A snapshot view of some vertical distributions of water parameters at a deep (200 m) station in the fjord-like Golfo Dulce, embayment, Costa Rica

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Received 30-XI-2005. Corrected 02-II-2006. Accepted 30-III-2006.

Abstract: Temperature, salinity, dissolved oxygen and inorganic nutrients were measured at a single station in the water column (200 m) of Golfo Dulce, a fjord-like embayment on the Pacific coast of Costa Rica, from June 1993 to September 1995. Eight sampling field trips were carried out and water samples were collected with 5 L Niskin bottles at 10 m depth intervals. Temperature vertical profiles revealed a thermocline between 25 and 60 m. Salinity profiles evidenced a surface layer containing a halocline around 40 m, overlaying a thick 34 ‰ layer on top of a large bottom layer of 35 ‰. Surface-oxygen saturation percentages were usually high, but from 60 m depth down to the bottom (200 m), dissolved oxygen concentrations were low during the whole study, ranging from 3.00 mg/L to 0.20 mg/L, although anoxic conditions were not detected. Bottom waters were rich in inorganic phosphate, silicate, and nitrate, suggesting that its main source is the sporadic influx of ocean water mass entering the gulf at the sill depth (60 m). The pattern of the vertical nitrite concentration suggested that the anammox process can result as a consequence of bacteria existing at low oxygen concentrations at depth. These observations are in agreement with those reported in other surveys since 1971. Rev. Biol. Trop. 54 (Suppl. 1): 193-200. Epub 2006 Sept. 30.

Key words: temperature, salinity, dissolved oxygen, inorganic nutrients, tropical fjord, anoxic seawater, Costa Rica, Pacific Ocean, Golfo Dulce.

Golfo Dulce is a tropical fjord-like embayment located in the south Pacific coast of Costa Rica, between 08°23’ and 08°45’ N, and 83°05’ and 83°29’ W (Fig. 1A). Spanish explorers, Juan de Castañeda and Hernán Ponce de León, discovered the gulf in 1519 (Fernández 1905). The gulf extends approximately 30 km from its mouth to Rincón Bay (Fig. 1B). The average width is about 12 km, in a range of 8.5 to 17.5 km. Partially separating the gulf from the adjacent Pacific Ocean, there is a sill about 60 m deep at the entrance of the gulf, lacking soft sediment cover due to the sweeping of strong tidal currents there (Hebbeln *et al.* 1996). From there, the bottom begins to deepen towards a region that consists of an elongated and narrow area of approximately 12 km^2, at a depth of 200 m (Fig. 1B). A layer of young and soft sediments 10 m or more thick, mainly turbidites with wood and leaf fragments (Hebbeln *et al.* 1996, León-Morales and Vargas 1998), covers this area. Golfo Dulce lies in a climatic region subjected to a well-defined dry season from February to March, a rainy season from May to

December. January is generally a transitional month. Some meteorological data gathered within the period of this study by the Instituto Meteorológico Nacional (2000), in a local station at 08º 36' N and 82º 59' W, altitude 8 m, is included in Table 1. This zone experienced a total monthly amount of 275.2 mm of rain on June 1993, whereas on October it raised to 501.5 mm. April 1994 totaled 208.3 mm, July 459.7 mm, and in 1995, May received 410.9 mm and September 523.3 mm.

Richards *et al.* (1971) first described the Golfo Dulce main oceanographic characteristic, as a transient anoxic basin. The gulf was further evaluated in a multidisciplinary research program, conducted jointly by the Centro de Investigación en Ciencias del Mar y Limnología (CIMAR, Universidad de Costa Rica), and the Zentrum für Marine Tropenökologie (ZMT, University of Bremen), during the period 1993-1994 (Córdoba and Vargas 1996, Thamdrup *et al.* 1996, Vargas and Wolff 1996). Golfo Dulce was included among four contrasting coastal ecosystems to be investigated upon its current oceanographic characteristics and its pollution status (García *et al.* 2006, Acuña-González *et al.* 2004, García-Céspedes *et al.* 2004, Spongberg 2004b). Dalsgaard *et al.* (2003) discovered that, besides the usual denitrification processes within the nitrogen biogeochemical global cycle, the anaerobic oxidation of ammonia with nitrite, the anammox reaction, also is at work in the anoxic deep waters of Golfo Dulce. Recently, Svendsen *et al.* (2006) Have developed a model for water circulationn in Golfo Dulce.

