that northern Atlantic surface temperatures increase by a few tenths of degree and circulation intensifies by 1–2 Sv, if the Mediterranean outflow is included. According to Ozgokmen et al. (2001) the Mediterranean Outflow constitutes a fundamental factor in the establishment of the Azores Current.

Thorpe and Bigg (2000) modelled the consequences of the global warming on the exchange through the Strait of Gibraltar. They suggested that the Mediterranean outflow may become warmer and more saline, but less dense, and hence shallower. The volume of the exchange at the Strait of Gibraltar seems to be relatively insensitive to future climate change (Thorpe and Bigg, 2000).

5. Final remarks

The exchanges through the Strait of Gibraltar constitute a key in control of the biogeochemical cycles and processes in the entire Mediterranean basin. However the role of the Mediterranean outflow in the control of the world climate change is based in a speculative chain of hypothesis that requires further studies before to carry out an artificial interruption of the water exchanges through the Strait.

The international regulations have succeeded in reducing the inputs of several pollutants in the Mediterranean basin such as lead, organochlorine compounds or radionuclides. The management of the local sources in the Iberian Pyrite Belt (SW Spain) can reduce the Atlantic input of trace metals. However the increase of the nutrient concentrations in the Mediterranean waters constitutes a more complex issue. The progressive increase of the coastal population, especially in the southern Mediterranean coasts (Baric and Gasparovic, 1992) will result in eutrophication and an increased risk of pollution in these areas unless well managed. The present and forthcoming increase of nutrient concentrations in the deep Mediterranean waters could be compensate by an intensification of the Mediterranean outflow into the Atlantic Ocean. The increase of the cross-section by planning the topography of sill (increasing the depth of the Strait) will be associated with a higher outflow of the deep Mediterranean waters (Bryden et al., 1994). Consequently the higher net loss of nutrients would compensate the increase of the external inputs into the Mediterranean waters.

Both opposite anthropogenic modifications of exchanges, by a partial/total dam or the planning at sill, require more in-depth studies. A permanent monitoring of the exchanges of substances at the Strait as already exist for water fluxes (García Lafuente et al., 2002) will be convenient.

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