

A physical-oceanographic study of Golfo Dulce, Costa Rica

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Abstract: A physical-oceanographic investigation based on field experiments and applications of a numerical model was carried out in Golfo Dulce, a fjord-like gulf at the Pacific coast of Costa Rica. Due to the nearness to equator the effect of the Coriolis force on the circulation is negligible. Cross gulf gradients are therefore mainly related to the runoff pattern, local wind and topographic effects. The upper layer is characterized by low salinity and high temperature. Local wind effects and topographic steering results in marked across gulf velocity gradients in the upper layer. Along-gulf gradients in temperature and salinity are maintained by the freshwater runoff from the four rivers in the inner part of the gulf. A three-layer current structure is dominating in the sill area while in the deeper inner part of the gulf a two-layer estuarine circulation takes place above slowly moving deep water. *Rev. Biol. Trop.* 54 (Suppl. 1): 000-000. Epub 2006 Jul. 31.

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Golfo Dulce, a periodically anoxic fjord-like embayment on the Pacific coast of Central America, is one of the largest embayments, on the southwestern Pacific coast of Costa Rica. Being an important protected region of Costa Rica, Golfo Dulce is normally included in Costa Rican marine biology studies (e.g. León & Vargas 1998, Morales-Ramírez 2001, Rodríguez-Fonseca 2001, Silva-Benavides & Bonilla, 2001, Dean 2004). Furthermore, increasing pressure on the environment due to coastal zone development (fishery, aquaculture, urbanization, etc.) has increased the need for mapping of the vulnerable ecosystem of the gulf. In a recent study for example, Carrillo *et al.* (2000) found that Golfo Dulce reserve seems to be achieving only partial success in protecting marine mammals wildlife and found that species were consistently less abundant in Golfo Dulce Forest Reserve than in other protected areas.

Recent oceanographic works have contributed to understand the Golfo Dulce marine system. A review of the literature is provided by Quesada and Cortés (2006). Quesada-Alpizar and Morales-Ramírez (2004) studied the vertical profiles of temperature, salinity and dissolved oxygen at five sampling stations in the Golfo Dulce. Their results showed a strong vertical stratification of the water column associated to the morphology of Golfo Dulce's basin and to the effects of El Niño-Southern Oscillation (ENSO). Dalsgaard *et al.* (2003) discovered that in the anoxic waters of Golfo Dulce the anaerobic oxidation of ammonium with nitrite-the 'anammox' reaction, performed by bacteria-was responsible for a significant fraction of N₂ production in marine sediments and it accounts for 19-35% of the total N₂ formation in the water column. They reported that water-column chemistry in Golfo Dulce is

very similar to that in oxygen-depleted zones of the oceans in which one-half to one-third of the global nitrogen removal is believed to occur.

Sedimentation processes in Golfo Dulce were investigated by Hebbeln & Cortés (2001). They found that a large proportion of non-biogenic material reflects the dominance of terrigenous sediment input to Golfo Dulce and that biogenic components such as organic carbon and carbonate are also supplied from terrigenous sources. The two components, however, originate from different parts of the coast surrounding the gulf. Studying the trace metal composition in marine sediments from several Costa Rican sites García-Céspedes *et al.* (2004) found that Golfo Dulce is an impacted estuary and presented higher metal concentrations when compared with other sites. Additionally, Sponberg (2004) found that in general Golfo Dulce show moderate polychlorinated biphenyls (PCB) contamination, despite the pristine nature of the gulf and surrounding lands and reported that the port of Golfito had the highest overall concentrations, ranging up to 15.7 µg/g dw sediment.

The present work was motivated by a multidisciplinary research program that was carried out in Golfo Dulce during 1993-1994: The Victor Hensen Costa Rica expedition, see Vargas and Wolff (1996). The overall goal of that program was to establish a basis for the conservation and sustainable management of the Pacific coastal areas of Costa Rica. However, the physical section of the research program covered just a modest part. The need for a more throughout investigation of the physics of the gulf was the background for the investigations that were carried out

in 1999 and 2001 in cooperation between the Center for Research in Marine and Limnology Sciences (CIMAR), University of Costa Rica, the Geophysical Institute, University of Bergen and the Center for Studies of Environment and Resources, University of Bergen. This paper reports our main results.

DESCRIPTION OF THE AREA

Topography: Golfo Dulce is a broad fjord-like embayment approximately 50 km long and 10-15 km wide, Figure 1. It is situated between 8°27' N and 8°45' N on the west coast of Costa Rica. The outer part of the gulf is oriented towards north (looking up-gulf) turning gradually towards northwest in the inner part. A sill area 20 km inward from the entrance

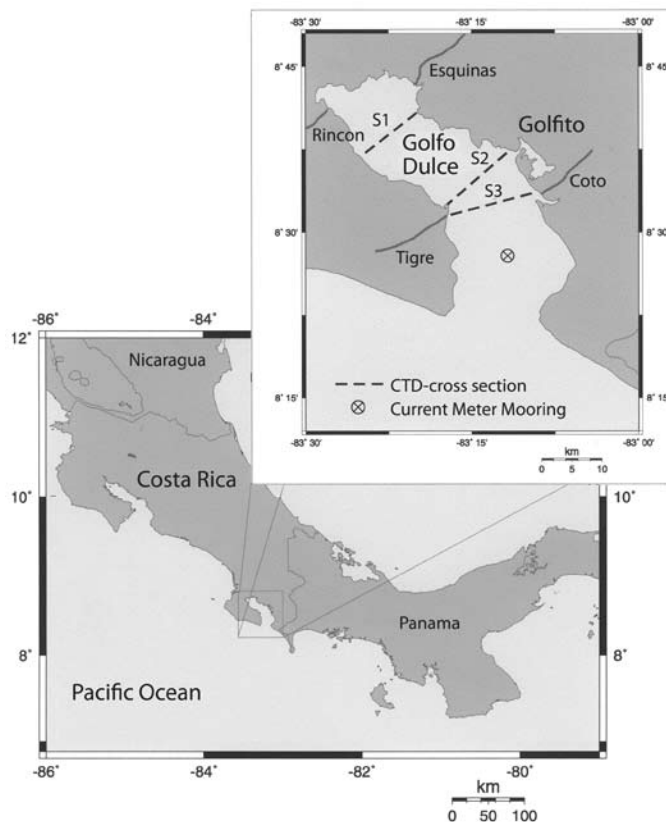


Fig. 1. Sketch of Costa Rica and of Golfo Dulce showing the positions of the CTD-transsects S1-S3, the position of the current meter mooring and the main rivers.

separates an inner deep basin with a flat bottom of maximum depth 215 meter from a shallow outer basin. The effective sill depth is about 60 meter and prevents water in the inner basin from free exchange with the adjacent coastal water masses. Anoxic conditions have been reported in the inner basin, but it is not established whether these conditions are permanently, Brenes & León (1988); Richards *et al.* (1971). The wide entrance of the gulf suggests that above sill level the exchange with the water masses at the narrow shelf takes place unobstructed. The gulf is strongly stratified all year round with an upper brackish layer of 40-50 meter above an almost homogeneous high salinity layer below.

Climate and wind: The climate is humid tropical with a marked rainy season from May to November. Precipitation exceeds evaporation at least eight months of the year (Herrera 1985). Monthly average precipitation varies from a maximum of above 700 millimeter in October to a minimum of about 100 millimeter in February (Fig. 2) resembling the dominant Pacific Central

American precipitation mode described by Taylor and Alfaro (2005). The total rainfall per year is more than 4.5 meter. The main part of the freshwater flow is expected to be channeled into the four rivers; Coto, Tigre, Esquinas and Rincón (Fig. 1). Estimated discharge from the four rivers is shown in Figure 3.

The wind conditions are characterized by a monsoon like pattern. Zonal component of the wind is eastward almost all around the year and the meridian component tends to be northward during the rainy season and southward during the dry season.

The tide: During the Lunar month the tidal range varies between 2 and 4 meters in the inner part of the Gulf. The barotropic tidal component is weakest in the inner deeper part, $\sim 0.1 \text{ ms}^{-1}$, while in the shallow sill area it is strong (0.5 ms^{-1}). According to simulations with a two-dimensional model, Quirós (1989, 1990), the tide in the gulf may be characterized in three zones; (i) the sluggish tidal currents ($< 0.5 \text{ m s}^{-1}$) in the inner deep basin; (ii) a zone

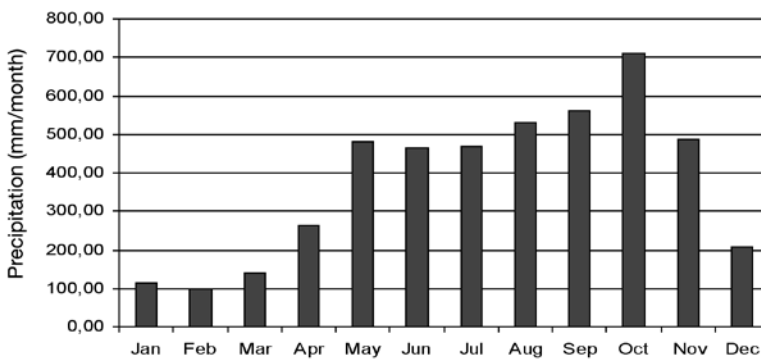


Fig. 2. Monthly precipitation (mm/month) in the catchment basin of Golfo Dulce.

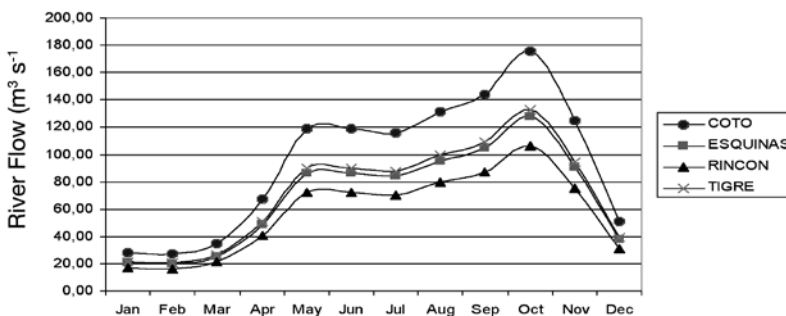


Fig. 3. Estimated freshwater discharge from the four main rivers (Coto, Esquinas, Rincón and Tigre) entering Golfo Dulce.