Umaña (1998) has described the Golfo Dulce drainage basins: the major freshwater inputs are from two rivers, Esquinas and Coto-Colorado, both along the northeast side of the gulf, and seven smaller rivers along the internal arc of the Peninsula, conforming to the west-south margin of the gulf. The Rincón river is the most important in the inner gulf region (Fig. 1B). Besides rainfall, these riverine sources influence the estuarine character of the gulf. Freshwater also enters the gulf as diffuse runoff from the near mountainous system. The town of Golfito (population near 8 000) produces sewage and oil wastes discharged untreated at an eastern shore bay, where a small port is located (Fig. 1B). An important amount of sediment load reaches the gulf since deforestation and gold mining has occurred, and is still in progress, around its borderline areas, at times even in and at nearby protected zones and the Corcovado National Park (Acuña-González *et al.* 2004, García-Céspedes *et al.* 2004, Spongberg 2004a, b).

TABLE 1
Meteorological Data for Estación Coto 47
(08º36' N and 82º59' W, altitude 8 m), Costa Rica

Year (Month)	Rain (mm)	Temperature (ºC)	
		Maximum	Minimum
1993			
June	275.2	31.5	22.9
October	501.5	30.8	21.2
1994			
April	208.3	33.0	21.4
July	459.7	30.9	21.8
December	231.5	31.7	22.0
1995			
May	410.9	31.2	23.0
September	523.3	32.4	21.7

Data presented and discussed herein were collected during the rainy seasons of different years, between June 1993 and September 1995, in a total of eight cruises to a station on the deepest (200 m) region of Golfo Dulce (08º41' N and 83º23' W, Fig. 1B). Such visits were not part of a systematic oceanographic survey, but opportunity surveys associated to other CIMAR activities. Therefore, in order to strengthen the features of the profiles showed here, additional information on temperature, salinity and dissolved oxygen from a cruise carried out by two of the authors (Córdoba and Vargas 1996) on January 12, 1994, was included.

Water samples were taken from surface to bottom (200 m) along the water column,

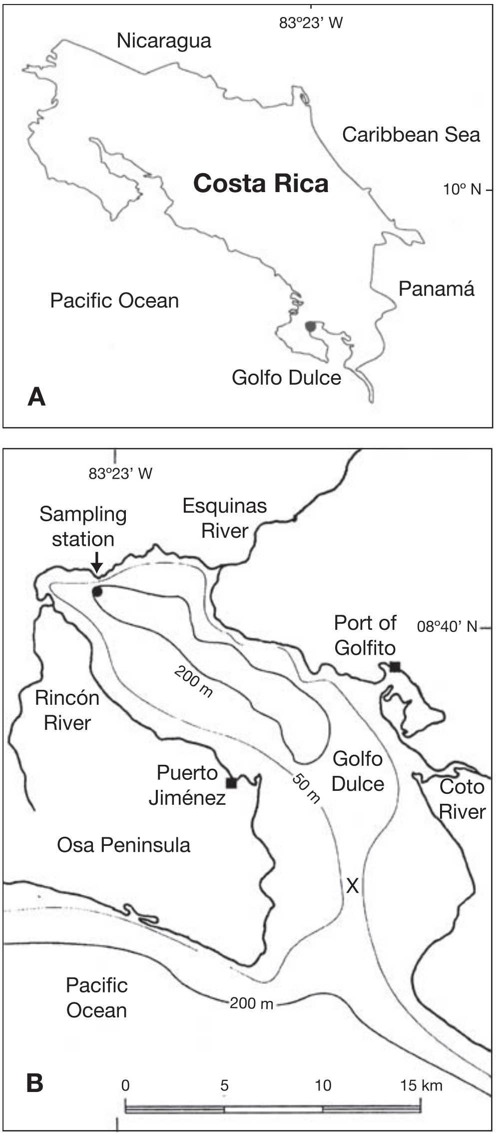

Fig. 1. A. Costa Rica, Central America, location of Golfo Dulce on the Pacific coast. B. Golfo Dulce, location of the sampling station in the inner gulf. X: sill location.

