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## Flow induced by upwelling winds in an equatorward facing bay: Gulf of Arauco, Chile

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[1] Shipborne observations of hydrographic and flow velocity profiles were combined with wind velocity measurements to describe the characteristics of the wind-induced flow in an equatorward facing bay of central Chile in South America. The measurements, which were taken from two transects and one anchor station, were made during late austral spring, between 4 and 10 December 2000. Most observations concentrated on Boca Grande, a transect that crossed the deep, northern (equatorward) entrance to the bay. The other transect crossed the smaller and shallower, westward entrance to the bay, Boca Chica. The anchor station was located inside the bay, close to Boca Chica. The period of observations was characterized by persistent upwelling winds of up to 17 m/s. The direction of the wind showed very little variability, but its magnitude exhibited well-defined diurnal fluctuations. Wind speeds peaked at around sunset (2100 local time), which coincided with the deepest pycnocline location. The shallowest pycnocline depth appeared a couple of hours after sunrise. These pycnocline oscillations had amplitudes of ~5 m and were believed to propagate poleward along the coast and dissipate at the shallow entrance in Boca Chica. This mechanism could have mixed low-oxygen, nutrient-rich waters into the photic zone and enhanced the primary productivity. Observed flows at the Boca Grande transect consisted of downwind flow over the shallow ends and upwind flow in the deepest part. This wind-induced pattern is believed to cause a pair of counterrotating gyres that allow near-surface divergence and ventilation of upwelled subsurface waters at the southern end of the bay. This is the region where the highest concentrations of chlorophyll are identified in color imagery. *INDEX TERMS:* 4279

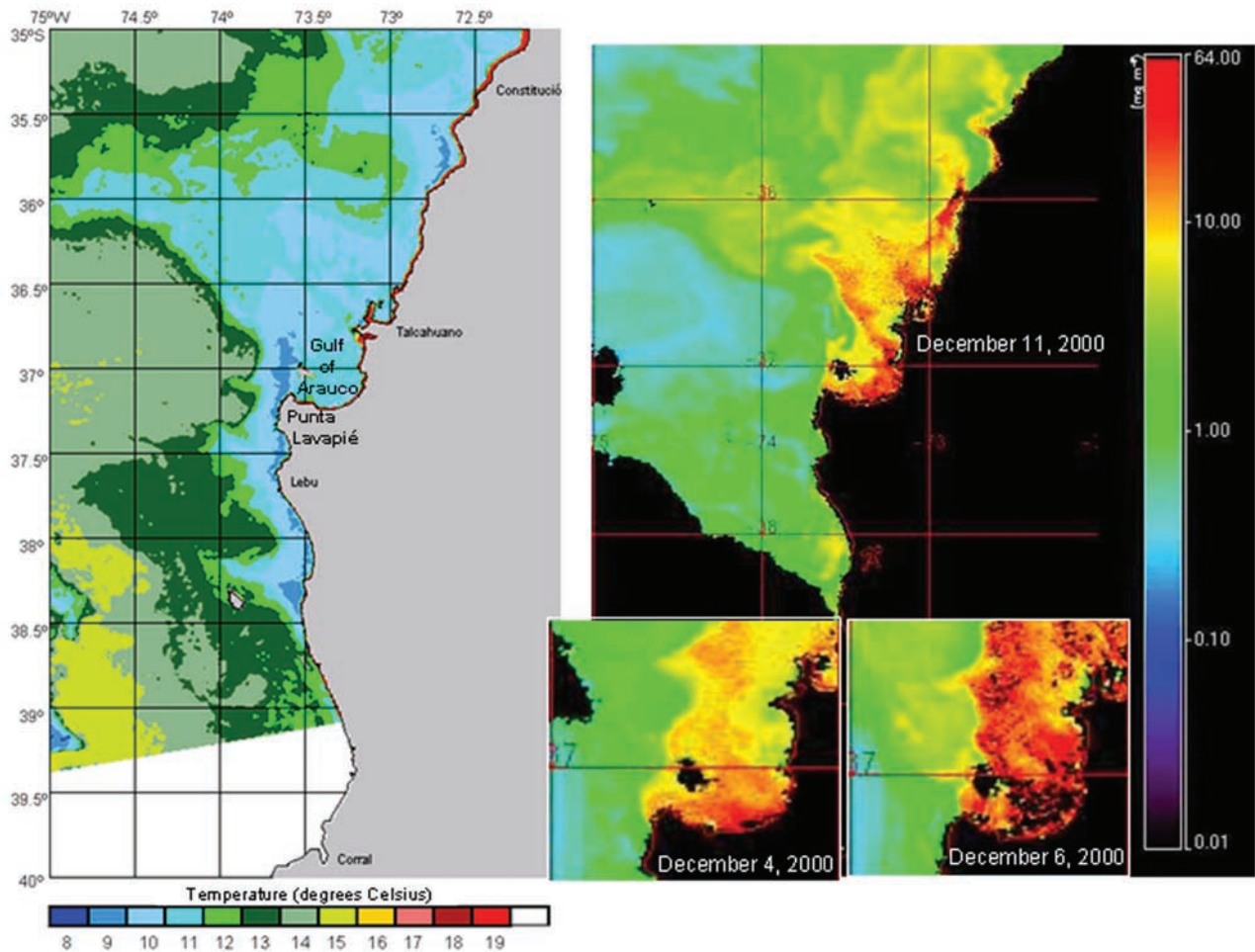
Oceanography: General: Upwelling and convergences; 4219 Oceanography: General: Continental shelf processes; 4227 Oceanography: General: Diurnal, seasonal, and annual cycles; *KEYWORDS:* equatorward facing bay, upwelling, Gulf of Arauco, circulation

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### 1. Introduction

[2] Equatorward facing bays that appear adjacent to eastern boundary currents usually represent locations of upwelling and productivity that may be favored by changes of coastline orientation [e.g., *Figueroa and Moffat*, 2000]. Two typical examples of these systems are the Gulf of Arauco in central Chile (Figure 1) and Monterey Bay in central California in the United States [e.g., *Rosenfeld et al.*, 1994]. Despite long-term interest in systems of high productivity, there is still a large gap in the basic understanding

of the physical mechanisms that affect these bays and their influence on the biological productivity inherent to these systems. An overarching objective should be to try to understand why these systems are highly productive. A key to the answer should be to understand the wind-induced circulation and mixing in these embayments. With that in mind the objective of this work was to increase our understanding of the wind-induced flow in the Gulf of Arauco, an equatorward facing bay in central Chile. This was done with a combination of shipborne, underway acoustic Doppler current profiler (ADCP) measurements, conductivity-temperature-depth (CTD) profiles at fixed stations, and anchor time series obtained between 4 and 10 December 2000 during the austral upwelling season. Although *Djurfeldt*



**Figure 1.** Sea surface temperature and color in the area of central Chile on 11 December 2000. Inserts of color in the Gulf of Arauco for 4 and 6 December illustrate the largest productivity in the gulf appearing on the southern end and also show a front that emanates northward from Punta Lavapié.

[1989] used a similar approach to address the circulation in the Gulf of Arauco, this is the first time that the gulf circulation is studied with observations of high resolution in the horizontal plane (hundreds of meters). Also, these observations are among the few of their kind in an equatorward facing bay adjacent to an eastern boundary current. In particular, the Gulf of Arauco appears to enhance the formation of filaments and eddies that export nutrient-rich, upwelled waters to the open ocean [Cáceres, 1992; Mesias *et al.*, 2001] owing to the abrupt change of orientation of coastline and bathymetry. The present study continues to address some of the reasons that explain the high biological productivity of the region and the function of the gulf as a spawning and nursery area for small pelagic fishes and copepods that encroach upon the coastal area during the upwelling season [Castro *et al.*, 1993].