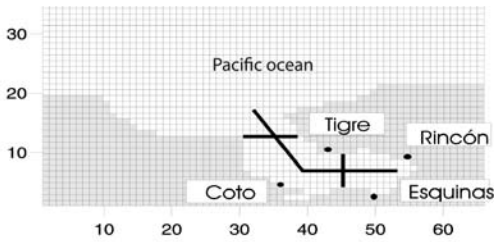


Fig. 4. A rotated map as implemented in the model, with the horizontal grid sells and land contours. The circles mark the positions of the four rivers and the lines the location of the vertical sections of the figures presented in the results.

between Puerto Jiménez and Golfito where formations of large eddies take place during rising tides, and (iii) the mouth area where the tidal wave passing over shallow areas creating relatively strong currents. The model is homogeneous and thus do not give any information about the forced internal (baroclinic) tide which may be considerable in the gulf.

METHODS

The investigation is based on field experiments and numerical simulations. The field program was carried out in Golfo Dulce from a small boat (R/V Kais of CIMAR) on three short cruises in 1999: 27-29 January, 1-2 February and 17-18 November respectively, and one cruise on 21-22 February 2001. The purpose of the program was to sample data to describe the main characteristics of circulation and hydrography of Golfo Dulce.

The model simulations are carried out with a model developed by Berntsen *et al.* (1996). It is a modified version of the Princeton Ocean Model (POM) developed at Princeton University by Blumberg and Mellor (1987). For technical reasons we rotated 180° the map of Golfo Dulce and created a new coordinate system, which did not correspond to the real north-south/east-west directions (Fig. 4). Also for convenience, we transformed all the forcing functions into the rotated coordinate system of the model, including the directional wind vectors from Oort (1983). Figure 5 describes the wind components for this rotated system.

Hydrography: A ME-ECO 234 CTD, measuring temperature, conductivity and pressure, was used on the three cruises in repeated mapping of the hydrography of Golfo Dulce, covering stations distributed along three selected cross sections in the gulf (S1, S2 and S3 in Figure 1). The data are averaged over 2 m intervals and presented as vertical cross sections, Figures 6a-c, 7a-c, and 8a-b.

Currents: Both Eulerian (small current meters) and Lagrangian (drifting drogues) methods were used in the current measuring part of the field program.

Euler method: On the two cruises 27 - 29 January and 1-2 February a mooring was deployed on the sill a few kilometers inward from the entrance area of the gulf (Fig. 1). Sensor Data, SD 6000, current meters were used, Gytre (1996). Rig positions, selected measuring depths

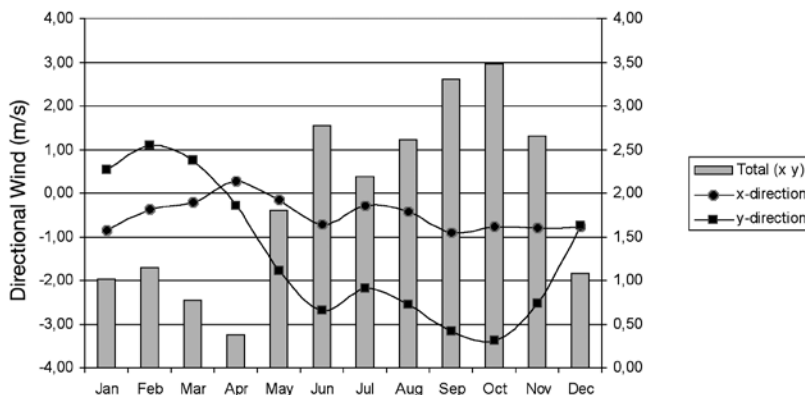


Fig. 5. The lines show the 180° rotated x, y-vector components ($m s^{-1}$) of the wind used in the model. Bars present total surface wind ($m s^{-1}$) calculated as the vector product of the x and y components.

and sampling periods are shown in Table 1 and the observations are shown as stick plots in Figure 9. The sampling interval was 5 minutes. Since the rig operations were made by hand, the rigs were made rather slight and had to be looked after during the sampling periods. The sampling periods were therefore short.

Lagrange method: The circulation of the brackish layer was mapped with drifting drogues deployed along cross sections of the gulf and recovered after 10-30 minutes drifting period.

The drogue is a simple construction consisting of a floating body (15x10x5 cm), attached

to a cross by a 40 cm string. The velocities are estimated from the drifting distance (determined by satellite navigation) and the drifting time. Data about the drifting experiments are listed in Table 2.

Each drogue was drifting 15-25 minutes (followed by the boat). The arrows within each cross section, reflect therefore not a synoptic picture of the current. However, each mapping is carried out within the same tidal phase, either raising or falling tide, and with about the same wind conditions.

The wind conditions during the experiments were the following:

TABLE 1
Rig data

Rig station	Position	Measuring depths (m)	Deployed time	Recover time
GD I	08.28.0 N 83.12.0 W	2, 5, 10, 46	12:25 01.27.99	15:10 01.27.99
GD II	08.28.0 N 83.12.0 W	2, 12, 52	14:30 02.02.99	16:00 02.02.99

TABLE 2
Drift experiments in Golfo Dulce, 27-29 January 1999 and 21-22 February 2001 (Local time)

Exp. No. and date	Position out	Time	Position in	Time	Distance (m)	Speed (cm s ⁻¹)	Dir. (deg.)	Tidal phase (local time)	Tidal range (cm)
1: 27.01-99	N 08.26.906 W 83.10.937	12.44	N 08.26.906 W 83.10.937	12.59	141	3	232	High: 10.35 Low: 16.35	224
2: 27.01-99	N 08.27.065 W 83.14.196	13.56	N 08.26.761 W 83.14.175	14.38	564	22	176	High: 10.35 Low: 16.35	224
3: 29.01-99	N 08.33.579 W 83.11.375	09.58	N 08.33.992 W 83.11.382	10.30	765	39	359	Low: 06.28 High: 12.47	266
4: 29.01-99	N 08.33.493 W 83.14.107	10.44	N 08.33.663 W 83.14.212	11.05	369	29	328	Low: 06.28 High: 12.47	266
5: 29.01-99	N 08.33.517 W 83.17.524	11.51	N 08.33.545 W 83.17.763	12.16	441	29	276	Low: 06.28 High: 12.47	266
1: 21.02-01	N 08.37.01 W 83.14.03	08.50	N 08.37.66 W 83.15.65	14.04	4521	24	303	Low: 07.43 High: 13.57	172
2: 21.02-01	N 08.35.00 W 83.16.03	09.30	N 08.35.08 W 83.16.82	13.03	1789	14	261	Low: 07.43 High: 13.57	172
3: 21.02-01	N 08.33.51 W 83.17.06	09.51	N 08.33.31 W 83.17.51	12.47	1584	9	245	Low: 07.43 High: 13.57	172
4: 22.02-01	N 08.39.99 W 83.19.09	09.20	N 08.39.78 W 83.18.89	11.25	525	7	136	Low: 08.22 High: 14.34	189
5: 22.02-01	N 08.38.85 W 83.19.79	09.45	N 08.38.53 W 83.19.71	12.10	945	7	165	Low: 08.22 High: 14.34	189
6: 22.02-01	N 08.37.07 W 83.21.08	10.05	N 08.36.23 W 83.20.73	12.41	1684	18	157	Low: 08.22 High: 14.34	189

- 27.01.99 Exp. 1 and 2: almost calm.
 29.01.99 Exp. 3-5: increasing in-gulf wind (breeze).
 21.02.01 Exp. 1-3: gentle breeze in-gulf.
 22.02.01 Exp. 4-6: gentle breeze out-gulf

The numerical model: The model is a modified version of the *Princeton Ocean Model* which is a three dimensional (σ -coordinate) coastal ocean model developed by Blumberg & Mellor (1987). The modified version is developed by Berntsen *et al.* (1996), and the major modifications from POM are found in the advection terms, the implicit time calculations and the splitting in time into 2- and 3-dimensional calculations. The basic equations are: the momentum equation, continuity equation, the conservation equations of temperature and salinity respectively, and a turbulence closure model for the turbulent kinetic energy; Mellor and Yamada (1982). The prognostic variables of the physical model are:

- *three components of water velocity*
- *temperature*
- *salinity*

It is assumed in the model that the weight of the fluid in an arbitrary water column in the model identically balances the pressure (hydrostatic assumption). Density fluctuations are neglected unless the differences are multiplied by the gravitational acceleration (Boussinesq approximation). For more details about the model, see Berntsen *et al.* (1996) and Appendix.

Implementation of the model: Golfo Dulce and the adjacent coastal areas are covered by a 66 by 48 grid net, i.e. a resolution of 2x2 km (Fig. 4). Vertically (σ -coordinate) the model is divided in 24 σ -layers where $\sigma = 0$ and $\sigma = 1$ represents the surface and bottom respectively.

In a transition zone represented by the outer 10 grid cells towards the open boundaries a Flow Relaxation Scheme (FRS) is applied, Martinsen and Engedahl (1987). FRS dampens

feed back effects and drags the model towards the values at the open boundaries.

External forcing: The external forcing functions in the model are represented by surface wind, air-sea heat flux, freshwater runoff and forcing at the ocean boundaries and in addition the steering effect by the topography.

Freshwater runoff

The monthly mean discharge to the catchment basin (Figure 2) for model use is distributed amongst the four main rivers (Coto, Tigre, Esquinas and Rincón) by dividing the coastlines on each side of the river mouths by the total coastlines inside Golfo Dulce, Figure 3. Each of the rivers is represented in one horizontal grid cell. The temperatures of the river water are based on data from the Coto river system (Michels per. com. unpublished data).

Wind

The 180° rotated monthly mean wind field in Figure 5 is used in the model run. The wind is not spatially resolved, i. e. all surface grid cells are forced with the same stress.

Air-sea heat flux

Air-sea heat fluxes are approximated by a calibration of sea temperature in the surface grid cells. The calibration procedure drags modeled (T_{mod}) surface temperature towards observed (T_{obs}); $\Delta T = K_T (T_{obs} - T_{mod})$, $K_T = 1.736 \cdot 10^{-5}$ is a calibration constant. T_{obs} are monthly averages taken from Levitus & Boyer (1994).

Ocean boundaries

The tide appears on the open ocean boundaries in Figure 11, and is represented by surface elevations and tidal velocity ($m s^{-1}$). Tidal runs along the x-axis (the model east-west direction). The amplitudes are based on data from the station Quepos. Due to topographic effects the data are not expected to be representative

for the open coastal ocean. Based on a rough estimate the observed tidal amplitudes are therefore scaled by a factor 0.7 to give off coast amplitudes for use in the model simulations. The tidal velocities are calculated from the surface amplitude assuming an average depth of 1000 meter in the boundary Zone.