at 10 m depth intervals, using a hand winch equipped with a wire meter, and a 5 L Niskin bottle. Temperature and salinity were measured *in situ*, using a temperature sensor from a YSI model 55 oxygen meter and a refractometer calibrated with standard sea water. For dissolved oxygen determinations, the Winkler method was applied (Strickland and Parsons 1972). Samples were drawn into 300 mL BOD bottles immediately after they were lifted on deck, and pickled by the addition of manganous sulphate and alkaline iodide solutions. The analyses were completed at the shore facilities. 500 mL polyethylene bottles were filled after the BOD bottles, stored in a cooler while in the boat, and then frozen in the laboratory until the analysis was commenced for the spectrophotometric determinations of inorganic micronutrients in seawater, conducted according to Strickland and Parsons (1972), but scaling for 10.0 mL sample volumes.

At the station in the deepest northern portion of the gulf, seawater temperature vertical gradients (Fig. 2) were evident. Major gradients occurred in the first 60 m (range 1.3 to 2.1 ºC/10 m), which revealed an ongoing surface layer mixing process. A thermocline was found between 25 and 60 m depths, the interval varying according to the oceanographic and meteorological characteristics during the sampling dates. Surface temperature values were in the range of 27.0 to 30.0 ºC (average and standard deviation of 29.3 ± 1.0 ºC), reduced to lower values at 100 m deep (range 14 to 20 ºC, average 17.1 ± 1.8 ºC). Deeper than 150 m, the temperature range was 12.0 to 18.0 ºC, average 16.2 ± 1.8 ºC. The water column temperature, gradually and slowly decreased from 100 m down to the bottom, in an average rate of about 0.13 ºC/10 m. This vertical structure of the water column is also subject to the influence of the El Niño phenomenon (Quesada-Alpízar and Morales-Ramírez 2004, 2006).

Surface salinity during the eight sampling trips ranged between 20 and 32 ‰. At this locality, the influence of freshwater from the Esquinas and Rincón rivers was perceptible, since several low salinity values were measured. Other variations probably were related to rainfall, as well as evaporation. Low surface salinities coincided with the rainiest periods, and it was apparent that the fresh runoff and rainwaters on top of the lower saltier layer formed or originated off the sill, mixed progressively; prevailing winds, conjointly with tidal currents being the most likely cause. A

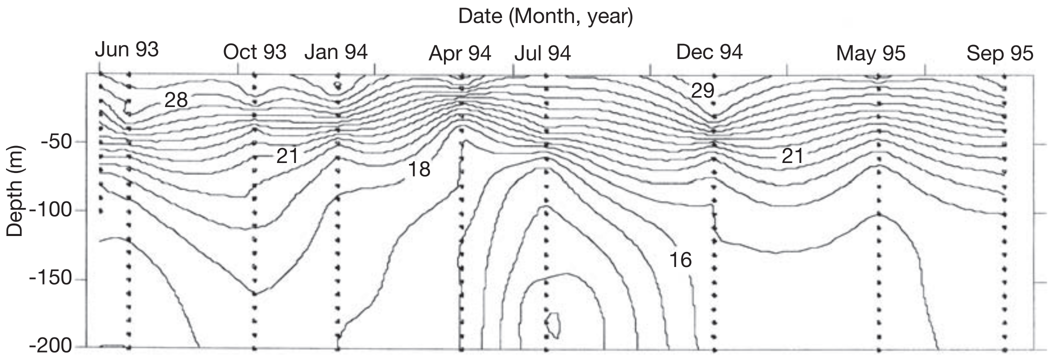

Fig. 2. Temperature (ºC) temporal variation in the water column of the deepest point of Golfo Dulce, Costa Rica, 1993-1995.

halocline might be placed between 10 and 50 m depths, depending on the oceanographic and meteorological conditions during the sampling date, although a figure of 40 m deep could be taken as an acceptable average for this gulf. In all cases, two bottom layers (Fig. 3) characterized the water column. A thick oscillating up and down layer of water of 34 ‰ separated the mixing upper layer from the large bottom water mass of 35 ‰. Both temperature and salinity vertical profiles suggested that the waters below 60 m were almost stagnant or under a slow circulating bottom system, relatively isolated from the upper layer. It was also apparent that even at the distant sampling site (nearly 44 km) from the sill (60 m deep), an upper layer of some 50 to 60 m in thickness, was still present, with physical features of temperature and salinity under a broad trend of variation with depth.