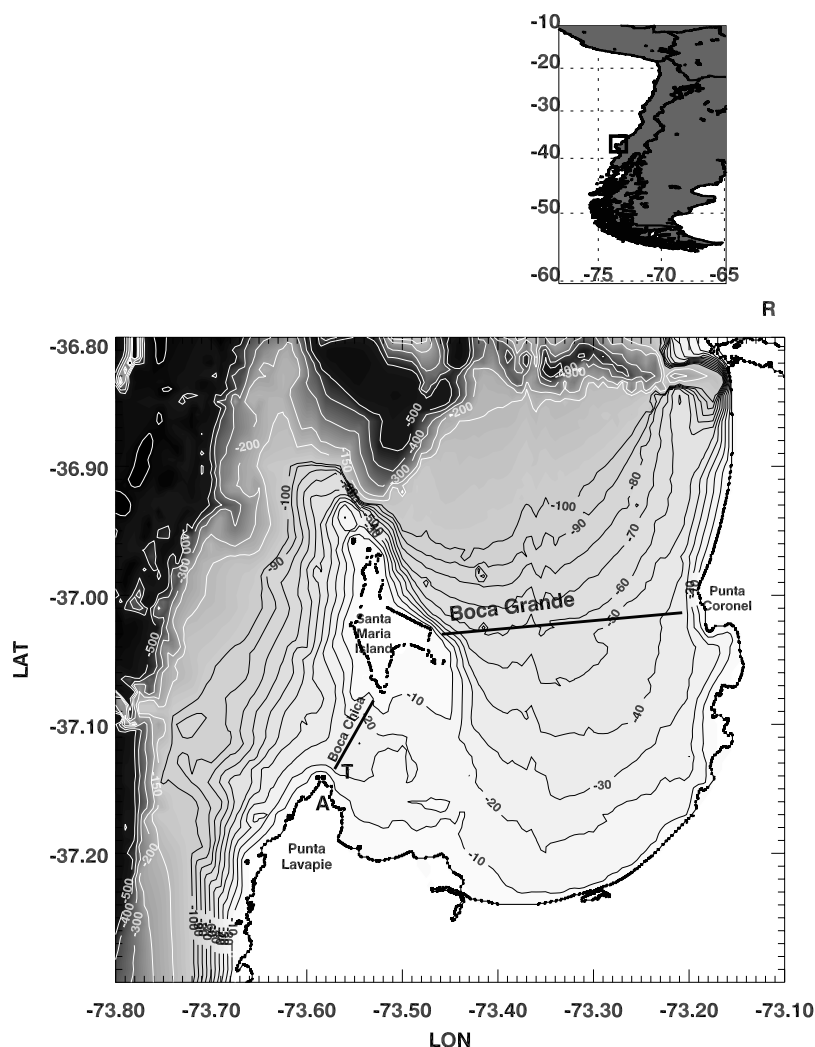
## 2. Study Area

[3] The Gulf of Arauco is an embayment with an approximate “U”- or crescent-shaped opening equatorward, located off the central coast of Chile at 37°S (Figure 2). It is characterized by a marked change in the general orientation of the coastline from N-S to E-W. The presence of Isla

Santa María, on the west, gives it its crescent appearance. In the N-S direction the gulf extends for almost 20 km from Boca Grande to the coast on the south, and in the E-W direction it stretches for ~25 km from Boca Chica on the west to the coast on the east. Its surface area is ~500 km<sup>2</sup>.

[4] The bathymetry of the gulf is relatively smooth with isobaths roughly following the coastline. Immediately to the north, the smooth isobaths are drastically modified by the Bio-Bio Canyon, which cuts through the entire continental shelf on the Itata Terrace [e.g., Djurfeldt, 1989; Sobarzo *et al.*, 2001]. Maximum depths at Boca Grande, in the northern entrance, are 60 m. The presence of Isla Santa María makes Boca Chica a shallow area of restricted water exchange with the adjacent continental shelf to the west.

[5] Wind forcing in the area of the gulf presents a well-defined semiannual signal. Winds are southwesterly, upwelling favorable, during most of the austral spring and summer (September to March) and shift to predominantly northerly and northwesterly directions in late autumn and winter (May to July) with transitional periods of variable winds in April and August [Saavedra, 1980; Parada, 1999; Parada *et al.*, 2001]. They are believed to be the main driving agent of the nontidal circulation in the gulf [Parada *et al.*, 2001]. Autumn-winter winds are associated with



**Figure 2.** Map of the study area in the Gulf of Arauco showing the two transects where observations took place: Boca Grande and Boca Chica. The fixed station was located at “T.” The bathymetry of the area is shown in shaded contours at intervals of 10 m between 0 and 100 m. The contour interval changes to 100 m from 100 to 500 m. The bathymetry to the south of Punta Lavapié is only nominal. The anemometer was located at “A,” and the radiation measurements were taken at “R.” The top panel shows the location of the Gulf of Arauco in the context of a portion of South America.

synoptic-scale winds that affect the Chilean coast. Spring-summer winds feature a sea breeze regime with its onshore component peaking at around 3–5 m/s in the afternoon (between 1500 and 2000 local time) and reversing to weakly offshore at night. This summer regime is developed by the large air temperature gradients between land and ocean that are boosted by the relatively cold waters of the coastal ocean (typically 11°–15°C) and the relatively large heat fluxes from the atmosphere.

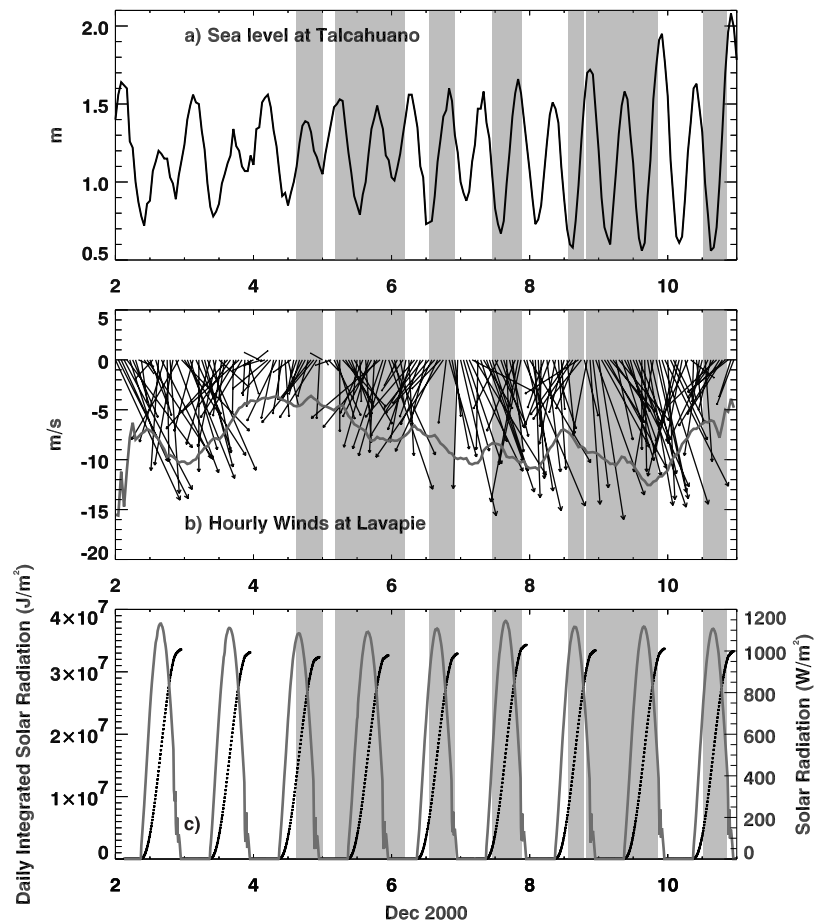
[6] The gulf receives buoyancy forcing from local (atmospheric) and advective (from upwelling) heat fluxes and from freshwater discharge. During the summer, atmospheric heat fluxes exhibit marked diurnal variations related to periods of appreciable solar radiation during the day (Figure 3). This buoyancy forcing should readjust the baroclinic pressure field and induce some type of circulation with diurnal variability. Freshwater inputs to the gulf should only be influential to the subtidal circulation in the winter, when the Bio-Bio River discharge reaches values of close to

3000 m<sup>3</sup>/s [Sobarzo *et al.*, 1993]. In the summer, freshwater influence on the hydrodynamics of the gulf is minimal, typically 200 m<sup>3</sup>/s.

[7] The tides in the Gulf of Arauco are mixed with semidiurnal dominance. Typical neap to spring tidal ranges oscillate between 0.5 and 1.5 m, a threefold increase that should cause fortnightly variations in the subtidal flows of the gulf. This issue remains to be explored formally. The observations described in this study were carried out under weak river discharge conditions and around neap tides, so tides and buoyancy from river forcing were weak and exerted minimal influence in the patterns observed.

### 3. Data Collection and Processing

[8] A variety of sampling activities took place in the Gulf of Arauco between 4 and 10 December 2000. Hydrographic variables consisting of current velocity, temperature, salinity, and density were collected in combination with biological



**Figure 3.** (a) Tidal forcing, (b) wind forcing, and (c) daily solar radiation, instantaneous and integrated, in the area of the Gulf of Arauco during the period of study. The shaded times denote when hydrographic and flow measurements took place. The tides (Figure 3a) were recorded in Talcahuano, just to the north of the gulf. The winds (Figure 3b) were measured at Punta Lavapié (“A” in Figure 2) and show the direction from which the wind blew, which was southerly for the entire period. The wind speed is shown as the solid line in (Figure 3b). The solar radiation (Figure 3c) in watts per square meter is plotted in a shaded line that increases and decreases within each day. The integrated solar radiation (in joules per square meter) increases throughout the day.