Salinity and temperature at the ocean boundaries are based on monthly data from Equatorial Pacific, Levitus & Boyer (1994). Continuous salinity and temperature data at the ocean boundaries are obtained by linear interpolation of the monthly data.

FIELD RESULTS

Hydrography: January 28-February 3 1999: An upper layer with weak vertical gradients in both temperature and salinity is a prevailing pattern in the whole Golfo Dulce in this period (Figs. 6a-c). A strong thermocline and some weaker halocline, covering a depth level of about 20 meter, form a transition between the upper layer and an almost homogeneous deep layer. The depth of the upper layer is about 20 meter. In the outer shallow part of the Gulf both the thermocline and the halocline reach almost the bottom, Fig. 6c.

In the upper layer the temperature of the water increases and the salinity decreases from the inner part and towards the mouth.

November 17-18 1999: A strong halocline is predominant in the upper 5 meter (Fig. 7 a-c). The thermocline also starts near the surface, however is much weaker than the halocline and reach down to a depth of about 60 meter. The temperature is almost 28°C in the surface, decreasing to about 17°C in 60 m depth. Over the same depth range the salinity increase from less than 20 to about 34.5.

21-22 February 2001: The observations show a vertical structure essentially different from that observed in the “dry season” in 1999 (Figs. 8a-b). A strong pycnocline reflects a very buoyant upper 30 meter layer above an

almost homogeneous deep layer. The temperature decreases from about 31°C to about 15 °C between the surface and the deep layer while the salinity increases from 33 to 35 over the same depth range.

Current: 1999 The two short time series of current measurements from the sill area show both a three-layer structure (Fig. 9). In the first period, 27 January the current shifted from down-gulf to up-gulf directed current in the middle of the three hours measuring period in both of the two upper measuring depths, 2 and 5m. The measurements are taken in the middle of a period with falling tide. Except in the end of the period the current is down-gulf in 10 m and up-gulf in 46m depth.

The vertical current distribution in the second measuring period, 2 February which started in the middle of a period with rising tide, show also a three layer structure with up-gulf flow in the surface and bottom layer (2 m and 52 m respectively) and down-gulf flow in 12 m.

The drifting drogues experiments 1 & 2, January 27 (Fig. 10A) are taken during falling tide (Table 2). It was almost calm during the two experiments. A down-gulf flow appears on the western side of the gulf while on eastern side the upper layer water masses are almost stagnant.

The experiments 3-5, January 29 (Fig. 10A), were taken during maximum rising tide and the weather condition was characterized by an increasing in-gulf breeze. An in-gulf flow dominates the flow pattern of the surface layer in the whole cross-section of the gulf.

2001: Two drifting drogue experiments were carried out during 21-22 February (Fig. 10B). Both experiments took place during rising tide (Table 2). Gentle up-gulf breeze prevailed the 21st while wind of the same strength, but down-gulf, was dominating the 22nd. The flow direction and the cross-gulf velocity gradient are opposite in these two days. While the velocity is up-gulf and increasing from west to east in the cross-section the 21st it is down-gulf with a decreasing velocity from west to east the 22nd.

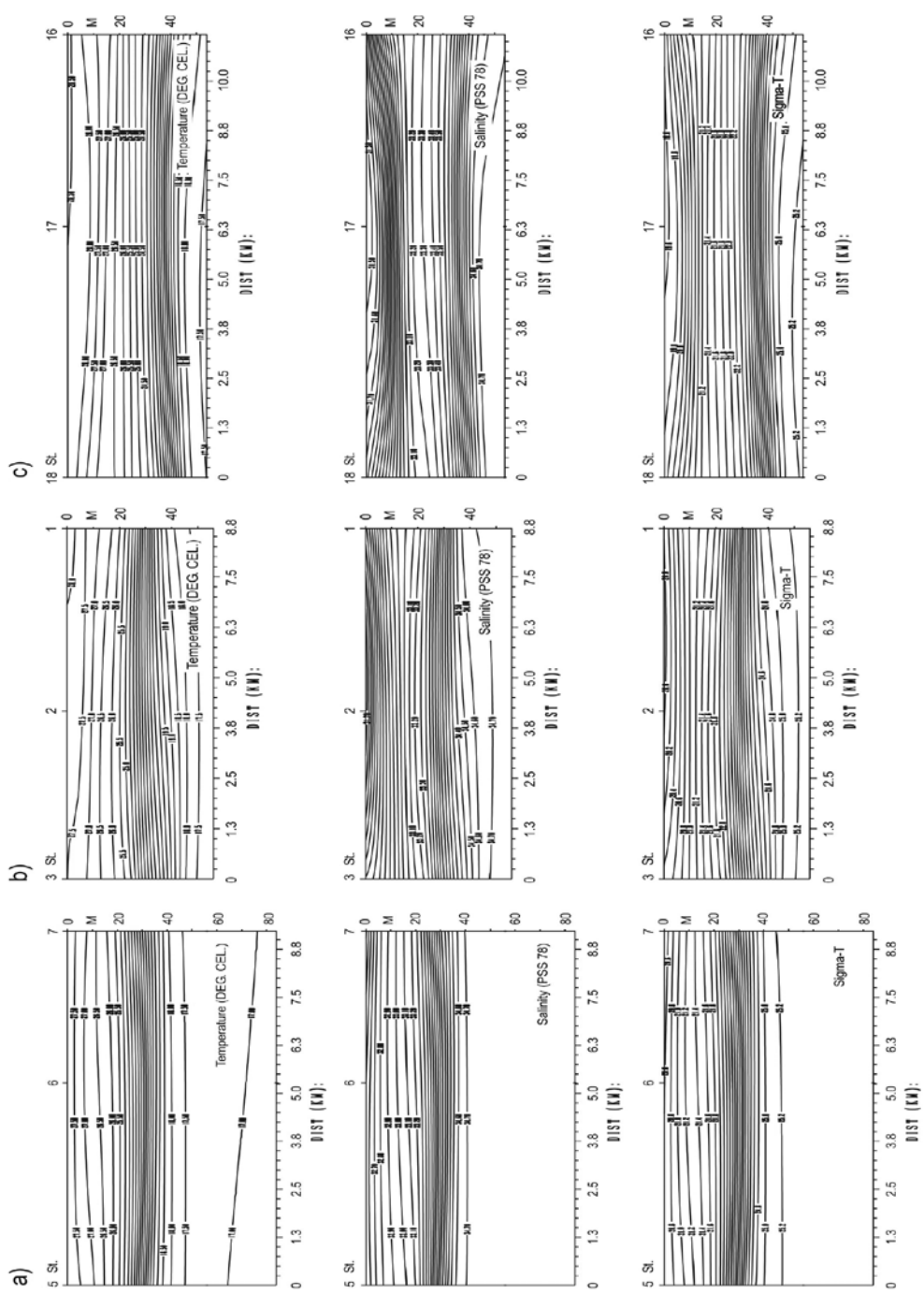


Fig. 6. Observed vertical distribution of temperature, salinity and density in cross sections in January 1999 (looking up-gulf): a) Section S1, 28 January, b) Section S2, 28 January and c) Section S3, 29 January. Golfo Dulce, Pacific coast of Costa Rica.

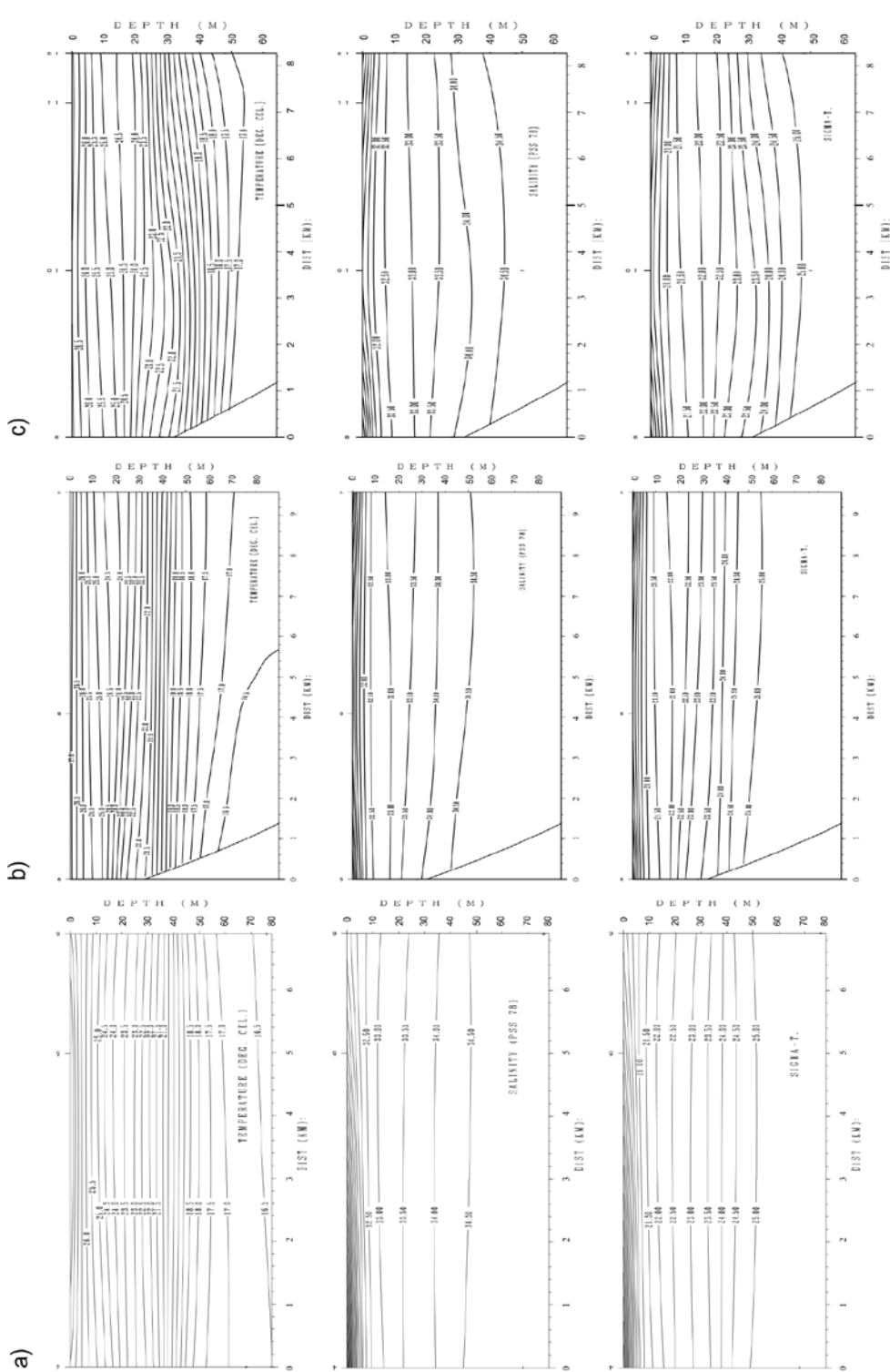


Fig. 7. Observed vertical distribution of temperature, salinity and density in cross sections in November 1999 (looking up-gulf): a) Section S1, 17 November, b) Section S2, 18 November and c) Section S3, 18 November. Golfo Dulce, Pacific coast of Costa Rica.