Surface-oxygen saturation percentages ranged from 124 % to 81 %, except for the July and December 1994 sampling cruises, when values were lower, 47.9 % and 67.5 % respectively, and the vertical profiles showed a subsurface maximum in the first 10-20 m, not apparent in the other cruises. These low saturation percentages concurred with low salinities (20 and 25 ‰, respectively), and high temperatures (27.0 and 30.0 ºC, respectively). It was probable that these surface minima were due to the oxidation of organic matter carried in excess by runoff waters in times of high precipitation (Table 1). In all cruises, an oxycline was detected, and in general, dissolved oxygen concentrations (DOC) diminished regularly along the water column (Fig. 4), in a way that at depths of 60 m they had attained between 7.5 % and 60 % of their value at the surface. Kuever *et al.* (1996) determined high microbiological activity produced by high numbers of bacteria and plankton, in the first 40 m of the Golfo Dulce water column, depth that characterized

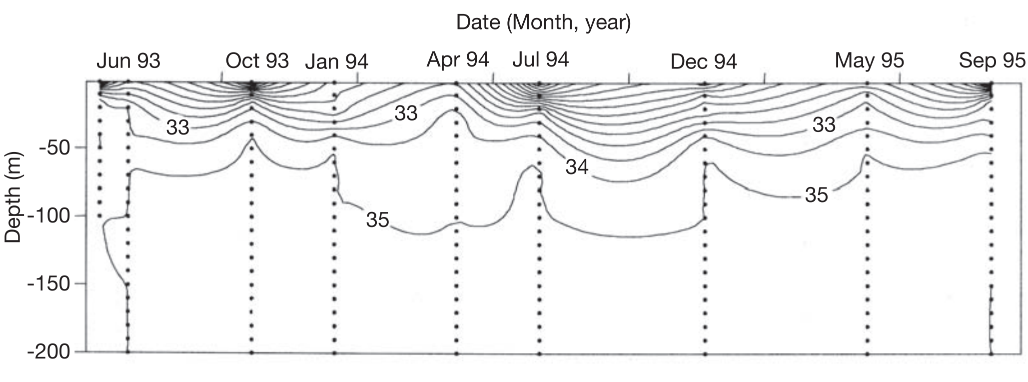

Fig. 3. Salinity (‰) temporal variation in the water column of the deepest point of Golfo Dulce, Costa Rica, 1993-1995.

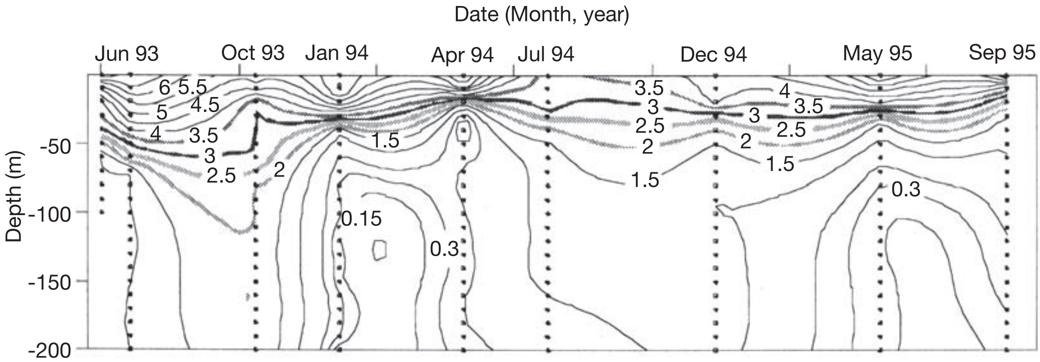

Fig. 4. Dissolved oxygen concentration (mg·l^{-1}) temporal variation in the water column of the deepest point of Golfo Dulce, Costa Rica, 1993-1995.

