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Phytoplankton dynamics in the Gulf of Aqaba (Eilat, Red Sea): A simulation study of mariculture effects

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ABSTRACT

The northern Gulf of Aqaba is an oligotrophic water body hosting valuable coral reefs. In the Gulf, phytoplankton dynamics are driven by an annual cycle of stratification and mixing. Superimposed on that fairly regular pattern was the establishment of a shallow-water fish-farm initiative that increased gradually until its activity was terminated in June 2008. Nutrient, water temperature, irradiation, phytoplankton data gathered in the area during the years 2007–2009, covering the peak of the fish-farm activity and its cessation, were analyzed by means of statistical analyses and ecological models of phytoplankton dynamics. Two datasets, one from an open water station and one next to the fish farms, were used. Results show that nutrient concentrations and, consequently, phytoplankton abundance and seasonal succession were radically altered by the pollution originating from the fish-farm in the sampling station closer to it, and also that the fish-farm might even have influenced the open water station.

1. Introduction

Coral reefs are among the most productive and biologically diverse ecosystems on Earth and supply people with goods and services as seafood, recreational possibilities, coastal protection, as well as aesthetic and cultural benefits (Moberg and Folke, 1999). The coral reef off the coast of the cities of Eilat (Israel) and Aqaba (Jordan) stretches over 1200 m along the east and west coasts of the Gulf of Aqaba (Bay of Eilat). This coral reef supports a thriving economy based primarily on tourism. Natural and anthropogenic factors threaten this important source of revenue; in particular, sea-water quality is worsening due to pollution caused by human activities in the coastal zones surrounding the gulf, e.g., metallurgical industries, hotels and resorts, port activities and fish farming (Loya and Kramarsky-Winter, 2003; Loya et al., 2004; Chen et al., 2007, 2008; Lazar et al., 2008). Global climate change may also be a contributory factor: dust is deposited in the gulf by sand storms due to desertification processes, which favor phytoplankton growth. These processes could be aggravated by water-warming and acidification caused by an anthropogenic increase in atmospheric greenhouse gases, and an increase in UV radiation due to ozone depletion, although it must be stressed that evidences for statistically significant warming or acidification of the Gulf of Aqaba have not been found yet to our knowledge. For their nutrient supply, the productive coral reefs in the Gulf of Aqaba subsist, to a large degree, on allochthonous plankton, providing nitrogen fluxes from the phytoplankton to the coral reef (Yahel et al., 1998; Richter et al., 2001). Therefore, the inter-annual variability in the intensity and timing of phytoplankton blooms, triggered by water-column mixing, and nutrient injections from the fish farm activity, might have serious consequences for the upper trophic levels in the Gulf of Aqaba and its food web, including coral reef stability (Labiosa et al., 2003). Indeed, nutrients excreted by farmed fish can be readily taken up by phytoplankton and stimulate their growth, which can potentially lead to localized eutrophication, especially in coastal areas of poor flushing (Brown et al., 1987; Aure and Stigebrandt, 1990; Wu et al., 1994; Wu 1995). This study investigates the impact of fish-farming activities and their cessation on water quality and phytoplankton dynamics in the Northern Gulf of Aqaba.

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1.1. Seasonal phytoplankton dynamics in the northern Gulf of Aqaba

The Gulf of Aqaba is characterized by seasonal cycles of stratification and mixing, similar to other subtropical oligotrophic seas. Small perturbations, such as transient cooling, which induces convection, and wind events driving upwelling can, at times, inject deep water into the euphotic layer, making nutrients available for phytoplankton growth (Labiosa et al., 2003). The water column of the northern Gulf of Aqaba is stratified during summer and, under usual conditions, surface water nutrient levels are depleted to levels near the limits of detection (Levanon-Spanier et al., 1979; Mackey et al., 2007). During the summer months, dry atmospheric deposition is a significant source of nutrients in the euphotic zone, supporting transient phytoplankton blooms (Chen et al., 2007; Paytan et al., 2009). Beginning in the fall, the cooling of surface waters initiates a convective mixing along with the erosion of the thermocline, and a deeply (usually 300 m, occasionally down to the bottom) mixed water body is observed by winter (Wolf-Vecht et al., 1992). In summer and fall, when nutrient concentrations are very low, picophytoplankton (cells < 2 μm) (*Prochlorococcus* and *Synechococcus*) abound in the surface water; with *Prochlorococcus* as the main component of the community during aestival stratification (Lindell and Post, 1995; Post et al., 1996; Mackey et al., 2007). During summer, *Prochlorococcus* and *Synechococcus* populations in the Gulf of Aqaba are exposed to phosphate limitation (Fuller et al., 2005; Mackey et al., 2009). During winter and early spring, the convective component of entrainment is strong enough to mix the surface waters below the critical depth, as well as bring to the surface (Labiosa et al., 2003) large quantities of nutrients, which maintain the nitrogen-phosphorus ratio close to the Redfield ratio (Häse et al., 2006). The increase in nutrient availability following autumnal mixing leads to the replacement of picophytoplankton with larger *Chlorophyceae* and *Cryptophyceae* (Al-Najjar et al., 2007). Indeed, phytoplankton patterns follow the seasonal hydrological cycle in the Gulf of Aqaba (Iluz et al., 2008).