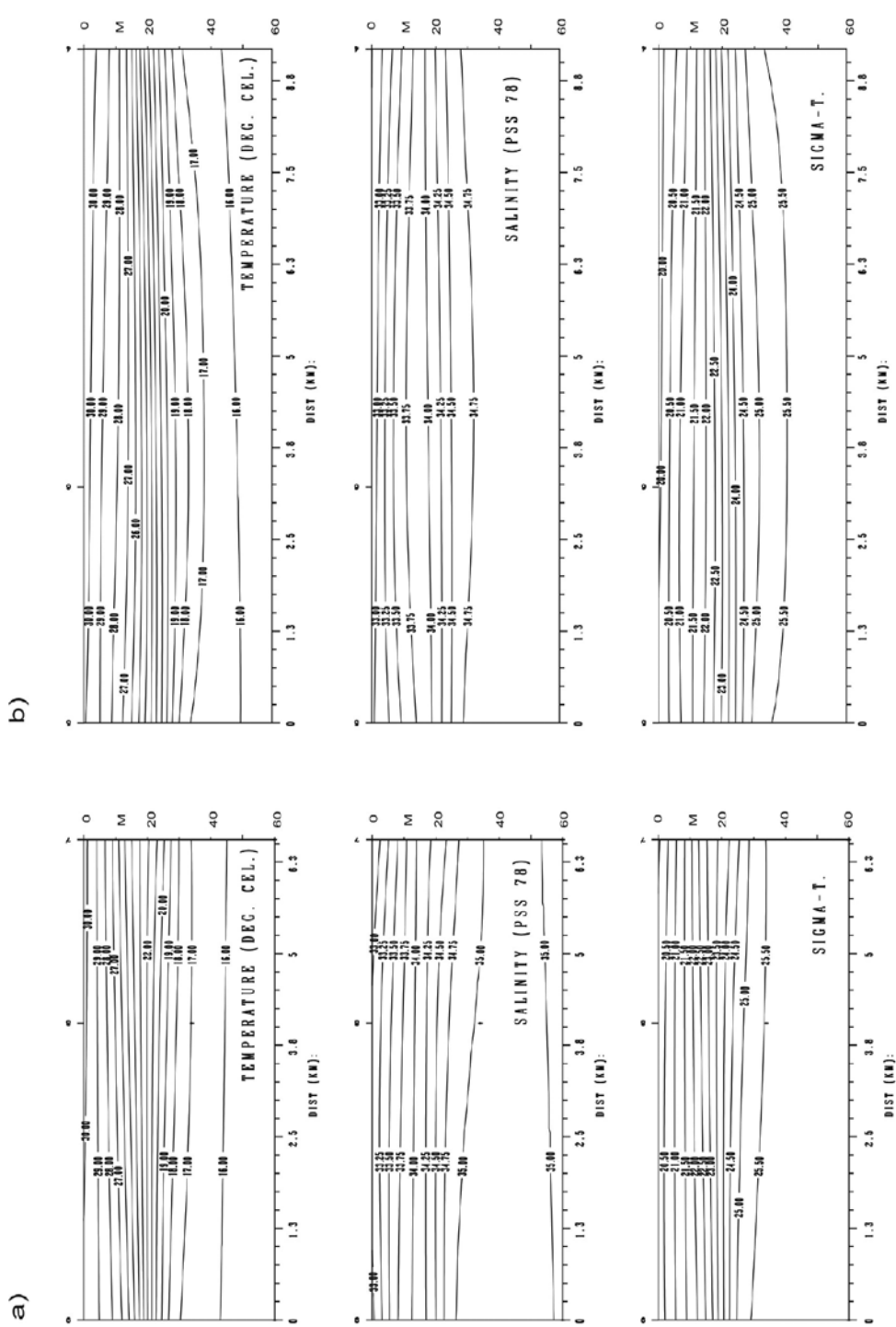
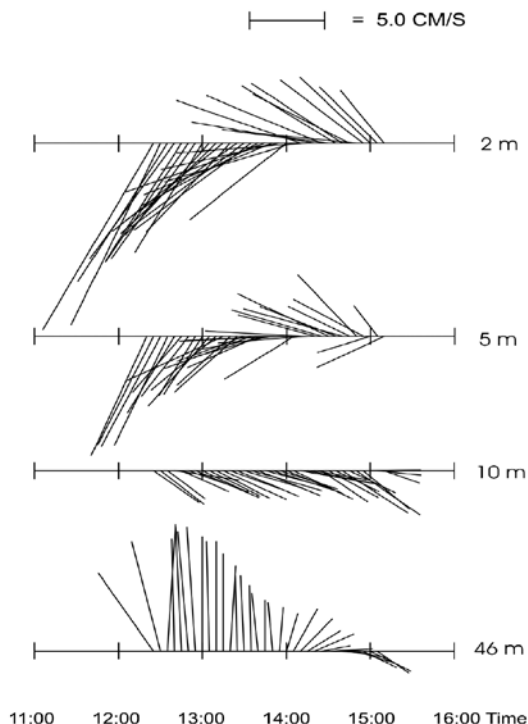


Fig. 8. Observed vertical distribution of temperature, salinity and density in cross sections in February 2001 (looking up-gulf): a) Section S1, 22 February, and b) Section S2, 21 February. Golfo Dulce, Pacific coast of Costa Rica.

Golfo Dulce

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Golfo Dulce

Time = 99 02 02 POS: N08 27.3 W83 12.0

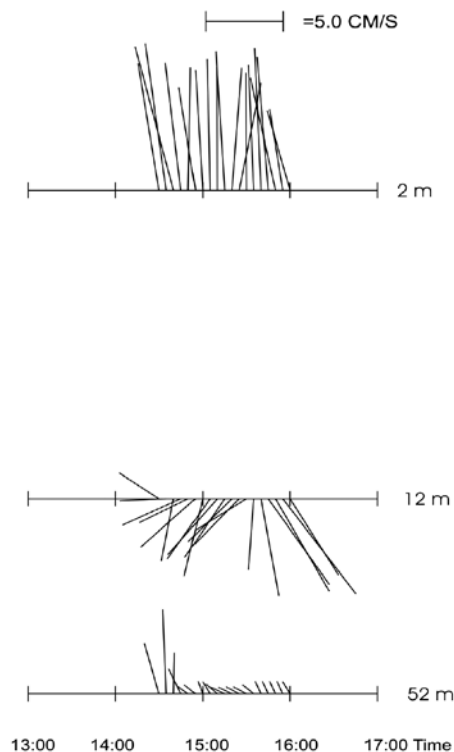


Fig. 9. Current velocities from the mooring in the sill area of Golfo Dulce, 27 January (left) and 2 February (right).

MODEL RESULTS

Initialization

The model is initialized with conditions corresponding to the vertical structure at the open boundary, Levitus & Boyer (1994).

Simulation procedure

The simulations within each month are run with monthly averages of the surface wind, freshwater runoff, sea-surface temperature and open boundaries values of temperature and salinity, while the tide is represented by hourly values. The model output is presented as monthly values. The annual simulations are initiated on January the 2nd.

Bottom topography

The bottom topography used in the model is shown in Figure 11. The original bottom matrix is smoothed to avoid too steep depth gradients between adjacent grid cells.

Hydrography: The predicted vertical salinity distributions in the longitudinal transects, Figure 12, seems relatively stable at all seasons below 30 meters. The salinity in the water column above 30 meters varies according to the seasonal variations in the freshwater runoff, resulting in low surface layer salinity and a strong halocline inside the gulf during the rainy season and more mixed surface layer and weaker halocline during the dry season.