the photic zone. From the 60 m depth down to the bottom, we found the DOC were substantially low during the whole study, in the range of 3.00 mg/L to 0.20 mg/L, average 0.91 ± 0.62 mg/L (n = 57), but anoxic conditions were not observed. Such state of low-oxygen content indicated that there was in effect consumption of oxygen by decomposition of sinking remnants of organisms, like those described by Hebbeln *et al.* (1996), Kuever *et al.* (1996) and Thamdrup *et al.* (1996) for Golfo Dulce bottom waters and sediments. In Fig. 4, the intermediate 1.5 and 2.0 mg/L DOC isopleths established a boundary that coincided with the water mass of 34 ‰.

Due to its geomorphologic shape (similar to a deep funnel) and the water circulation patterns (Hebbeln *et al.* 1996), this basin may act as a nutrient trap; consequently, inorganic phosphate concentrations (IPC) should be expected to be higher in deep waters. In general, the IPC in the water column at our station in Golfo Dulce increased with depth as shown in Fig. 5, from a near depleted surface layer to values in the range of 1.8 to 2.6 µmol/L at depths beyond 100 m, in good agreement with the results of Thamdrup *et al.* (1996). Considering the two salinity layers of bottom water (Fig. 3), for the top one of 34 ‰, IPC ranged from 0.13 to 3.61 µmol/L (average and standard deviation of 1.36 ± 1.03 µmol/L, n = 18). For the bottom one of 35 ‰ IPC ranged from 0.57 to 3.00 µmol/L (average and standard deviation of 2.17 ± 0.52 µmol/L, n = 35). Inorganic silicate

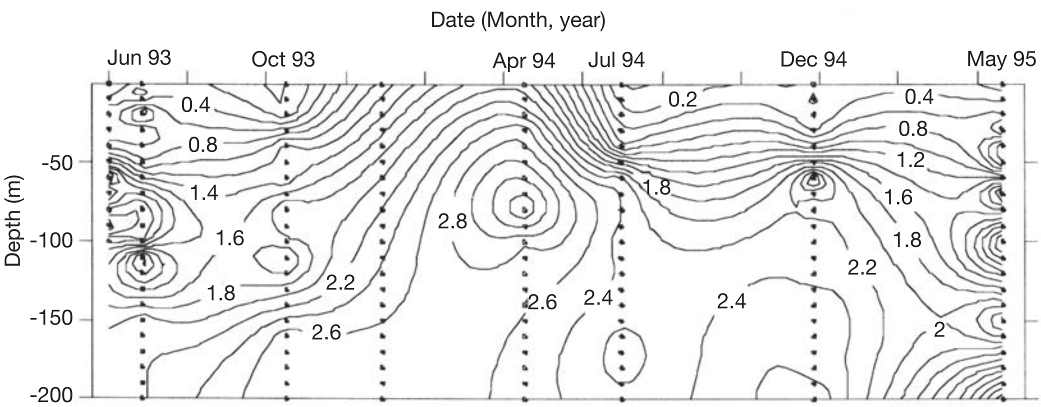

Fig. 5. Inorganic Phosphate concentration (µmol/L) temporal variation in the water column of the deepest point of Golfo Dulce, Costa Rica.

concentrations (ISC) showed a sharp decrease within the upper surface layer (Fig. 6). Surface ISC in the range of 15.1 to 106.0 µmol/L were used up to between 85 to 100 % in the first 10 m, and then increased with depth to concentrations in the range of 20.0 to 55.0 µmol/L in the 34 ‰ layer and from 20.0 to 87.7 µmol/L in the 35 ‰ bottom layer. Nitrate appears to be a mayor inorganic nitrogen nutrient in the basin. Occasionally, nitrate enters the gulf through land runoff streams as shown by the June 1993 and December 1994 high surface concentrations, but usually the water mass that enters at the sill depth provides the bulk amounts. The most obvious features in the inorganic nitrate concentrations (INAC) vertical profiles (Fig. 7), were a markedly depletion over the oxic zone, likely related to denitrification processes (Thamdrup *et al.* 1996), and then an important increase with depth. The INAC above the 34 ‰ ranged between non-detectable by the used analytical method (Strickland and Parsons 1972) and 7.73 µmol/L. Within the bottom layers, at the 34 ‰ layer the range was from non-detectable by the used analytical method, to 28.1 µmol/L, (average and standard deviation of 11.2 ± 8.1 µmol/L, n = 19). In the 35 ‰ layer the range was from non-detectable by the used analytical method, to 26.4 µmol/L, (average and standard deviation of 13.0 ± 7.8 µmol/L, n = 39). These averages were higher than those measured by Thamdrup *et al.* 1996, but the