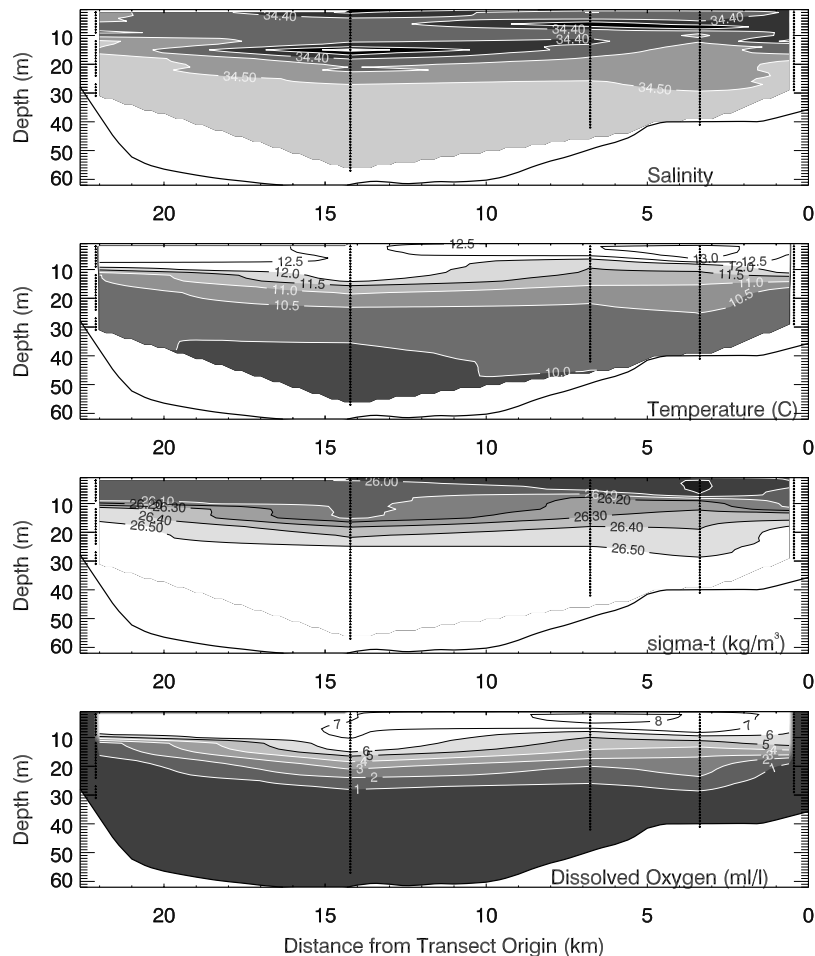
variables (nutrients, chlorophyll, and ichthyoplankton) along two transects and one fixed station. Only the hydrographic variables are reported here. The first transect was located across Boca Grande, between Punta Puchoco and Punta Espolón on Isla Santa María (Figure 2). The second transect crossed Boca Chica between Punta Lavapié and Isla Santa María (Figure 2). The fixed station was located within 2 km to the east of Punta Lavapié (Figure 2).

[9] The Boca Grande transect (Figure 2) was the most intensively sampled during the period of study. The transect was repeated 8 times over a 25-hour period on 5 and 6 December. Current velocity measurements were recorded underway and hydrographic stations were carried out at the end of each transect repetition. Individual repetitions of the Boca Grande transect, which typically lasted 3 hours, were also carried out on 4, 6, and 8 December. In the Boca Chica transect (Figure 2), hydrographic and underway current velocity profiles were sampled for 10 hours on 7 December. Wind and sea conditions hindered sampling throughout a full semidiurnal cycle and allowed only seven repetitions of the transect. The fixed (anchored) station off Punta Lavapié was

occupied for 25 hours from 8 to 9 December 2000. Measurements of velocity profiles were combined with hydrographic data collected every hour.

[10] A 307.2-kHz Workhorse RD Instruments acoustic Doppler current profiler (ADCP) was mounted on a boom on the starboard side of the R/V *Kay-Kay* of the Universidad de Concepción in Chile. Underway data collection took place at speeds between 2.5 and 3 m/s and consisted of 2-s pings, with a bin size of 1 m, that were averaged over 2 min to give a spatial resolution between 300 and 360 m. The first bin was centered at a depth of 3 m. Navigation data were obtained with a Trimble 2000D Global Positioning System and used to calibrate the ADCP compass according to *Joyce* [1989]. Bad data were identified and eliminated from further analysis following the criteria presented by *Valle-Levinson and Atkinson* [1999]. For the anchored station off Lavapié on 8 and 9 December the ADCP pinged at 5-s intervals that were averaged over 30 min.

[11] A SeaBird SBE19 conductivity-temperature-depth (CTD) recorder with an oxygen sensor was used to obtain profiles of temperature, salinity, and density. Data were



**Figure 4.** Hydrographic sections across Boca Grande at the northern entrance to the Gulf of Arauco. The symbols denote the location of the conductivity-temperature-depth profiles. A well-defined pycnocline, thermocline, and oxycline appear between 10 and 20 m depth looking northward.

recorded at 2 Hz, processed with the manufacturer's software, and averaged to 1-m bins. Wind data were recorded with a RM Young 05103 anemometer located on Punta Lavapié ( $37^{\circ}10'S$ ,  $73^{\circ}35'W$ , Figure 2). Solar radiation in watts per square meter was measured at Bellavista ( $36^{\circ}47'S$ ,  $73^{\circ}07'W$ , Figure 2).

[12] For the data collected during the transect repetitions at Boca Grande on 5 and 6 December a least squares fit to semidiurnal (period of 12.42 hours inherent of the M2 constituent, the lunar semidiurnal tidal constituent) and diurnal (period of 23.93 hours of the K1 constituent, the diurnal tidal constituent) harmonics, as well as for a subtidal or net flow, was performed as in the *Valle-Levinson et al.* [2000] work. The fit had typical rms errors between fitted and observed signals of 0.03–0.05 m/s. A similar approach was used for the transect repetitions at Boca Chica on 7 December but fitting a semidiurnal harmonic only because of the sampling period (10 hours). In this case the rms errors were smaller because the currents were weaker.

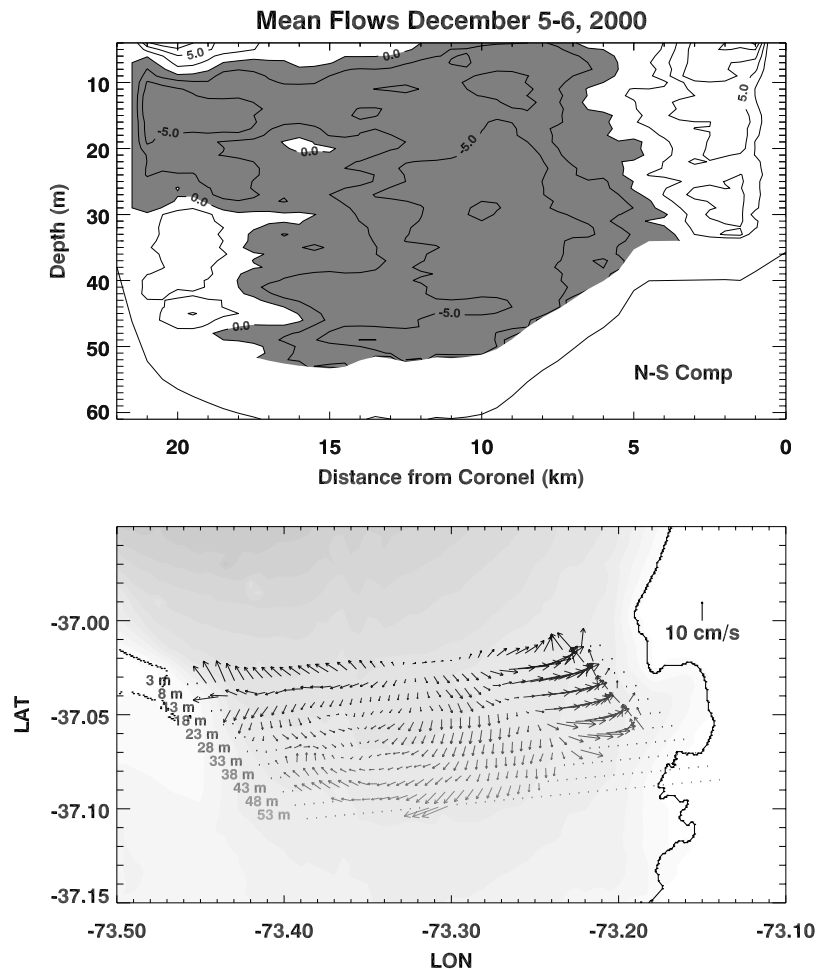
## 4. Data Description

### 4.1. Forcing From Tides and Winds

[13] During the 7 days of sampling (4–10 December), tidal forcing was predominantly semidiurnal but concen-