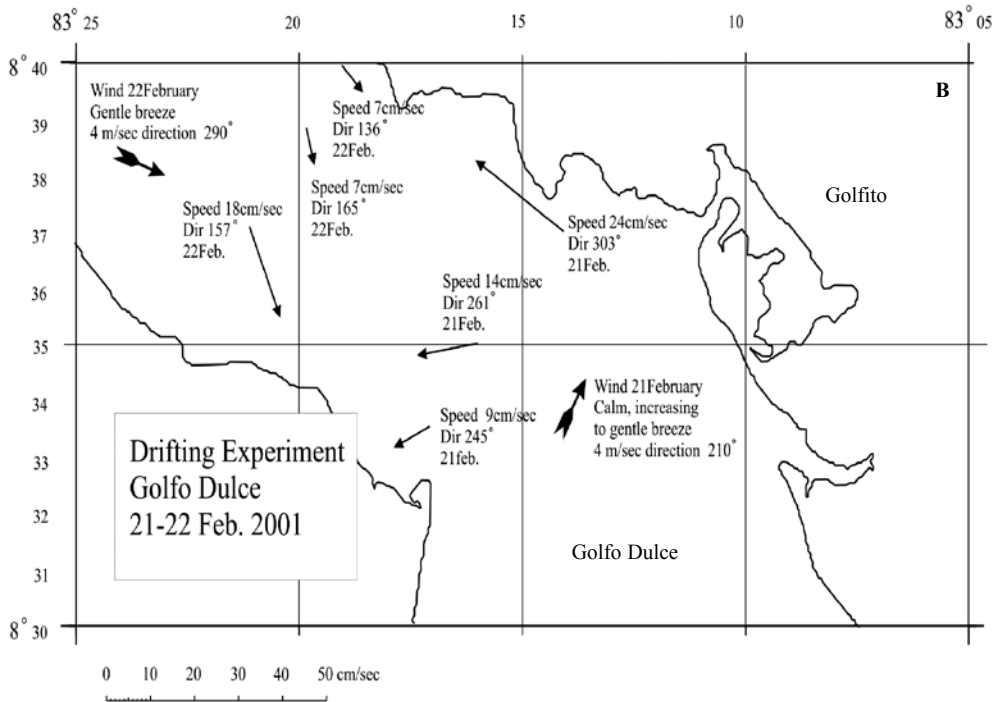
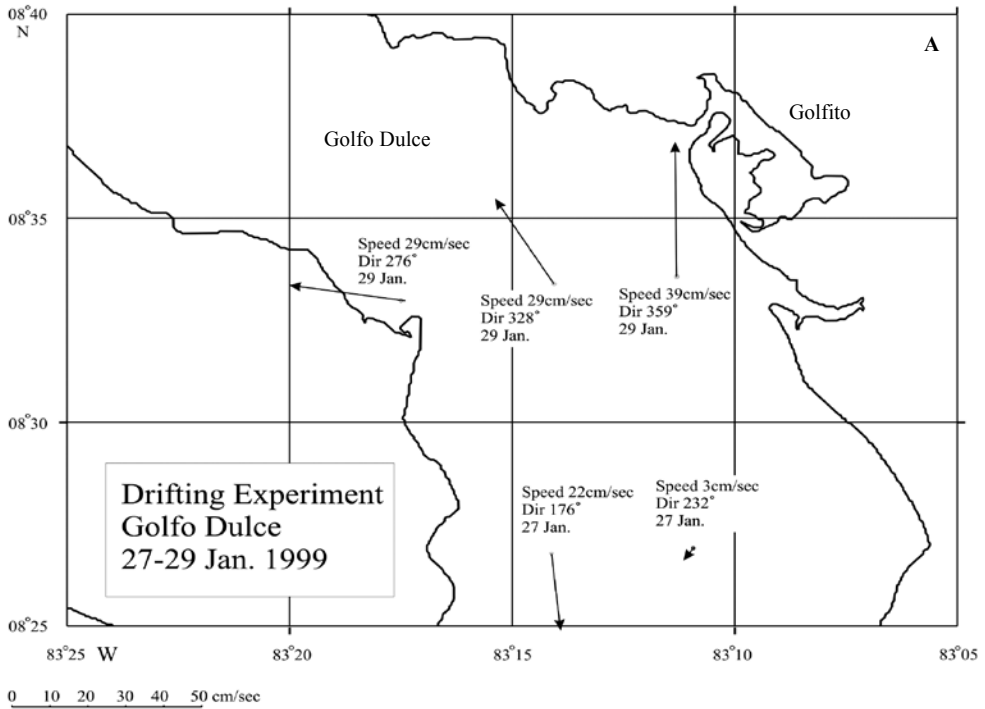


Fig. 10. A. Drifter experiments performed 27 and 29 January 1999. B. Drifter experiments performed 21 and 22 February 2001. Golfo Dulce, Pacific coast of Costa Rica.

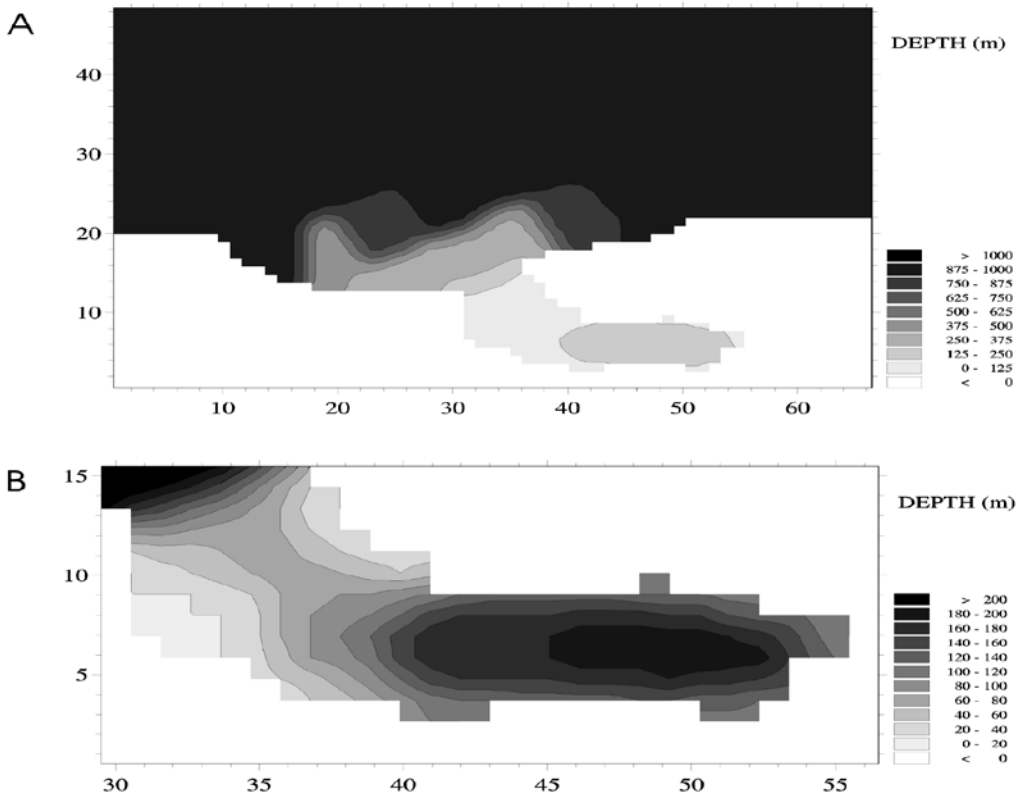


Fig. 11. The bottom topography of the total model area (upper panel) and the bottom topography of Golfo Dulce (lower panel). The scales to the right show the depths corresponding to each contour.

During the rainy season the surface water is cooled slightly by mixing with river water while there is an increase in temperature in the deep inner gulf water compared to the initial conditions (Fig. 13) which indicates that mixing between the upper warm layer and deep water takes place.

Circulation: The prevailing wind direction is onshore during the rainy season. Wind seems to partly reduce the freshwater driven outflow in the surface layer in this season (Fig. 14). In the dry season the prevailing wind direction is offshore, i.e. the wind driven and the freshwater driven current component has the same direction creating a relatively strong down-gulf surface layer current.

In the adjacent coastal zone to the gulf the surface current has an irregular pattern

with a marked eddy structure in February and December (Fig. 14).

The simulations reveal an estuarine circulation pattern, with an out-flowing brackish surface layer and a compensating in-flowing coastal water between the depth levels 5 and 30 meter in the sill area (Fig. 15). Marked seasonal variations appear in both the depth of the surface layer and the vertical extension of the out-flowing water. Relatively strong currents near the sill and weaker currents in the inner deeper part of the gulf seem to be the general pattern in all seasons.

Vertical cross sections in the central gulf (Fig. 16) show a clockwise circulation pattern. In-gulf flow dominates most of the western gulf and the deeper central basin during the wet season. The boundary between in- and out-flowing water has a more clear-cut vertical

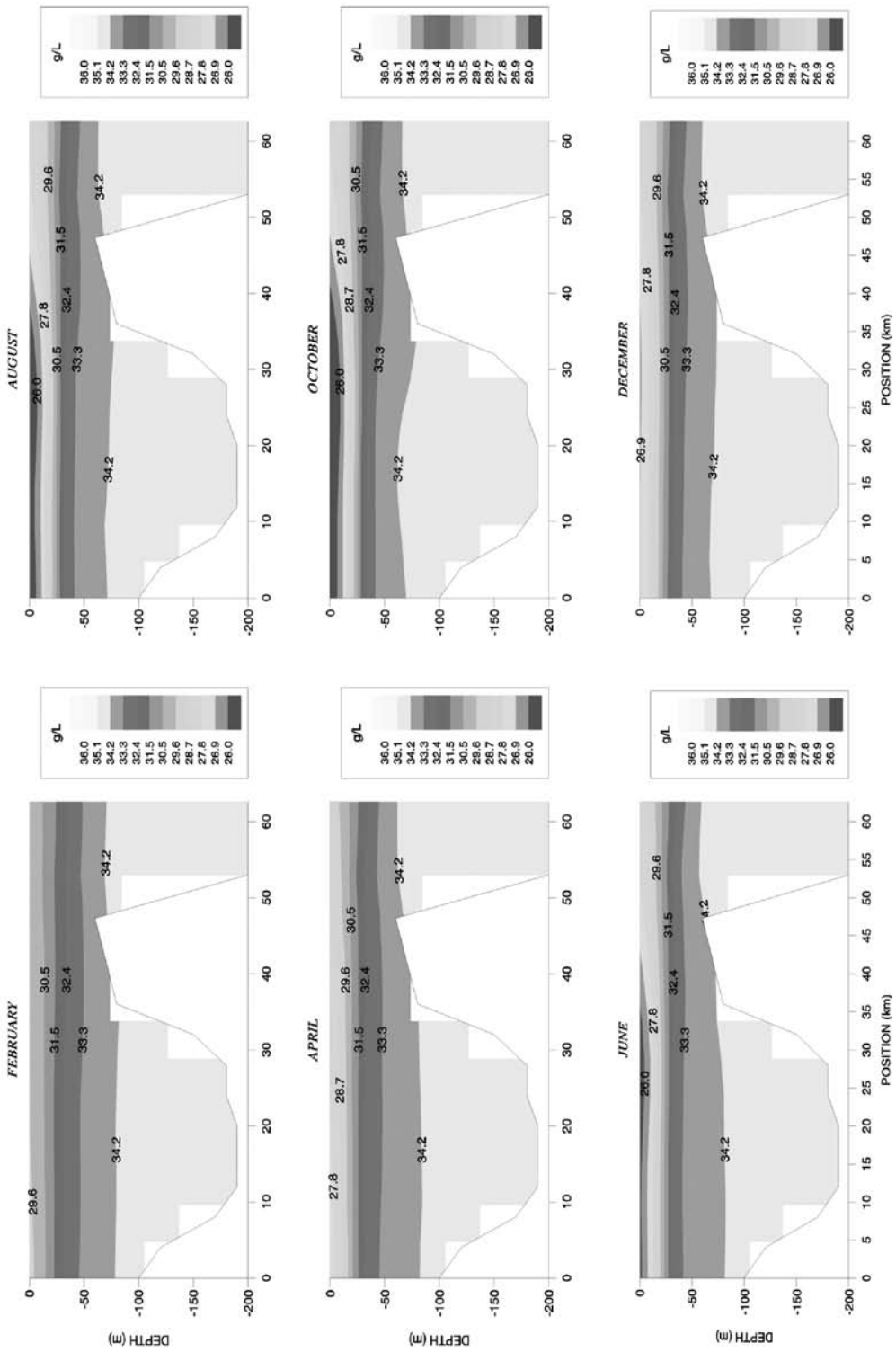


Fig. 12. Simulated monthly average of salinity in a vertical section along the central Golfo Dulce (see Fig. 11).