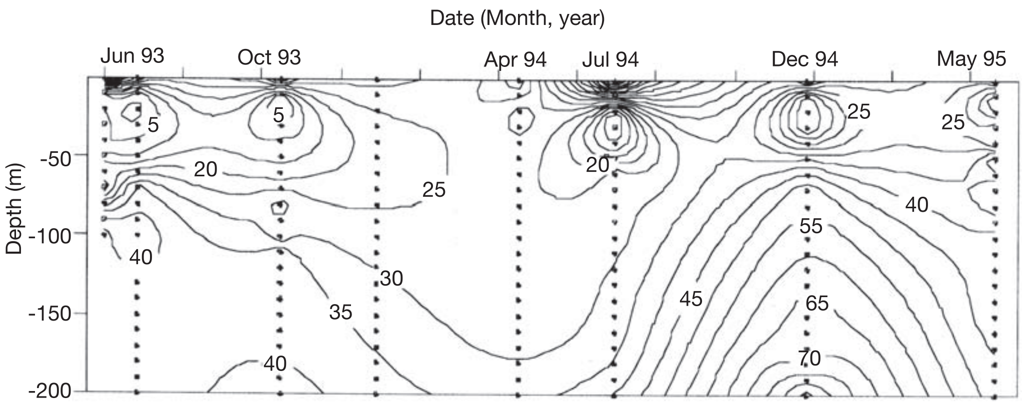

Fig. 6. Inorganic Silicate concentration (µmol/L) temporal variation in the water column of the deepest point of Golfo Dulce, Costa Rica, 1993-1995.

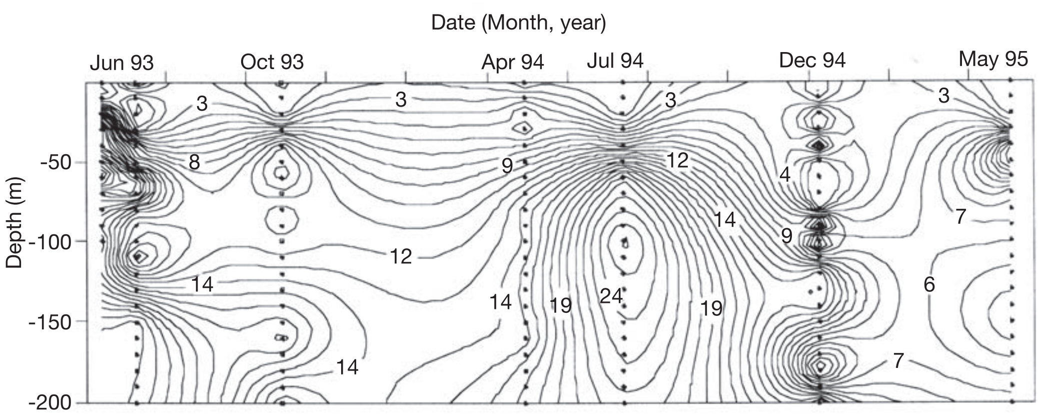

Fig. 7. Inorganic Nitrate concentration (µmol/L) temporal variation in the water column of the deepest point of Golfo Dulce, Costa Rica, 1993-1995.