trated in neap tides (Figure 3a). Between 4 and 7 December the minimum tidal amplitude  $a$  of 0.25 m would yield a depth-averaged tidal current amplitude  $u_0$  that equals  $2aY\sigma/A$  [Stigebrandt, 1977] or  $\sim 0.04$  m/s, where  $\sigma$  is the frequency of the semidiurnal tide ( $2\pi/12.42$  hours),  $Y$  is the area of the basin to the south of Boca Grande ( $\sim 5 \times 10^8$  m<sup>2</sup>), and  $A$  is the area of the cross section at Boca Grande ( $\sim 1 \times 10^6$  m<sup>2</sup>). Therefore tidal forcing was weak and should have had a small influence on the observed patterns of subtidal flow. Note that the tidal amplitude can reach 0.9 m during spring tides (almost a fourfold increase), so tidal forcing should be more influential then.

[14] During the 7 days of sampling the wind was strong and steady from the south (Figure 3b). Its magnitude increased from the beginning to the end of our experiments and in general showed a diurnal fluctuation consistent with a sea breeze regime, as indicated by the 3-hour running mean. The daily maximum magnitude appeared close to midnight UT or 2000–2100 local time, right around sunset (in the austral summer). As seen later, this timing, in which the peak of the vertical flux of horizontal momentum by the wind stress coincides with the end of the vertical (downward) flux of heat at the air-water interface, at least during our sampling period, may allow vertical exchange of properties in the water column. Such vertical exchange should have important

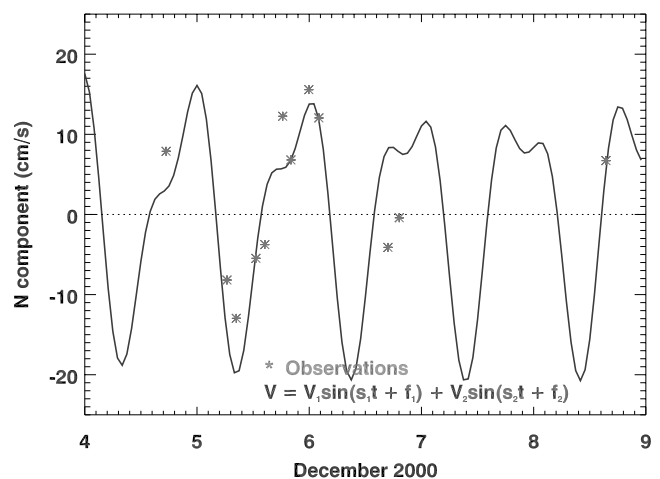


**Figure 5.** Mean flows obtained at Boca Grande during 25 hours of transect sampling at Boca Grande. (top) Contours, looking northward, denoting N-S component of the flow (in centimeters per second). Positive (open) contours denote northward flow. Line contours interval is 2.5 cm/s. The zero isotach delineates the dark region that shows net inflow. (bottom) Vector representation of the mean flow at different depths at Boca Grande. Each depth level is displaced in latitude and longitude for better visualization.

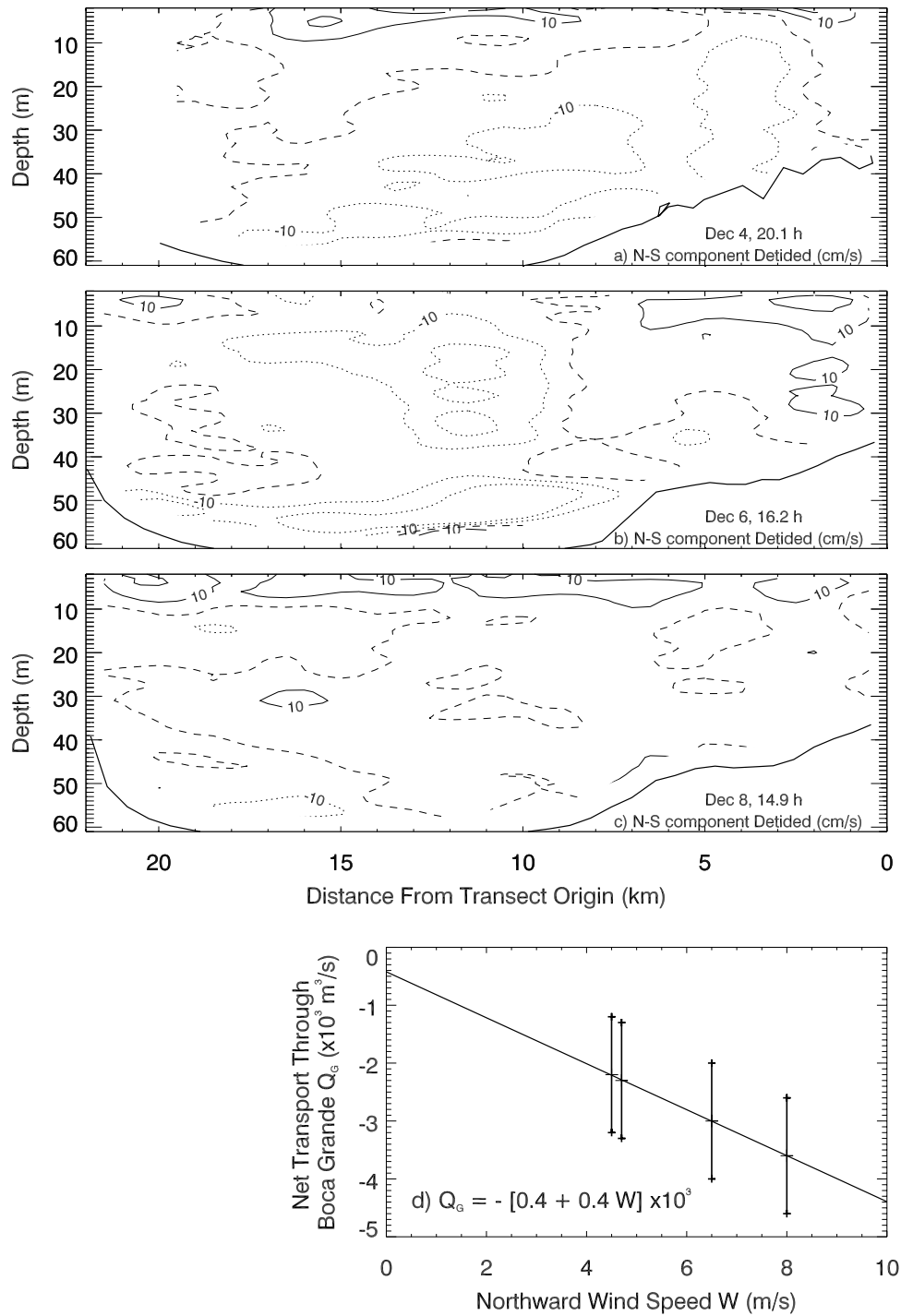
implications for the productivity of the gulf. Sections 4.2 and 4.3 present the flow and hydrographic distributions observed at Boca Grande and Boca Chica, respectively.

**4.2. Boca Grande**

[15] The hydrographic distribution obtained from five CTD casts across Boca Grande on 6 December (Figure 4) showed a well-defined pycnocline, tracing the thermocline, and a strong oxycline between depths of 10 and 20 m. The upper layer is warmed by atmospheric heating, reaching 14°C, and is well oxygenated up to 9 mL/L. The characteristics of the upper layer were in sharp contrast to the lower layer, where the deepest water was ~8°C and <1 mL/L. These water characteristics were typical of upwelled waters from the Gunther Current (or the Peru-Chile Undercurrent), which is the poleward undercurrent frequently found underneath the Humboldt (or Peru-Chile) Current [Strub *et al.*, 1998; Sobarzo *et al.*, 2001]. The wind forcing and the hydrographic conditions observed were thus indicative of an active upwelling situation that is explored next with the net or subtidal flows.



