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A biogeochemical model for phosphorus and nitrogen cycling in the Eastern Mediterranean Sea
Part 2. Response of nutrient cycles and primary production to anthropogenic forcing: 1950–2000

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ABSTRACT

Anthropogenic inputs of nutrient phosphorus (P) and nitrogen (N) to the Eastern Mediterranean Sea (EMS) increased significantly after 1950. Nonetheless, the EMS remained ultra-oligotrophic, with eutrophication only affecting a restricted number of nearshore areas. To better understand this apparent contradiction, we reconstructed the external inputs of reactive P and N to the EMS for the period 1950 to 2000. Although the inputs associated with atmospheric deposition and river discharge more than doubled, the inflow of surface water from the Western Mediterranean Sea (WMS) remained the dominant source of nutrient P and N to the EMS during the second half of the 20th century. The combined external input of reactive P rose by 24% from 1950 to 1985, followed by a slight decline. In contrast, the external reactive N input increased continuously from 1950 to 2000, with a 62% higher input in 2000 compared to 1950. When imposing the reconstructed inputs to the dynamic model of P and N cycling in the EMS developed in the companion paper, a maximum increase of primary production of only 16% is predicted. According to the model, integrated over the period 1950–2000, outflow of Levantine Intermediate Water (LIW) to the WMS exported the equivalent of about one third of the P supplied in excess of the 1950 input, while another one third was translocated to the Eastern Mediterranean Deep Water (EMDW). Together, both mechanisms efficiently counteracted enhanced P input to the EMS, by drawing nutrient P away from primary producers in the surface waters. Furthermore, between 1950 and 2000, inorganic and organic dissolved N:P ratios increased in all water masses. Thus, the EMS became even more P limited because of anthropogenic nutrient inputs. A model simulation incorporating the circulation changes accompanying the Eastern Mediterranean Transient (EMT) between 1987 and 2000 yielded a 4% increase of EMS primary productivity relative to the baseline scenario.

1. Introduction

The Eastern Mediterranean Sea (EMS) is nearly completely surrounded by land. In addition, the watershed of the EMS is experiencing rapid demographic growth and economic development, much of which is concentrated in the coastal areas. Relative to 1970, the number of people living in the countries bordering the EMS had increased by 50% by the year 2000 — in 2025 it will have doubled (UNEP/MAP, 2012). The resulting anthropogenic pressures on the EMS raise concerns about the environmental and ecological consequences, including the impacts of habitat loss, eutrophication, overfishing, invasive species, pathogens and climate change (UNEP-MAP-RAC/SPA, 2010).

A dominant anthropogenic driver of ecological change of marine environments is the increased supply of macronutrients, in particular phosphorus (P) and nitrogen (N). Worldwide, anthropogenic P and N loadings have risen dramatically since the 1950s (Galloway et al., 2004; Mackenzie et al., 2002; Seitzinger et al., 2005). This is also the case for the EMS (this paper). However, while in other semi-enclosed marine basins, such as the Baltic Sea, increased supplies of P and N have caused widespread eutrophication in both coastal and open water areas (Gray et al., 2002; Helcom, 2010; Larsson et al., 1985), in the EMS eutrophication appears to be limited to a few specific coastal areas (Karydis and Kitsiou, 2012). The existing evidence does not support significant

Abbreviations: EMS, Eastern Mediterranean Sea; SW, surface water; LIW, Levantine Intermediate Water; EMDW, Eastern Mediterranean Deep Water; WMS, Western Mediterranean Sea; PO_4, dissolved inorganic phosphorus; DOP, dissolved organic phosphorus; POP, particulate organic phosphorus; NO_3, dissolved nitrate plus nitrite; NH_4, dissolved ammonium; DON, dissolved organic nitrogen; PON, particulate organic nitrogen; EMT, Eastern Mediterranean Transient; MAW, Modified Atlantic Water; ADW, Adriatic Deep Water.

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increases in primary production or inorganic nutrient concentrations at the scale of the entire EMS (Krom et al., 2010; Van Cappellen et al., in press).

In the companion paper, we developed a dynamic mass balance model for the coupled P and N cycles in the EMS (Van Cappellen et al., in press). The model is based on a simple representation of the water cycle of the EMS. However, in contrast to most previous mass balance studies of the EMS (e.g., Béthoux et al., 1998; Krom et al., 2004; Ribera d'Alcalà et al., 2003), the model explicitly accounts for the organic reservoirs of P and N. The model was initialized for the year 1950, assuming relatively limited prior anthropogenic disturbance of the nutrient cycles (Béthoux et al., 1998). The model explains the ultra-oligotrophic nature of the EMS and the systematically higher-than-Redfield N:P ratios observed in the water column. Results of sensitivity analyses underline the key roles of circulation within the EMS, water exchanges with adjacent basins, most importantly with the Western Mediterranean Sea (WMS), and the nature and extent of organic P and N recycling processes.

In the present paper, we reconstruct the P and N loadings to the EMS for the period 1950–2000. The latter time interval is chosen because (1) the available information sources provide a reasonable coverage for this time period, and (2) the EMS experienced the largest inputs of anthropogenic P and N during the second half of the 20th century. The time-dependent P and N loadings from 1950 to 2000 are then imposed as input to the coupled P and N cycling model, which is run forward in time starting from the initial 1950 conditions. The goal of the simulations is to predict the basin-wide changes in P and N cycling and primary production driven by the inputs of anthropogenic nutrients, on a decadal timescale. Particular attention is given to the fate of the excess anthropogenic nutrients added to the EMS, the partitioning of the nutrient elements between their inorganic and organic pools, the changes in water column N:P ratios, and the implications for nutrient data acquisition. Where possible, the predictions are compared to existing data, including data that were not used in developing and initializing the coupled P and N cycling model.