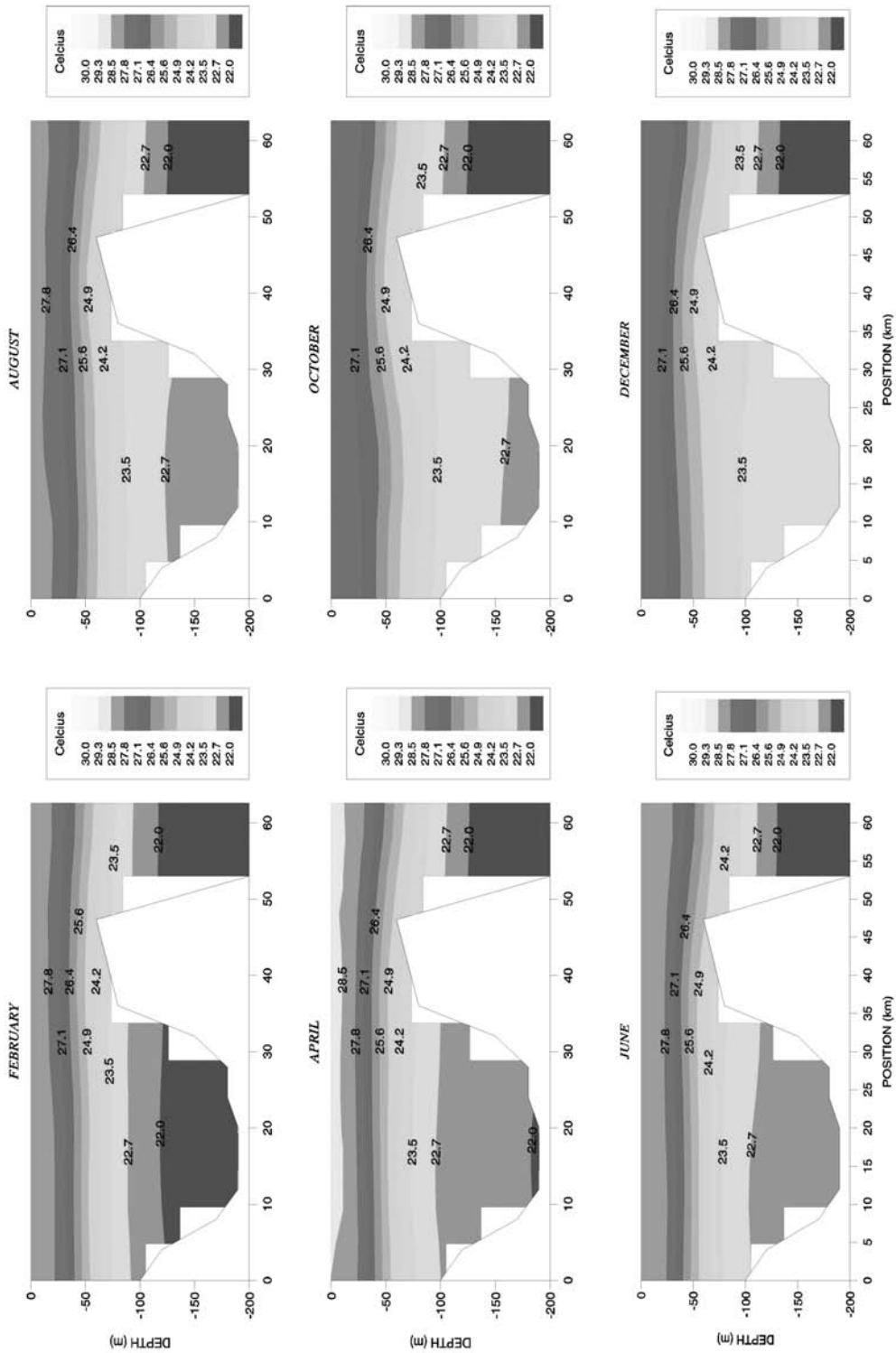


Fig. 1.3. Simulated monthly average of temperature in a vertical section along the central Golfo Dulce (see Fig. 11).

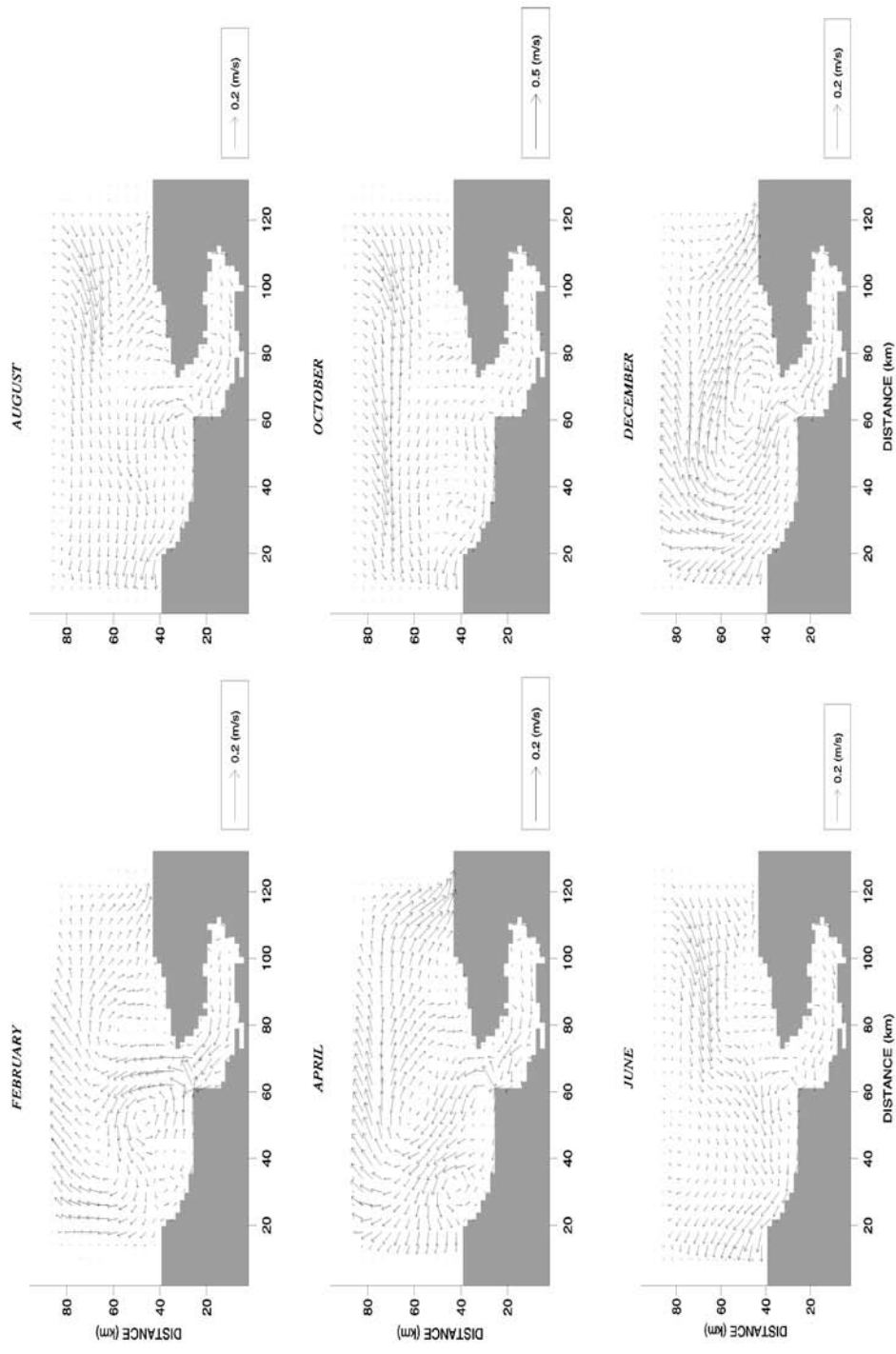


Fig. 14. Simulated monthly average of horizontal surface layer currents ($m s^{-1}$) in Golfo Dulce.