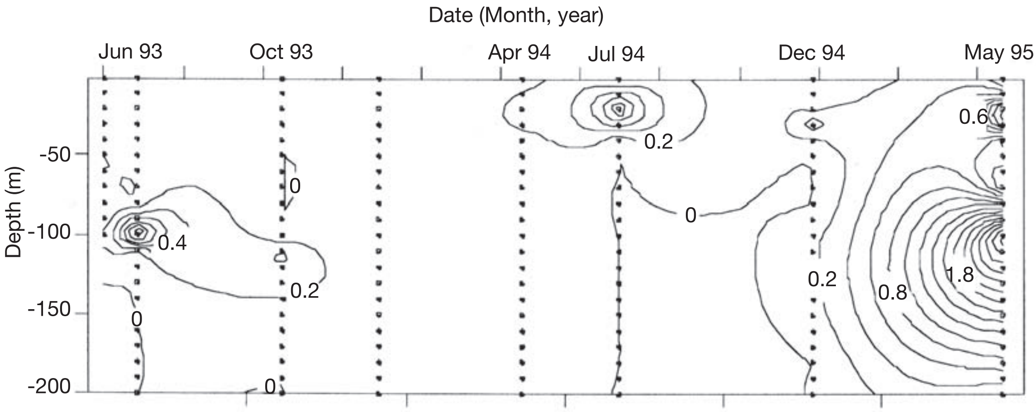

Fig. 8. Inorganic Nitrite concentration (µmol/L) temporal variation in the water column of the deepest point of Golfo Dulce, Costa Rica, 1993-1995.

pattern was similar. The inorganic nitrite concentrations (INIC) in the water column, were very low or practically absent, that is, within or below the detection limits of the analytical technique (Strickland and Parsons 1972, Meier and Zünd 1993), specially for the June and October 1993 and the July and December 1994 cruises (Fig. 8). The active mechanism here may be the anammox process (Dalsgaard *et al.* 2003), a microbial process that consumes nitrite and could be of major importance in those marine environments with very low oxygen concentrations (Devol 2003), as is the case of the deep waters of Golfo Dulce.

ACKNOWLEDGMENTS

To Alberto León, Eleazar Ruiz, and Davis Morera for their help in the field, and to two anonymous reviewers for their comments on the first draft. The Instituto Meteorológico Nacional de Costa Rica provided data from Estación Coto 47. The Universidad de Costa Rica, (CIMAR), project 808-AO-506, and the Costa Rica-United States of America (CR-USA) Foundation for Cooperation, partially supported the preparation of this manuscript.

RESUMEN

Se midió la temperatura, la salinidad, el oxígeno disuelto y los nutrimentos inorgánicos, en un punto fijo de la columna de agua (200 m) de Golfo Dulce, una cuenca tipo fiordo, en la costa Pacífica de Costa Rica, de junio de 1993 a septiembre de 1995. Se llevó a cabo un total de ocho cruceros y las muestras de agua se recolectaron con botellas de Niskin de 5 L, a intervalos de 10 m de profundidad. Los perfiles verticales de temperatura revelaron la presencia de una termoclina entre 25 y 60 m. Los perfiles de salinidad pusieron en evidencia una capa superficial en la que se pudo ubicar una haloclina alrededor de los 40 m. Esta capa de agua superficial descansaba sobre una capa gruesa caracterizada por una salinidad de 34 ‰, la cual, a su vez, permanecía sobre otra capa profunda de 35 ‰. Los porcentajes de saturación de oxígeno en la capa superficial, por lo general fueron altos; sin embargo, las concentraciones de oxígeno disuelto de los 60 m de profundidad hasta el fondo (200 m) fueron bajas durante todo el estudio, en el ámbito de 3.00 mg/L a 0.20 mg/L, aunque no se detectaron condiciones anóxicas. Las aguas del fondo fueron ricas en los nutrimentos inorgánicos fosfato, silicato y nitrato, lo cual sugirió que su fuente principal es la masa de agua que penetra al golfo por el umbral (60 m). El patrón de la distribución de la concentración de nitrito sugirió que el proceso de anammox puede resultar como consecuencia de bacterias que viven a profundidades en las que la concentración de oxígeno disuelto es baja. Estas observaciones concuerdan con aquellas informadas en otros estudios llevados a cabo desde 1971.

Palabras clave: Temperatura, salinidad, oxígeno disuelto, nutrientes inorgánicos, fiordo tropical, agua de mar anóxica, Costa Rica, Océano Pacífico, Golfo Dulce.

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