1.2. Aim of the study

The aim of this study was to develop ecological models, based on a three-year (2007–2009) dataset, to analyze, simulate, and predict the phytoplankton dynamics in the surface layer (1 m depth) of the northern Gulf of Aqaba. The purpose is to clarify the role of the fish farm activity in a possible alteration of phytoplankton dynamics.

2. Materials and methods

2.1. Site description

The Gulf of Aqaba is one of two large gulfs in the Red Sea (Fig. 1), located east of the Sinai Peninsula and west of the Arabian mainland, and separated from the Red Sea by the 252-m-deep sill at the Straits of Tiran. This gulf is 170 km long and 14–24 km wide, with an average depth of 800 m and a maximum of 1830 m. For these reasons, the Gulf of Aqaba represents a small-scale, easy-to-access, regional analogue of larger oceanic oligotrophic systems (Chen et al., 2008). In the Gulf of Aqaba, the climate is extremely arid – the annual precipitation at the northern gulf averages only 30 mm – and hot, with summer air temperature reaching up to 45 °C and with prevailing northerly winds. Excess evaporation over this minimal precipitation is in the range of 2000 mm yr^{-1} (Monismith et al., 2006). No rivers flow into the gulf, and fresh water, other than rain, reaches it only occasionally during rare winter floods. The coral reef off the coast of Eilat and Aqaba, the two largest cities in this area, supports a thriving economy based primarily on tourism. Relative isolation from the main Red Sea and the Indian Ocean, intense solar radiation for most of the year, low plankton biomass and levels of particulate organic matter in the water column, characterize the Gulf of Aqaba. The low levels of nitrogen and phosphate are the main factors limiting primary production (Al-Qutob et al., 2002; Labiosa et al., 2003). This area is dominated by mineral dust deposition and is surrounded by deserts; anthropogenic air emissions can make a significant contribution to the level of various trace elements, such as Cu, Cd, Ni and Zn (Chen et al., 2008). In recent years, the atmospheric inputs of other nutrients gradually increased the likelihood of P limitation in the gulf (Chen et al., 2007). Consequently, P limitation in the ocean may be more prevalent than previously estimated, and the efficiency of P uptake among individual groups of phytoplankton may, in fact, control the phytoplankton species composition observed in a given community (Paytan and McLaughlin, 2007).

2.2. Sample collection

In this study, a monitoring database from two different sampling stations, the fish-farm station, situated several 100 m off the northern coast of the Gulf of Eilat (FFS, 29°32′ N, 34°56′ E), and Station A, on the Israeli/Jordanian/Egyptian border (STA, 29°28′N, 34°55′E) (Fig. 1), was used. The data were sampled over a period of three years (from January 14th, 2007, to December 28th, 2009) as part of the project "Protecting the Gulf of Aqaba from Anthropogenic and Natural Stress", supported by the NATO Science for Peace and Security Program (SPS), aboard the Queen of Sheba research vessel. Data were sampled during monthly cruises, for a total of 35 samplings, including measurements of chemical, physical, and biological parameters at the same depths. In particular, the concentration of chlorophyll *a*, nitrate (NO_3), phosphate (PO_4) and silicate ($SiOH_4$) as well as water temperature were sampled for both sampling stations at 1 m depth (Fig. 2 A-E). The concentration of nitrite (NO_2) and ammonium (NH_4^+) were also sampled but they were not used because they were excessively discontinuous (i.e., contained many gaps). In this work, we chose not to use the irradiance measurements from the sampling stations and, instead, we obtained them from the Interuniversity Institute for Marine Sciences (IUI), Eilat, where hourly observations of irradiance were available, thus providing our study with a dataset characterized by a much higher time resolution (Fig. 2F).

The fish farms were operational until June 17th, 2008 (final closure date), about halfway through the overall sampling period. The maximum sea depth at the FFS location was 56 m. The STA sampling point was about 13 km away from the FFS, had a 700 m maximum depth, and no apparent direct anthropogenic influence, thus representing a sort of control station with respect to the FFS location, which could be expected to be under the potential influence of human coastal processes, such as maricultural activities. To collect the water samples, a CTD-Rosette (Sea-Bird) equipped with 11 Teflon-coated Niskin bottles (12 L), a CTD (SBE 19-02, SeaBird), a photometer, LICOR (Li-190SA), and a fluorometer (Sea-Point Sensors Inc.), were used. Chlorophyll *a* samples (250 ml) were kept in a dark container and processed within 8 h of sampling, concentrated on 25 mm Whatman GF/F filters, extracted overnight in 90% acetone and measured using the fluorometric method described by Parsons et al. (1984). Extracted chlorophyll *a* measurements were used to calibrate the in situ fluorescence profiles measured during the same hydrocast. The CTD fluorescence profiles for hydrocasts with no extracted chlorophyll *a* were calibrated using extracted chlorophyll *a* data from the closest sampling dates. Colorimetric analyses (Grassohoff et al., 1999) were conducted using a Flow Injection Autoanalyzer (Lachat Instruments Model QuikChem 8000). The analyses were fully automated and peak areas were calibrated using standards prepared in nutrient-depleted filtered seawater.