**Figure 6.** Fit (solid line) of diurnal and semidiurnal constituents to the flow observations (asterisks) obtained at one point of the Boca Grande transect from 4 to 9 December 2000.

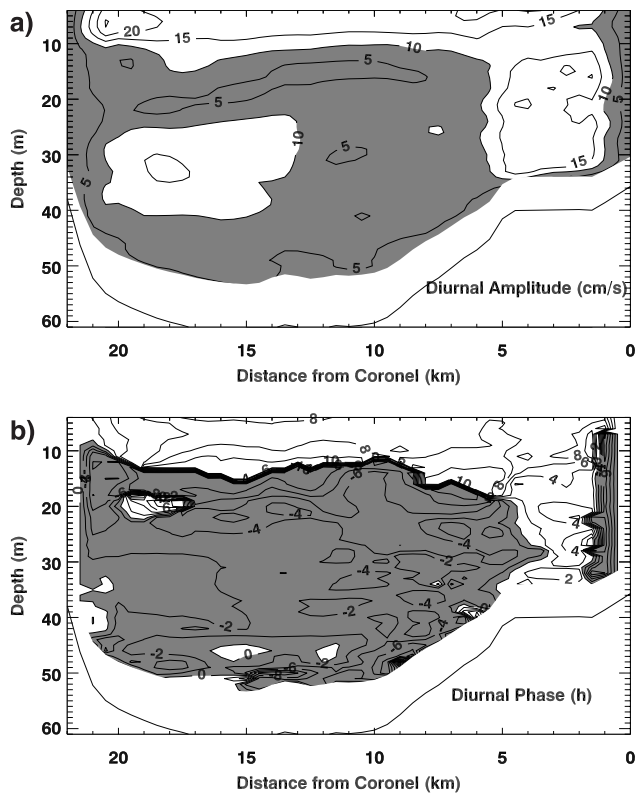


**Figure 7.** (a–c) Detided flow at Boca Grande for three different days and (d) net transport through Boca Grande as a function of northerly wind speed. In Figures 7a–7c, solid contours denote southward flow. Line contour interval is 10 cm/s with the zero isotach represented by a dashed line. Times in the middle of the transect are shown in UT (local time plus 3 hours). Figure 7d shows observed net transports (plus signs) during the 3 days (Figures 7a–7c) in addition to the net transport on 5 and 6 December depicted on Figure 5. The estimates also show the range of uncertainty of the transports as the entire transect was not resolved by sampling. The diagonal line represents the fit between wind speed and transport. Negative values in the ordinate denote southward transports caused by northward winds.

[16] The subtidal flow measured at Boca Grande during the 25-hour period of transect repetitions on 5 and 6 December indicated a net downwind flow over the shallow areas of the flanks of the gulf and a net upwind flow in the

deepest part in the middle of the section (Figure 5). These net flows were practically in the same direction throughout the water column and agreed with theoretical wind-induced patterns over a bay with a parabolic or triangular shape [e.g.,





**Figure 8.** (a) Amplitude (in centimeters per second) and phase (in hours) of the semimajor axis of the diurnal tidal ellipses derived from the fit to the 25-hour transect repetitions of 5 and 6 December. Flows are represented by open areas  $> 10$  cm/s. (b) Positive phase represented by open areas and negative phase represented by shaded areas. View is northward.

Csanady, 1973; Hearn *et al.*, 1987; Signell *et al.*, 1990; Wong, 1994; Friedrichs and Hamrick, 1996]. The upwind flow seems to recirculate in a clockwise fashion over the western portion of the gulf and in a counterclockwise fashion over the eastern side. The volume influx (southward) through Boca Grande was  $\sim 1.8 \times 10^4$  m<sup>3</sup>/s, while the volume outflux (northward) was  $\sim 1.5 \times 10^4$  m<sup>3</sup>/s. This represented a net upwelling-induced southward flux of  $\sim 3000$  m<sup>3</sup>/s, approximately two thirds of which was flushed through Boca Chica (see section 4.3) with the remainder probably recirculated in the gulf.

[17] The importance of wind forcing to the dynamics of the Gulf of Arauco is indeed corroborated by the Wedderburn number  $W_n$  [e.g., Geyer, 1997] that compares wind stresses to baroclinic influences and is commonly used to determine the wind stress influence on stratified lakes:

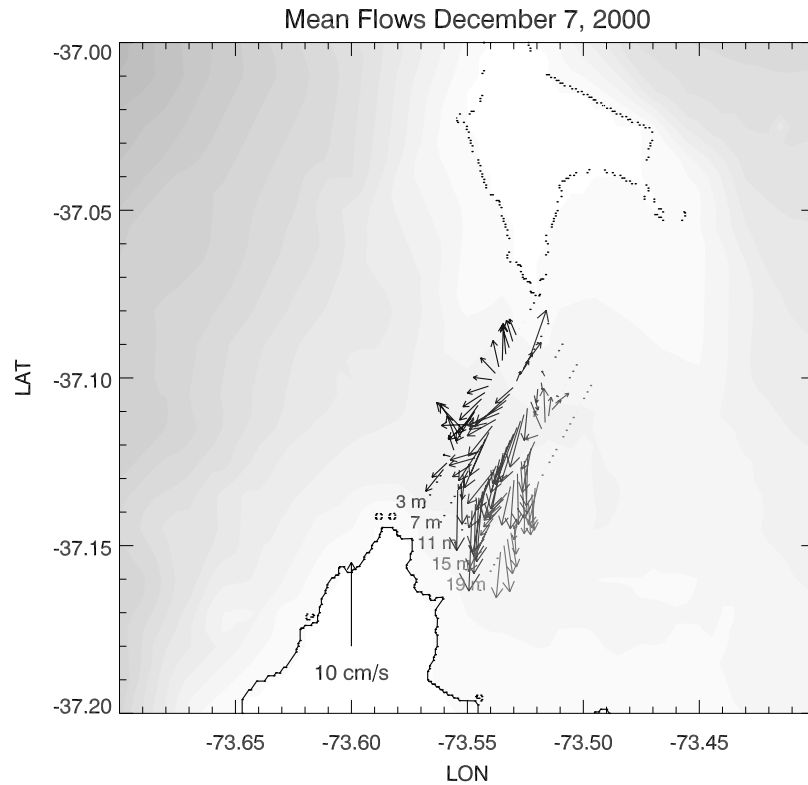
$$W_n = \frac{\tau_s L}{g \Delta \rho H_u^2},$$

where  $\tau_s$  is the wind stress,  $L$  is the length of the gulf (20 km),  $g$  is the acceleration due to gravity (9.8 m/s<sup>2</sup>),  $\Delta \rho$  is the density contrast in the gulf (0.5 kg/m<sup>3</sup>), and  $H_u$  is the thickness of the upper layer. During the period of measurements,  $\tau_s$  was typically 0.1 Pa, and  $H_u$  was 10–20 m. For these values,  $W_n$  could be between 1 and 4, which illustrates the importance of wind forcing.

[18] In order to investigate the persistence of the observed wind-induced pattern, we examined the data collected during the other individual crossings of Boca Grande on 4, 6, and 8 December. The observed currents during these crossings obviously had some tidal forcing influence, which had to be subtracted to obtain the net flows. The tidal signal for each period of observation was obtained from fitting semi-diurnal and diurnal harmonics to the entire time series (Figure 6). The assumption here was that both semidiurnal and diurnal contributions did not change over 5 days. This is a bit restrictive, but a longer time series is required to obtain a more reliable fit. In fact, a fit that included the S2 tidal constituent (period of 12 hours) did not improve the fit as the time series could not distinguish M2 from S2 in 5 days of data. The length of the time series required to isolate the individual contribution of these two constituents is given by the difference in their frequencies, i.e., 0.00282 hour<sup>-1</sup>, which is equivalent to 14.79 days.

[19] The detided flow showed persistent downwind flow at the surface and over the shallow sides and upwind flow (related to upwelled water) in the deeper portions of the transect (Figure 7). This pattern was consistent with that obtained with the 25-hour time series (Figure 5). The persistence of the water exchange patterns at Boca Grande indicated continuous upwelling during our period of observations (Figures 7a–7c) as the northward wind increased. The net volume inflow (volume influx minus volume outflux) through Boca Grande increased linearly with northward wind forcing (Figure 7d). This response was congruent with the wind-induced flow that arises mainly from surface stresses and the establishment of a barotropic pressure gradient. It should be noted that regardless of the dominant dynamics the net flux should be proportional to wind stress at these spatial scales. The volume fluxes extrapolated to calm conditions are undistinguishable from zero (400 m<sup>3</sup>/s, likely within measurement error), which agrees with the concept of no net volume flux for zero wind velocity. An alternative explanation for the flux patterns observed is that the separation of an upwelling jet at Punta Lavapié leads to the downstream formation of eddies, some of which are entrained into the Gulf of Arauco [Mesias *et al.*, 2001]. The relative influence of local and remote forcing mechanisms on the exchange patterns in the Gulf of Arauco, then, remains to be explored with longer time series.