2. Phosphorus and nitrogen inputs: 1950–2000

2.1. Anthropogenic forcing functions

In the model, the water column is divided in three layers: surface water (SW; 0–200 m), Levantine Intermediate Water (LIW, 200–500 m) and Eastern Mediterranean Deep Water (EMDW, >500 m). External inputs of reactive P and N are supplied to SW via rivers, inflow from the WMS plus atmospheric deposition, and to EMDW via deep water formation in the Adriatic and Aegean Seas. The model differentiates between the following reactive P pools: dissolved inorganic phosphorus (PO_4), dissolved organic P (DOP) and particulate organic P (POP). For N, the reactive pools are dissolved nitrate plus nitrite (NO_3), dissolved ammonium (NH_4), dissolved organic nitrogen (DON), and particulate organic nitrogen (PON).

Post-1950 changes of the inputs are considered to be mainly due to anthropogenic factors. The anthropogenic forcing function describing the input of a given P or N species *i* from an external source *j* is then defined as:

$$f_{ij=}\frac{\text{input flux}(t)}{\text{input flux}(1950)} \quad (1)$$

where time *t* corresponds to the year of interest. Values for the 1950 input fluxes are those given in Van Cappellen et al. (in press). The 1950 inputs of reactive P and N to the EMS are used as starting point for the model simulations.

Because the earliest research cruises in the EMS date back to the late 1950s, little data are available to assess the state of the EMS at earlier times. Our work further leans heavily on the systematic reconstruction of riverine P and N fluxes into the Mediterranean Sea by Ludwig et al. (2009). These authors carried out their analysis up to 1998. The model simulations therefore are limited to the second half of the 20th century, which is also the time interval when anthropogenic inputs of the limiting nutrient P to the EMS peaked (this paper). During the latter part of the 20th century, circulation in the EMS further underwent a major perturbation known as the Eastern Mediterranean Transient or EMT. As the latter is well characterized (Roether et al., 1996, 2007), we are able to account for the circulation changes accompanying the EMT in the model simulations. Thus, the time period 1950–2000 offers the opportunity to investigate the response of the P and N cycles in the EMS to changes in the inputs of the nutrient elements, while minimizing the effects of unknowns or potential confounding factors.

2.2. Rivers

Riverine inputs of P and N to the Ionian and Levantine Basins are obtained from Ludwig et al. (2009). These authors provide nutrient fluxes at river mouths for every 5 years between 1963 and 1998. (Note: between 1950 and 1963, we assume a linear forcing function for the riverine inputs, using the 1950 input fluxes estimated by Van Cappellen et al., in press). Ludwig and coworkers further estimate that, on average, 48% of the total riverine P flux is delivered as PO_4, 8% as DOP and the rest as particulate P. Because of the P-starved nature of the EMS, Van Cappellen et al. (in press) assume that 75% of the particulate riverine P flux is eventually solubilized to PO_4. For N, Ludwig and coworkers estimate that, on average, 75% of total N from rivers occurs as NO_3, 20% as DON and 5% as NH_4. In the absence of more definitive constraints, we impose the same, constant proportions of riverine P and N species during the period 1950 to 2000.

Closure of the Aswan High Dam in 1965 caused a major perturbation of the riverine supply of P to the EMS. According to Nixon (2003), before the dam was completed more than half of the reactive P delivered by the Nile River to the EMS was derived from the desorption of PO_4 from suspended particulate matter. After 1965, sediment was trapped in Lake Nasser, hence drastically reducing the P flux from the Nile River. As reactive N in rivers primarily occurs in the dissolved load, a similar drop of the Nile River N flux to the EMS did not occur. Rasmussen et al. (2009) further propose that by the end of the century, the P flux from the Nile delta to the EMS had recovered to pre-dam values, because of increasing sewage discharges into coastal lagoons and subsequent leakage into the EMS.

The reconstructed forcing functions for the surface flow inputs of P and N to the EMS are shown in Fig. 1 (see Supplementary material for numerical values). Note that, in addition to the nutrient fluxes delivered by rivers to the EMS, the forcing functions account for dissolved P and N supplied via the surface inflows from the Adriatic Sea and Aegean Sea. As the latter represent very small contributions to the total external inputs of reactive P and N to the EMS (<1%), they are kept constant during the simulations. The decrease in the forcing function for P during the late 1960s reflects the closure of the Aswan High Dam: by 1967 the riverine P influx to the EMS is estimated to have dropped to half of its 1950 value. After the 1967 minimum, the anthropogenic forcing function rises again due to the increasing use of P fertilizers and detergents, as well as expanding sewerage around the basin. It reaches a peak value of 2.2 in the early 1980s, followed by a decreasing trend because of the ban on P detergents and upgrades of wastewater treatment plants (Ludwig et al., 2009). Hence, by the year 2000, the riverine PO_4 and DOP inputs to the EMS are estimated to be comparable to those in the mid-1970s. Unlike P, the resulting forcing function for riverine inputs of N increases steadily from 1950 to 2000, to a maximum of 5.2 in 2000, due principally to the continued rise in diffuse agricultural and sewage inputs.

2.3. Inflow from the Western Mediterranean Sea (WMS)

According to our previous estimations, the inflow of Modified Atlantic Water (MAW) through the Straits of Sicily represents the major external