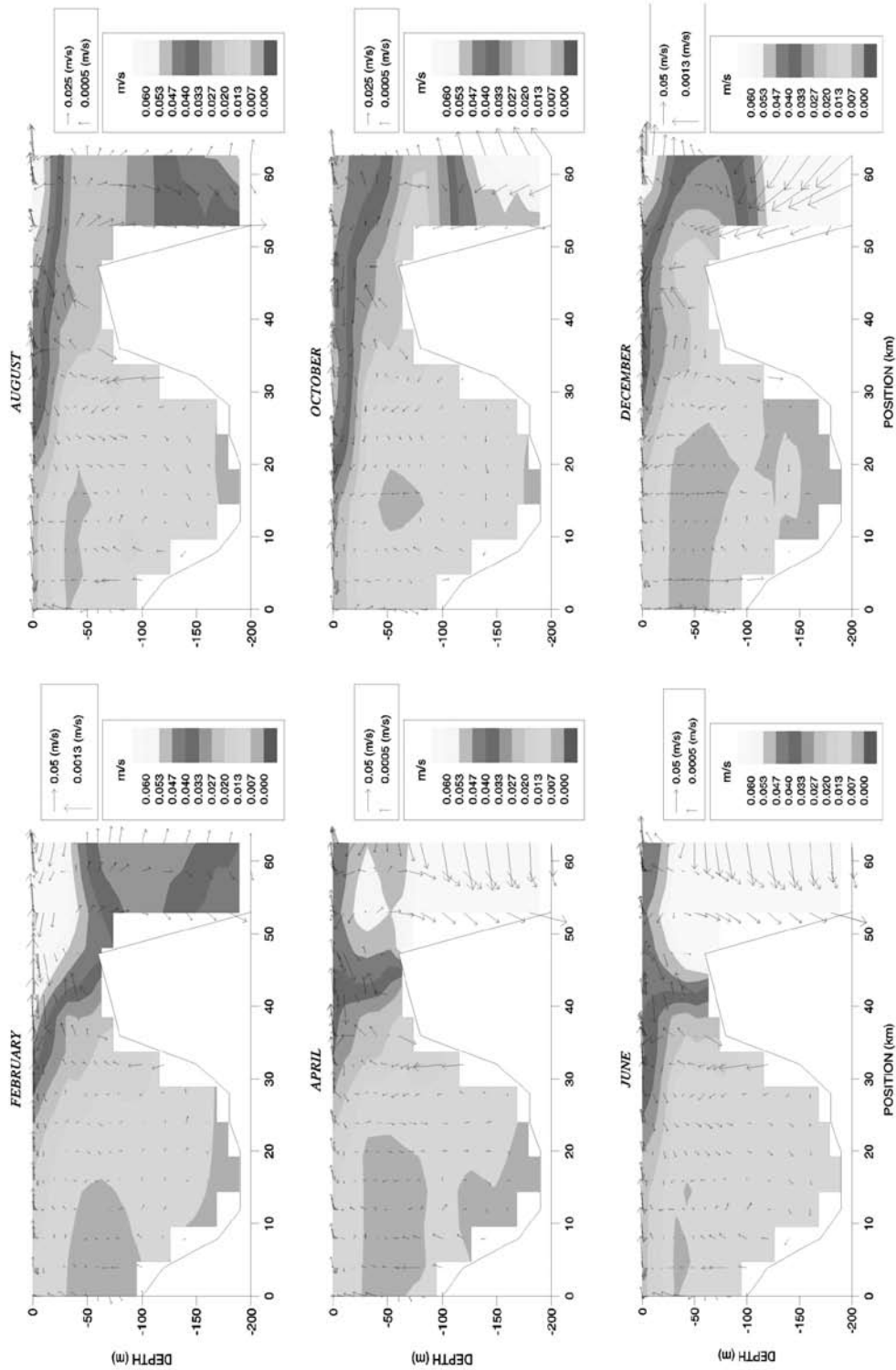


Fig. 15: Simulated monthly average of the currents ($m s^{-1}$) in a vertical section along the central Golfo Dulce. Because of the large difference between horizontal and vertical currents, the vectors represent different values (as indicated by the vector legends). The scale to the right show the values corresponding to each contour.

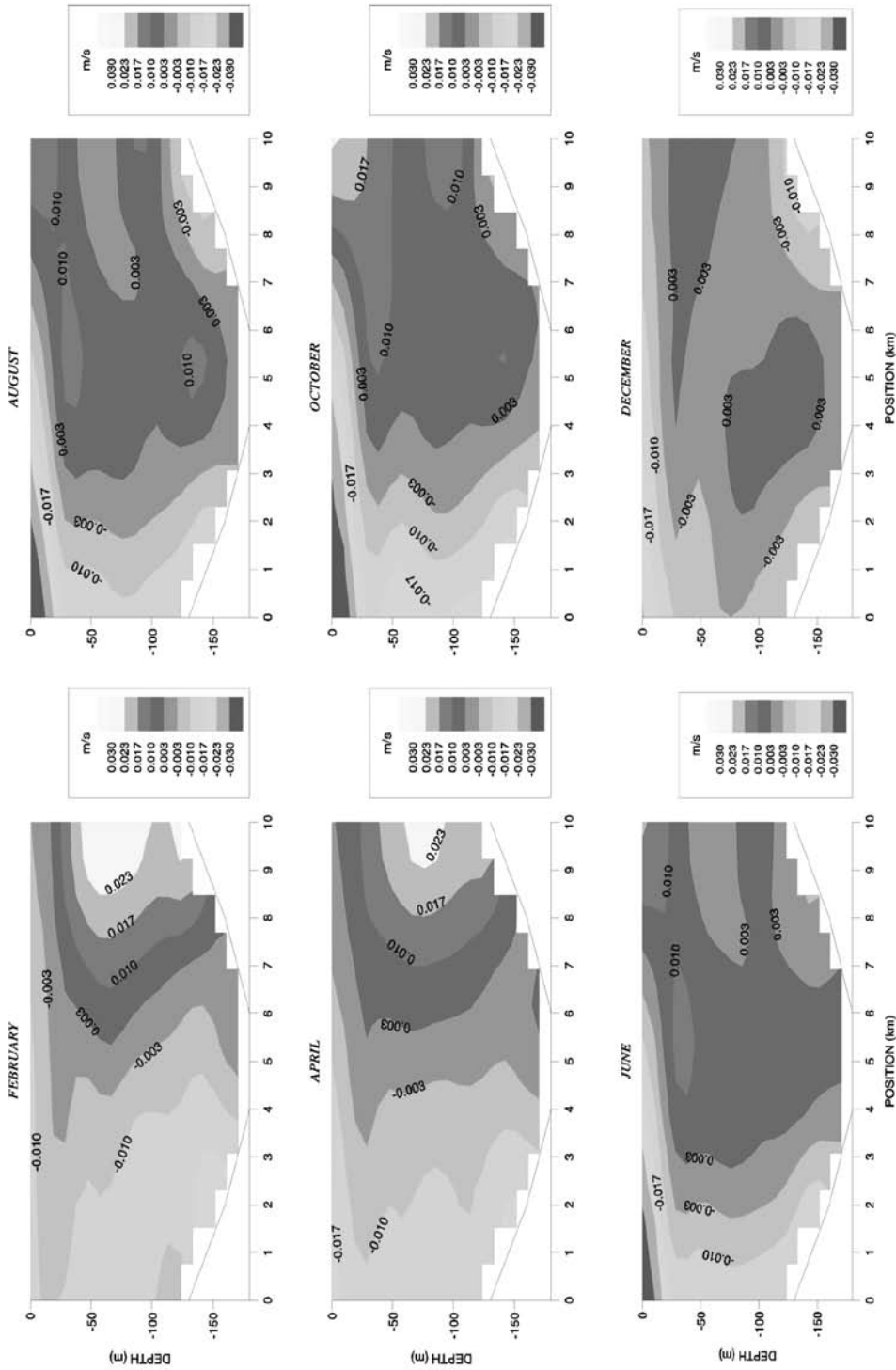


Fig. 16. Simulated monthly average of the currents ($m s^{-1}$) in a vertical cross section (looking out-gulf) near the center of Golfo Dulce. Contours show the vector component perpendicular to the plane of the section. Positive and negative values indicate in- and out-flowing water of Golfo Dulce respectively. The scale to the right shows the values corresponding to each contour.

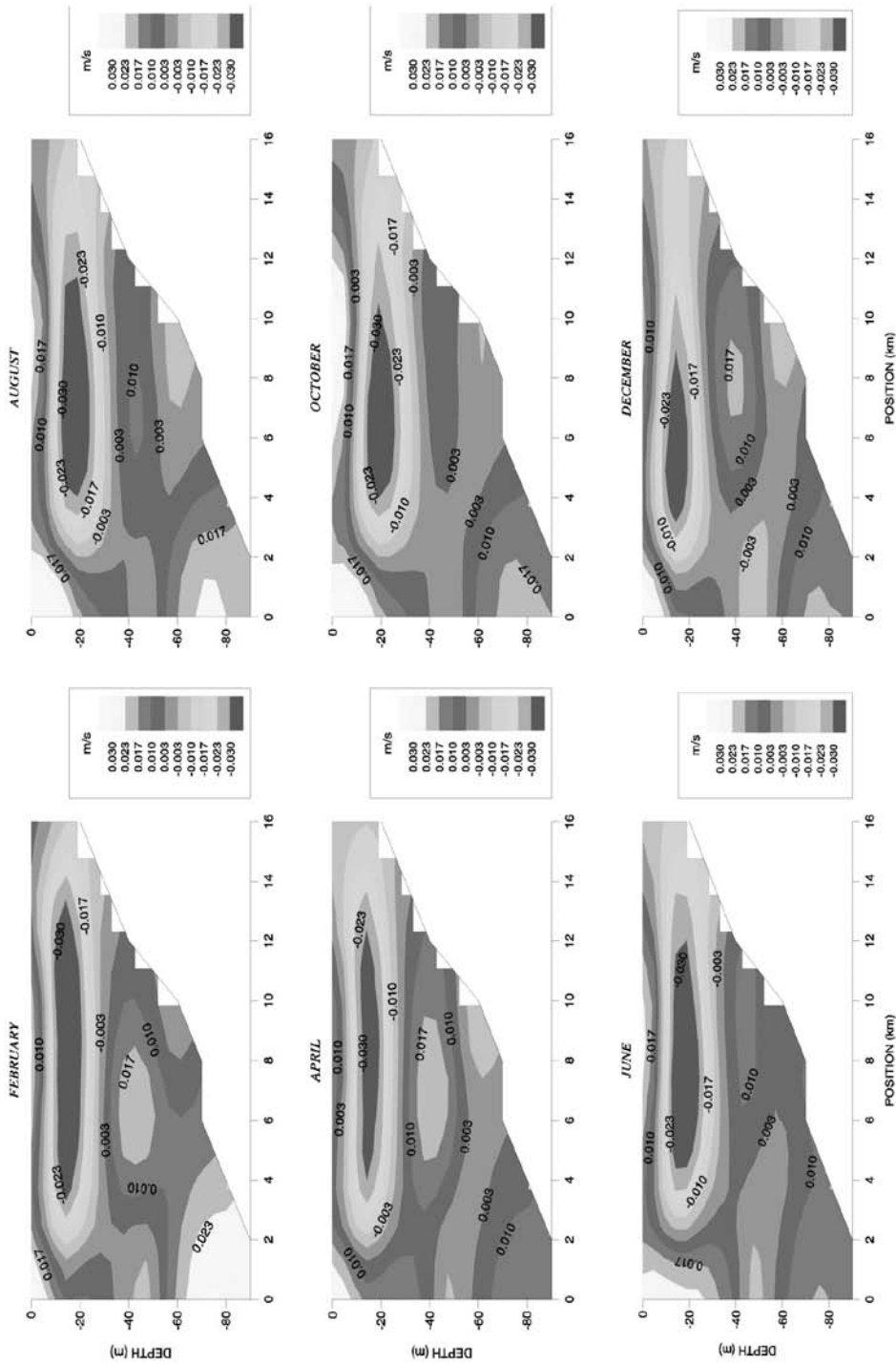


Fig. 17. Simulated monthly average of the currents ($m s^{-1}$) in a vertical section across the sill (looking out-gulf). Contours show the vector component perpendicular to the plane of the section. Positive and negative values indicate in- and out-flowing water of Golfo Dulce respectively. The scale to the right show the values corresponding to each contour.

boundary in the central gulf during the dry months in early spring.