[20] The distributions of the amplitude and phase (Figure 8) of the diurnal currents revealed the locations in Boca Grande that responded best to the sea breeze forcing. These distributions showed maximum diurnal variability at a surface layer that tilted upward toward the east (Figure 8a). They also exhibited large variability below the surface and near the ends of the transect. The diurnal phase distributions showed a subsurface layer with a 12-hour lag relative to the surface layer, which indicated flows in opposite directions (Figure 8b). The combination of the diurnal amplitude and phase distributions illustrated a surface layer, approximately delimited by the pycnocline (Figure 4), moving in the same direction as the sea breeze and a subsurface layer moving simultaneously in the opposite direction. The regions of greatest diurnal variability were likely related to local wind forcing. The band of minimum diurnal variability that almost crossed from one side to the other of Boca Grande (Figure 8a) represented the transitions in the vertical plane



**Figure 9.** Mean flows after a 10-hour period at Boca Chica. Representation is the same as in the bottom of Figure 5. They illustrate outflow at surface, southward flow below the surface, and inflow near the bottom.

of the oppositely directed flows. The other region of low variability in the deepest part of the section was likely connected to the relatively steady, southward flowing upwelled water that was forced remotely.

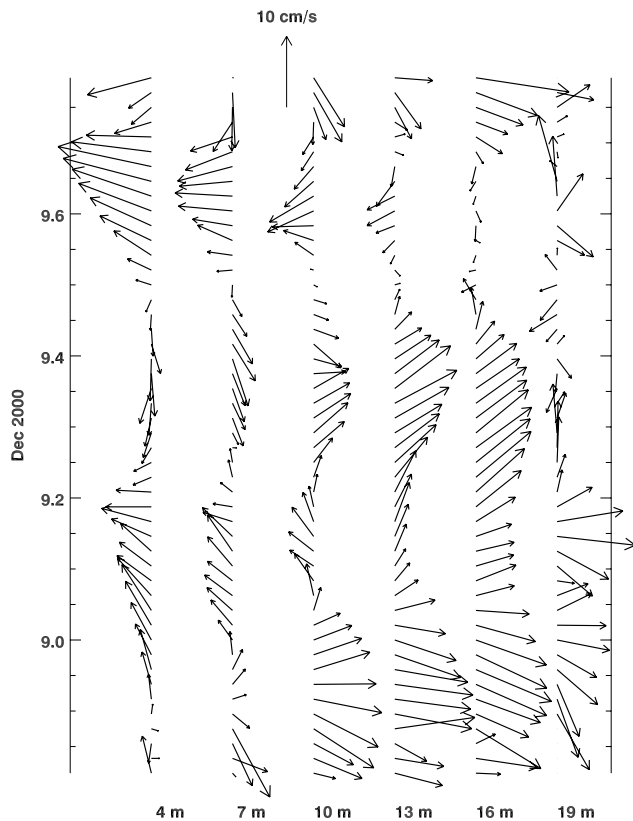
[21] The hydrographic and flow measurements described above indicated a southward advection of upwelled water through Boca Grande. This upwelled water is probably ventilated (reaches the surface) at regions that are shallow enough, i.e., at the depth equivalent to the thickness of the bottom layer, and where the surface layer diverges to the sides of the gulf at its southernmost end to give way to the upwelled waters. The proximity of the Gunther current to the coast might contribute to whether upwelled water has the appropriate characteristics to enhance productivity. It is unclear what controls the proximity of the Gunther Current to the coast. The section at Boca Grande must be the main pathway of low-oxygen (usually nutrient-rich) water that is advected to the southern part of the gulf. The persistence of the southward advection of upwelled water through Boca Grande should represent one of the reasons why the gulf is highly productive relative to its adjacent waters (Figure 1).

#### 4.3. Boca Chica

[22] The transect measurements across Boca Chica on 7 December 2000 were influenced by relatively strong winds that exceeded 15 m/s around sunset. Despite this wind forcing the distribution of net flows exhibited an exchange pattern consistent with estuarine-like flow but not directly forced by wind stress. Net surface outflow was restricted to the upper 3 m, southward flow across the mouth was

identified through most of the water column, and net inflow was observed near the bottom (Figure 9). The surface outflow tends to generate a region of persistent convergence that is oriented in the N-S direction just a few kilometers to the west of Boca Chica. This frontal region appears consistently in satellite imagery of sea surface temperature and color (Figure 1) and emanates from its anchor point at Punta Lavapié. At this transect the volume outflow (westward) was  $\sim 2.0 \times 10^3 \text{ m}^3/\text{s}$ , while the volume inflow (eastward) was  $\sim 0.3 \times 10^3 \text{ m}^3/\text{s}$ . This represented a net outflow of  $\sim 1700 \text{ m}^3/\text{s}$ , approximately two thirds of the net inflow through Boca Grande, although the fluxes at Boca Grande and Boca Chica were not measured simultaneously.

[23] The fixed station to the east of Punta Lavapié (just to the east of the Boca Chica transect on 8 and 9 December 2001, “T” in Figure 2) exhibited the same flow features (Figure 10) as the transect data, i.e., stronger ebb (westward) flows than flood (eastward) flows at the surface and stronger flood flows than ebb flows near the bottom. This time series displayed a well-defined semidiurnal signal from the dominant tidal forcing although maximum currents only reached 0.10 m/s. Despite these semidiurnal oscillations in the flow the hydrographic variables were dominated by a diurnal periodicity (Figure 11) that was weakly modified by semidiurnal influences. The distributions of temperature, sigma  $t$ , and dissolved oxygen showed smaller ranges than at Boca Grande (Figure 4), with relatively weak vertical gradients in the early hours of 9 December. At around 0600 or 0700 local time (time 9.4 in Figure 11) the temperature vertical range was from 10.1° to 10.8°C, the salinity vertical



**Figure 10.** Time series (in UT) of flows at different depths at anchored station “T” shown in Figure 2. North is pointing upward. Westward flow (out of the gulf) is predominantly observed near the surface (4 and 7 m), and eastward flow (into the gulf) dominates near the bottom (below 13 m).

range was from 34.48 to 34.49, the sigma  $t$  vertical range was from 26.4 to 26.5 kg/m<sup>3</sup>, and the vertical range in dissolved oxygen was from 3.3 to 3.9 mL/L. The weak vertical gradients during the early hours of the day suggest enhanced vertical mixing in Boca Chica relative to Boca Grande. This concept is further explored in section 4.4 by comparing the diurnal changes in stratification at both locations.

#### 4.4. Diurnal Changes in Stratification

[24] The water column stratification may be described in terms of one parameter  $\varphi$  that represents the energy required to completely mix the water column or the potential energy anomaly [e.g., *Simpson et al.*, 1990] in joules per cubic meter:

$$\phi = \frac{g}{h} \int_{-h}^0 (\rho - \bar{\rho})zdz$$

where  $\rho$ ,  $\bar{\rho}$ ,  $g$ ,  $z$ , and  $h$  are the water density as a function of depth, the depth-averaged water density, the acceleration due to gravity, the vertical coordinate (positive upward), and the water column depth, respectively. The values of  $\varphi$  from the eastern station at Boca Grande (Figure 8a) for 5 and 6 December indicate the greatest stratification (greatest values of  $\varphi$ ) late in the day, around 2000 local time, and weakest

