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Flux of nutrients in the Gulf of California: Geostrophic approach

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Abstract

Continental margins exert a strong influence on global biogeochemical cycles; however there have been relatively few attempts to quantify either the magnitude or nature of temporal variability in material fluxes. At present here are no reports on nutrient fluxes at the mouth of the Gulf of California (GC) so further information is needed to provide estimated values from direct measurements. From 1995–1999 during five cruises covering all seasons, seawater samples were collected and measured the nutrient content from the surface to the bottom (some deeper than 2500 m) from a repeated hydrographic sections at the mouth of the GC. This chemical and physical database is unique because it covers an area with important biogeochemical signs, which has been detected as one of the highest in primary productivity of the world oceans. These sections are perpendicular to the coastlines of the Mexican states of Baja California Sur (BCS) and Sinaloa. In this section, the most dynamic area was the surface waters in February 1999 with strong geostrophic currents and temperatures of 20 ± 1.5 °C; salinity 35.091 ± 0.156; pH 8.16 ± 0.13; phosphate 0.85 ± 0.42 μM, nitrate + nitrite 2.35 ± 2.94 μM, and ammonia 2.00 ± 1.25 μM (average ± standard deviation).

Geostrophic velocities were computed from high-resolution CTD sections across the entrance to the GC. During winter and spring, the outflow occurred near BCS and the inflow occurred either through the center of the section and/or along the Sinaloa coast. Both inflow and outflow cores were 45 km wide and extended deeper than 700 m. Summer and fall showed a complex pattern, alternating cores of inflow and outflow but with inflow along Sinaloa on all cruises. The maximum flow into the Gulf occurs during May in the center of the section while outflow was concentrated along BCS. Mascarenhas et al. [Mascarenhas, A., Castro, R., Collins, C.A., Durazo, R., 2004. Seasonal variation of geostrophic velocity and heat flux at the entrance to the Gulf of California, Mexico. J. Journal Geophysical Research, 2124.] calculated the section mean geostrophic velocity that was composed of two alternating cores of inflow and outflow. The two cores that were adjacent to either coast were broader and contained the highest inflow (0.40 m s^{-1}) and outflow (-0.25 m s^{-1}) velocities, supporting the general idea of inflow along the Sinaloa and an outflow along BCS.

The highest nutrient fluxes occur during El Niño conditions in November 1997 with outflows as high as 54.5 Tg yr^{-1} for Phosphate, 43.0 Tg yr^{-1} for Nitrate and 31.7 Tg yr^{-1} for Ammonia, this values were at least three times higher than in February 1999.
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1. Introduction

The Gulf of California or Sea of Cortez (henceforth GC) is a semi-enclosed large marine ecosystem bordered by the Baja California peninsula and by mainland Mexico between 23–32° N and 107–117° W

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(Fig. 1). It opens into the Pacific waters at its southern end.

The Pacific Ocean is the primary driver of the gulf's physical oceanography; filling it with Pacific water masses and forcing its tides, also controls local surface forces that influence the seasonal circulation, heat and salt balances (Castro et al., 2000; Lavín, 2002). The nutrient fluxes can be related to different forces within the GC. Since the tidal and the seasonal (annual and semiannual) frequencies permeate most of the gulf's oceanography, they have been extensively studied (Bustos-Serrano et al., 1996). Local air–sea interactions are far from negligible, because they control: sea surface temperature, average thermodynamics (heat and salt balance, sea level), mean thermohaline circulation and produce the Gulf of California Water (Lavín and Marinone, 2003). Strong wind events lasting from a few days to a couple of weeks are common in the gulf introducing considerable variability in surface circulation and air–sea heat fluxes.

To gain a better understanding of the GC hydrography and nutrient fluxes one needs to concentrate on direct measurements of the transfer of properties across the sea surface, and to focus on details of the forcing produced by the Pacific Ocean (seasonal and during El Niño), upwelling events (Bustos-Serrano et al., 2000), as well as the impact of internal waves (Filonov et al., 2000; Gaxiola-Castro et al., 2002; Konyaev and Filonov, 2002), vertical and horizontal mixing, jets and gyres (Martinez, 2002; Pegau et al., 2002; Trasviña and Graef, 1997).

The most important inter-annual meteorological and oceanographic perturbation in the GC is produced by El Niño (Baumgartner and Christensen, 1985; Lavín and Marinone, 2003) which originates at the Equatorial Pacific Ocean and affects not only the GC, but the whole Earth (Philander, 1990).

A wide range of nutrient concentrations are found at the GC (Alvarez-Borrego et al., 1978). Nutrient concentrations are higher with an increase in latitude, consistent with the river runoff near the coast of Sinaloa and with the characteristics of the water masses that converge at the mouth of the GC. The phytoplankton biomass responds to the nutrient inputs showing a spatial variability at the GC (Gaxiola-Castro et al., 1999). Photosynthetic pigment, pH and nutrient fluxes are excellent tools to evaluate the productivity of the GC (Bustos-Serrano et al., 1996).

The northern part of the GC is shallow, due to the large amount of sediments produced over the centuries by the Colorado River run-off. Winds, tidal action and upwelling characterize this large marine ecosystem which has mixed semi-diurnal tides and one of the greatest tidal ranges on Earth. In this region during the transition from high to low tide, the water level drops 9 m in less than one hour exposing more than 4 km of beach.

The GC is considered to be a large evaporative basin (Beron-Vera and Ripa, 2000), comparable with the Mediterranean and Red seas. The Gulf gains heat at an annual rate of 118 W m^{-2} (Castro et al., 1994), and therefore the water loss and heat gain modify the seawater properties creating an unique water mass and a strong exchange with the Pacific Ocean. This exchange takes place at the Pescadero Basin located at the mouth of the GC.

Historically the presence of mesoscale eddies in the southern GC have long been suggested by researches (Emilsson and Alatorre, 1997; Trasviña and Graef, 1997). More recently, numerical models and satellite images of the GC have shown the existence of multiple eddies with a spatial scale similar to the width of the gulf. Some of these eddies and their sense of rotation seems to be related with high chlorophyll concentrations and weakly related to sea surface temperature (Martinez, 2002; Pegau et al., 2002). Observations and numerical models show that eddies could extend into depths of 500–1000 m range. If the eddies transport materials, the distribution also will affect the nutrient concentration at specific levels in the water column, giving different values of nutrient fluxes.

Roden (1964) using sections at the GC mouth, found a surface outflow (0.10–0.15 m s^{-1}) from February to May, and an inflow between June and September (0.10 m s^{-1}), he defined a net outflow on the surface with speeds of 0.10 m s^{-1} in February and 0.21 m s^{-1} entering into the Gulf in August.

One of the early attempts to show that different water masses occupy the Gulf was made by Wyrtki (1967) and Torres-Orozco (1993) using *T*–*S* diagrams (Fig. 1) (Castro et al., 2000; Lavín and Marinone, 2003). Today, SST images show surface water currents and circulation patterns. At the mouth, the California Current Water had colder temperatures ($T<20$ °C) and less saline ($S<34.5$) waters; the NW transport evidenced warm water and intermediate salinity ($T>25$ °C; $34.6<S<34.9$) from the Eastern Tropical Pacific in the SE area and transport to the south showed high salinity and moderate temperature water ($S>34.9$; 22 °C$<T<$25 °C) from the upper gulf (Torres-Orozco, 1993).

At the entrance to the GC the convergence of al least three different water masses can be found: 1) Tropical

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