Increasing surface level towards the head of the gulf (longitudinal barotropic pressure gradient) caused by the freshwater runoff in combination with bottom topography may explain the predicted clockwise circulation pattern in the central part of Golfo Dulce.

There is a marked three-layer structure in the cross section in the sill area in all seasons, Figure 17, an out-flowing thin surface layer and deep water separated by an in-flowing intermediate layer.

DISCUSSION

It is expected that the rotation of the earth (Coriolis effect) has a negligible effect on the dynamics of the gulf due to the nearness to equator (contrary to high-latitude fjords). A rough two-layer approach ($H_{\text{upper}} = 20$ m, $H_{\text{lower}} = 200$ m, $\rho_{\text{upper}} = 1022$ kg m⁻³, $\rho_{\text{lower}} = 1024$ kg m⁻³, $f = 1.01 \times 10^{-5}$) based on observed density distribution gives a baroclinic Rossby radius of about 250 km, i.e. more than 15 times the width of the gulf. Results from the field measurements and the simulations on the other hand indicates that both wind, freshwater runoff, tides and topography have a significant influence on the circulation in Golfo Dulce.

The simulations indicate that freshwater runoff is more influential on the circulation than previously assumed. Although the freshwater driven current component is of less importance compared to the wind-driven component the freshwater runoff has an important influence on the effect of the wind (see e.g. Svendsen and Thompson 1978; Svendsen 1981). The strong halocline in the wet season prevents the wind energy to penetrate below the surface layer. The effect of the wind stress on the surface layer is therefore stronger in the wet season compared to the dry season.

The observed and simulated three-layer current structure in the sill area seems to be the dominating structure in all seasons while in the inner part of the gulf a two-layer estuarine

circulation takes place above slowly moving basin water. However, in periods a disorderly and strongly variable circulation pattern appears. In addition to the freshwater, which is supplied to the gulf from the four main rivers, a considerable part of the precipitation probably enters the gulf via many creeks and smaller rivers. Local pressure gradients originating in the near zone to the main rivers and the many smaller outlets together with local wind and the tide is the main causes for the varying surface circulation pattern revealed by the drifting drogue experiments. The most disorderly pattern with formations of several eddies appears in the transition period between up-(down-) and down- (up-) gulf flow.

The use of monthly oceanic wind fields (Oort 1983), with large spatial resolution, may not reflect the true effect of the wind in Golfo Dulce. The rough scaled wind fields and the monthly means do not account for local topography and short time events such as hurricanes.

Despite the rough scaled wind field and the fact that all precipitation is allocated into four main rivers in the model simulations it is expected that the simulated values presented in Figures 14-17, give a qualitative representative picture of the seasonal variation of the mean circulation. This because, as mentioned, the effect of the freshwater runoff is mainly through its stratification effect and that, through the mean process, the main effect of the tide which is left is the mixing effect. What is left is thus the wind as the main driving force.

The simulated hydrographic variables correspond roughly to the observed transects, Figures 6-8, and to previous observations (Richards *et al.* 1971; Brenes & León 1988; Thamdrup *et al.* 1996). Both the observations and the simulations show a stratified upper layer that is characterized by low salinity and temperature ranging between 25-33_{obs} and 26-32.5_{mod} and 17-28 C_{obs} and 24-28 C_{mod} respectively. Below about 40-50 meter is an almost homogeneous layer with salinity about 34.6_{obs} and 34.2_{mod} and temperature about 17 C_{obs} and 23 C_{mod}. In general, the simulated salinity is lower and the simulated temperature is higher

in the deep water than the observed. This is probably related to the σ -coordinate representation of the vertical in the model which is not always suitable in areas like Golfo Dulce with steep topography and strong stratification, Haney (1991). In such cases a σ -coordinate iso-surface in the horizontal direction may alternatively be inside and outside layers of distinct density which than can cause exaggerated mixing across density surfaces, i.e. to much low saline and warm upper layer water is mixed downward.

The dynamic response of Golfo Dulce to the different forces which affects circulation and exchange processes in the gulf is studied. An estimated baroclinic Rossby radius of about 250 km, i.e. about ten times the width of the gulf, indicates that the Coriolis effect is negligible. The circulation pattern is mainly determined by the wind stress, the tide and stratification. In addition adds weak estuarine components made up of local pressure gradients originating in the near zone to the main rivers and the many smaller outlets.

The exchange takes place through the wide mouth of the gulf bordering the adjacent coastal water. It is expected that the exchange is driven by the wind, both local within the gulf and coastal wind, and the tide. However, the scanty data base and simulations with monthly mean wind give no opportunity to determine the relative importance of the forces.

The complex interaction between the circulation and exchange components related to the different forces make it difficult to quantify the water transport in the gulf. To improve our ability to quantify fluxes is it necessary to carry out a more comprehensive measuring program and to procure more detailed information about the wind measured in inner and outer part of the gulf and at the coast.

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RESUMEN

Se llevó a cabo una investigación oceanográfica de algunos parámetros físicos basada en experimentos de campo y en las aplicaciones de un modelo numérico en el Golfo Dulce, un golfo tipo fiordo ubicado en la costa pacífica de Costa Rica. Se encontró que los efectos del viento local y la topografía están relacionados con marcados gradientes de velocidad a través del golfo en la capa superficial, mientras que los gradientes de temperatura y salinidad se mantienen a lo largo del mismo por el aporte fluvial de cuatro ríos en su parte interna. En general, la capa superficial se caracteriza por una salinidad baja y una temperatura alta. Debido a la cercanía con el ecuador el efecto de la fuerza de Coriolis sobre la circulación se consideró despreciable. Para la región somera de la boca del golfo se notó una estructura vertical de corrientes dividida en tres capas, mientras que la parte interna del estuario mostró una circulación de dos capas sobre aguas profundas de movimiento lento.

Palabras clave: Golfo Dulce, distribución salinidad/temperatura, circulación, proceso de intercambio, modelo numérico.

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APPENDIX

The model: The model is a modified version of the *Princeton Ocean Model* (POM) which is a three dimensional (σ -coordinate) coastal ocean model developed by Blumberg & Mellor (1987). The modified version is developed by Berntsen *et al.* (1996), and the major modifications from POM are found in the advection terms, the implicit time calculations and the splitting in time into 2- and 3-dimensional calculations.

The model has been applied in a number of studies. In fjords, however, the model was applied for the first time in the MARE NOR program, a coastal ecology program carried out in fjord and coastal areas of North-Norway, Cushman-Roisin *et al.* (1994), Asplin (1994), Leth (1995), Svendsen (1995).

The equations: The basic equations are: the momentum equation, continuity equation, the conservation equations of temperature and salinity respectively and a turbulence closure model for the turbulent kinetic energy; Mellor and Yamada (1982). The prognostic variables of the physical model are: the components of velocity in three dimensions (u , v and w), the potential temperature (T), the salinity (S) and the surface elevation η . Hydrostatic and Boussinesq approximation are assumed:

The continuity equation

$$\nabla \cdot \bar{u} + \frac{\partial w}{\partial z} = 0 \quad (\bar{u} = u\bar{i} + v\bar{j})$$

The Reynolds momentum equation

$$\begin{aligned} \frac{\partial u}{\partial t} + \bar{u} \cdot \nabla u + w \frac{\partial u}{\partial z} + fv &= -\frac{1}{\rho_o} \frac{\partial p}{\partial x} + \frac{\partial}{\partial z} \left(K_M \frac{\partial u}{\partial z} \right) + F_x \\ \frac{\partial v}{\partial t} + \bar{u} \cdot \nabla v + w \frac{\partial v}{\partial z} + fu &= -\frac{1}{\rho_o} \frac{\partial p}{\partial y} + \frac{\partial}{\partial z} \left(K_M \frac{\partial v}{\partial z} \right) + F_y \\ 0 &= -\frac{1}{\rho} \frac{\partial p}{\partial z} - g \end{aligned}$$

The pressure at depth z :

$$p(x, y, x, t) = p_{atm} + g\rho_o\eta + g \int_z^0 \rho(x, y, z', t) dz'$$

The equation for salinity and temperature

$$\frac{\partial \varphi}{\partial t} + \bar{u} \cdot \nabla \varphi + w \frac{\partial \varphi}{\partial z} = \frac{\partial}{\partial z} \left(K_H \frac{\partial \varphi}{\partial z} \right) + F_\varphi \quad \varphi: T \text{ or } S$$

The equation of state $\rho = \rho(T, S)$

The symbols:

x, y, z : coordinates. x, y : horizontal- and z : vertical axis (pos. upwards)

u, v, w : velocity components in x -, y -, and z -direction (m s^{-1})

t : time

ρ_0 : reference density (1000 kg m^{-3})

ρ : in situ density

p : pressure (dbar)

g : acceleration of gravity

φ : temperature T or salinity S

K_M : coefficient for turbulent diffusion of momentum (eddy viscosity) ($\text{m}^2 \text{ s}^{-1}$)

K_H : coefficient for turbulent diffusion of heat and salt ($\text{m}^2 \text{ s}^{-1}$)

F_x, F_y : components for turbulent diffusion of momentum (see below)

F_T, F_S : components for turb. diff. of heat and salt respectively (see below)

The terms F_x, F_y, F_T and F_S represent the small scale processes which not are resolved in the relatively coarse grid. In analogy with molecular diffusion the terms are expressed as following:

$$F_x = \frac{\partial}{\partial x} \left(2A_M \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left[A_M \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right]$$

$$F_y = \frac{\partial}{\partial y} \left(2A_M \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial x} \left[A_M \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right]$$

$$F_\varphi = \frac{\partial}{\partial x} \left(A_H \frac{\partial \varphi}{\partial x} \right) + \frac{\partial}{\partial y} \left(A_H \frac{\partial \varphi}{\partial y} \right)$$

A_M and A_H are coefficients of horizontal diffusion for momentum and heat and salt respectively and are computed according to Smagorinsky (1963).

For details about the model, boundary conditions, the turbulence closure sub-model and the transformations of the basic equations into a bottom following sigma coordinate system, see

Blumberg & Mellor (1987), Mellor and Yamada (1982) and Berntsen *et al.* (1996).