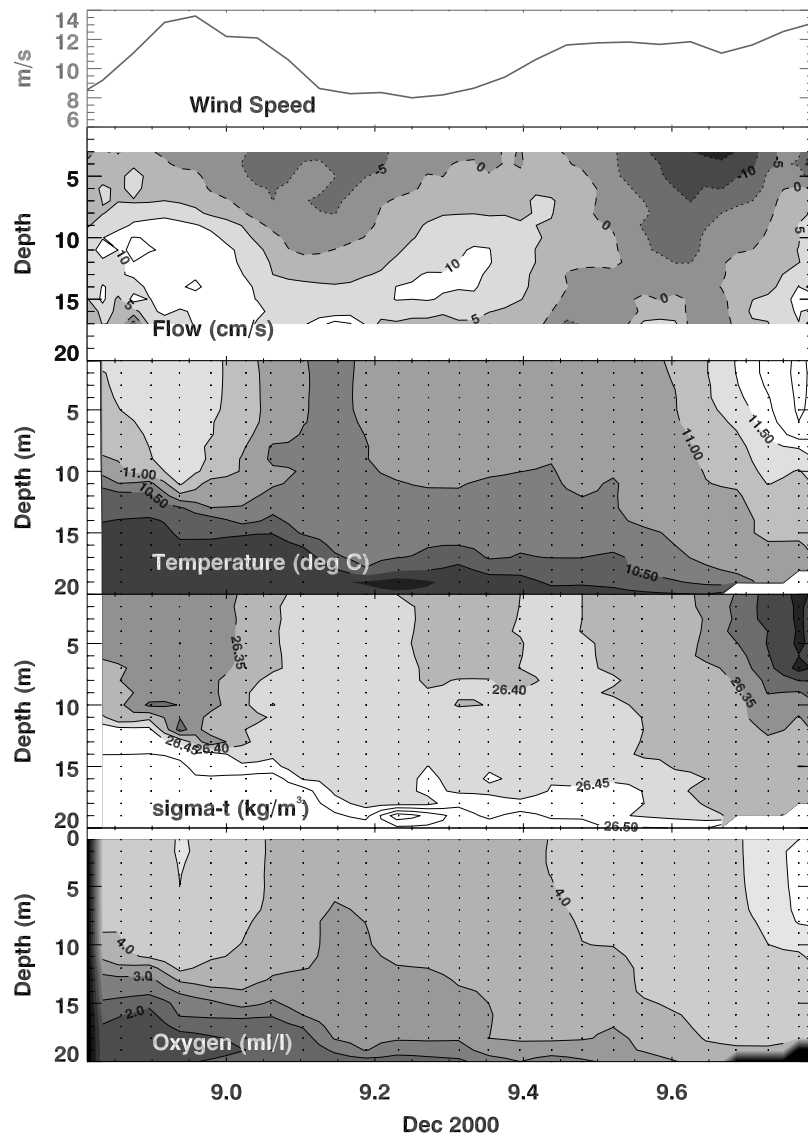
stratification early in the day, around 0600 (circles and plus signs in Figure 12a). These stratification patterns are very similar, qualitatively, to those observed in Boca Chica (asterisks in Figure 12a), although the values are markedly smaller. These patterns indicate (1) that stratification extremes are approximately in phase at both locations and (2) that Boca Grande is more stratified than Boca Chica by  $\sim 15$  J/m<sup>3</sup>. The causes for this difference in stratification can be explored through the changes of  $\varphi$  over time.

[25] The changes in  $\varphi$  over time, as shown in Figures 12b and 12c, should result from the competition between mixing and stratifying tendencies. Mixing tendencies include surface and bottom stresses, and stratifying tendencies include heat fluxes and advection of buoyancy. In the study area, bottom stresses are at least 1 order of magnitude weaker than surface stresses, and advection of buoyancy requires knowledge of the horizontal density gradients. Therefore only the temporal changes in  $\varphi$  owing to surface stresses ( $d\varphi/dt_w$ ) and heat fluxes ( $d\varphi/dt_Q$ ) were estimated with the data available. For these estimates the relationships  $d\varphi/dt_w \approx -1.6 \times 10^{-6} W^3/h$ , where  $W$  is the wind speed in meters per second, and  $d\varphi/dt_Q \approx 2 \times 10^{-7} Q$ , where  $Q$  is heat flux in watts per square meter, were used [*Simpson et al.*, 1990]. In this application it is assumed that the solar radiation shown in Figure 3c accounts for most of the heat flux. These relationships show that wind mixing power is inversely related to the local depth, so more mixing power per unit volume is expected at Boca Chica than at Boca Grande, and this should explain the weaker stratification of that location.

[26] The combined effect of  $d\varphi/dt_w$  and  $d\varphi/dt_Q$  results in negative values that indicate that destratification should occur for both Boca Grande (Figure 12b) and Boca Chica (Figure 12c) throughout the diurnal cycle. This destratification tendency agrees with the observed temporal changes in  $\varphi$  during the period between 0500 and 1000 but is opposite to that observed in the afternoon, when the wind is strongest and yet stratification increases. This result suggests that wind stresses and heat fluxes are enough to explain the stratification changes during the early daylight hours but are insufficient to account for the afternoon stratification. This discrepancy could be the result of (1) sensible and latent fluxes, not taken into consideration in the heat flux estimates, accounting for much larger heat fluxes than those measured from solar radiation, (2) advection of buoyancy, an element missing in the calculations, playing a crucial role in the stratification patterns of the Gulf of Arauco, or (3) a combination of both. The fact that maximum stratification is achieved approximately at the time of maximum wind speed suggests that wind forcing in this area acts more to advect buoyancy than to mix it at least at the time of positive heat fluxes (from air to water). This finding is consistent with that of *Atkinson et al.* [1989] in the South Atlantic Bight where Ekman transport overcame strong winds and large heat losses.

## 5. Discussion

[27] Two phenomena worth noting were identified in the Gulf of Arauco, and they are illustrated for Boca Grande in Figures 13 and 14. They are related to the generation of overtides and the formation and propagation of internal

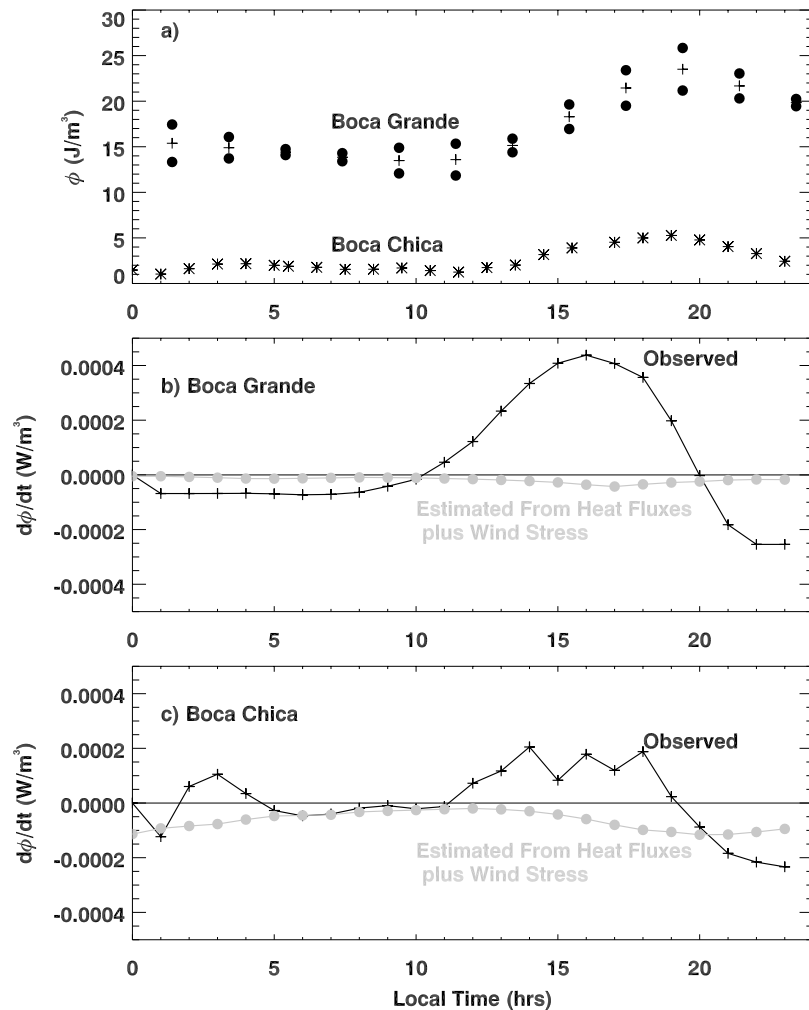


**Figure 11.** Time series of wind speed, flow, and hydrographic variables during the anchored station at “T” shown in Figure 2.

motions along the coast that dissipate in the shallow area of Boca Chica. The generation of overtides is suggested by the amplitude of the semidiurnal tidal currents, which was comparable to that of the diurnal currents but only over the shallow (<30 m) areas (Figure 13). The semidiurnal variability was negligible in the deep part of the section, which indicated that semidiurnal tidal forcing was unimportant at Boca Grande as expected from the small tidal ranges during the period of study. The relatively large semidiurnal amplitudes over the shallow regions must then reflect a harmonic response to diurnal forcing (overtide) that arises from nonlinearities related to bottom friction, advection, and/or continuity [e.g., Parker, 1991]. The specific mechanism that generated these semidiurnal overtides is a topic that merits more attention, but that may only be substantiated with a time series across Boca Grande of longer coverage than those obtained in this study.

[28] The formation and propagation of internal motions may be quite energetic as identified from the time series of

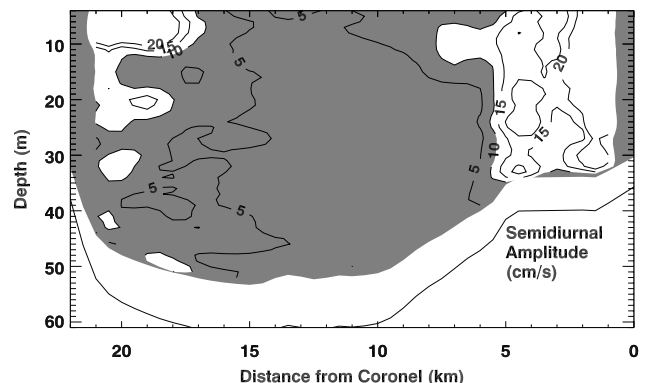
the hydrographic variables on the eastern side of Boca Grande (Figure 14). This time series illustrates diurnal vertical excursions of the pycnocline of around the 10-m range. The vertical excursions seem to be forced by vertical fluxes of (1) heat (through air-sea diurnal heating) and (2) horizontal momentum (through the diurnal sea breeze regime). The pycnocline is deepest in the early evening (2000–2100 local time) at the end of the landward wind, which approximately coincides with the end of the heat input to the sea surface. This diurnal perturbation of the pycnocline could generate internal motions that propagate with the coast on the left, as in an internal Kelvin wave, and would dissipate once they get to the shallow (<20 m) southwestern mouth of the gulf at Boca Chica. It is possible that, at that location, nutrients are mixed upward to the photic layer and enhance the productivity of the area. This hypothesis is consistent with a mechanism proposed by *Djurfeldt* [1989], although his mechanism was triggered by a wind reversal from southerly to northerly and had a



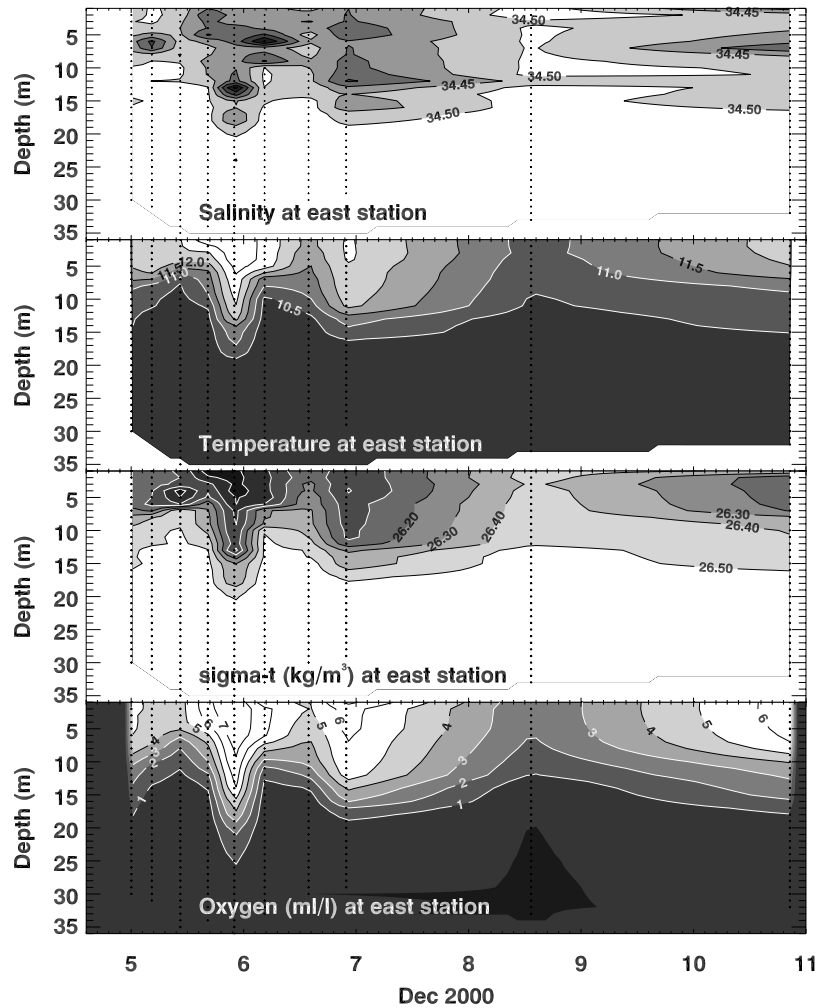
**Figure 12.** Diurnal variations of (a)  $\phi$  at Boca Grande and Boca Chica, (b)  $d\phi/dt$  at Boca Grande, and (c)  $d\phi/dt$  at Boca Chica. In Figure 12a the circles denote measurements on 5 and 6 December 2000. The plus signs denote the average  $\phi$  for both days. The asterisks indicate observed  $\phi$  on 8–9 December. In Figures 12b and 12c the solid lines represent observed values (derived from Figure 12a) and the shaded lines denote the estimates of  $d\phi/dt_W + d\phi/dt_Q$ .

periodicity of 2–5 days. The mechanism proposed herein occurs at a higher frequency, i.e., every day versus every 2–5 days. The hypothesis related to the diurnal periodicity is supported by the 25-hour time series measurements carried out to the east of Punta Lavapié (close to Boca Chica) that showed weakened vertical gradients in all hydrographic properties relative to those observed at Boca Grande. An alternative to this hypothesis is that the weakened vertical gradients could be caused entirely by wind-driven mixing. Such hypotheses are worth exploring with more comprehensive measurements.

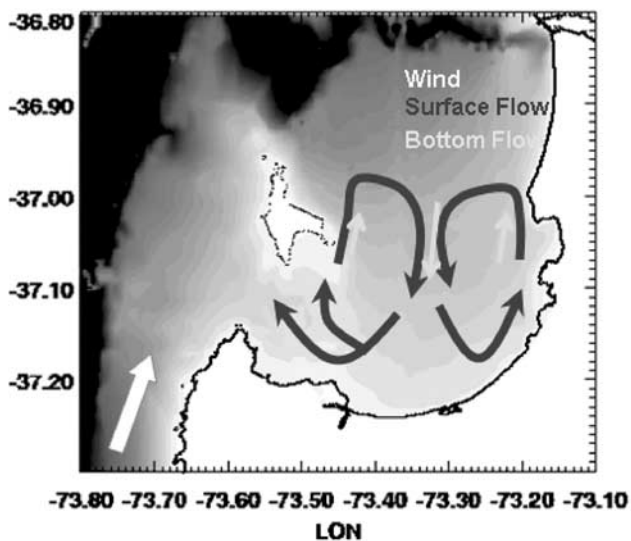
[29] The exchange pattern at Boca Chica was likely driven by remotely forced Ekman dynamics on the outer shelf or by curvature effects associated with flow around a headland [e.g., Pattiaratchi and Collins, 1987; Geyer, 1993]. The near-surface net flow away from the headland arises from a balance between centrifugal accelerations and pressure gradient. The near-bottom net flow toward the headland results from an imbalance in favor of the pressure gradient force owing to the weakening of the centrifugal accelerations as the flow decreases with depth. This has



**Figure 13.** Amplitude (in centimeters per second) of the semimajor axis of the semidiurnal tidal ellipses derived from the fit to the 25-hour transect repetitions of 5 and 6 December. Open areas indicate flows >10 cm/s.



**Figure 14.** Time series of hydrographic variables at the eastern end of Boca Grande. Small symbols denote the location and time (in UT, local plus 3 hours) of observations. The diurnal excursions of the pycnocline were resolved best on 5 and 6 December.



**Figure 15.** Schematic representation of the proposed circulation in the Gulf of Arauco during upwelling (southerly) winds.

been identified as a region of coastal flow separation by the modeling results of *Mesias et al.* [2001]. The mechanism that generates the exchange pattern at Boca Chica is another topic that is worth exploring further.

## 6. Summary

[30] Shipborne observations of current and hydrographic variables in an equatorward facing bay adjacent to a coastal upwelling center, the Gulf of Arauco in Chile, suggested two mechanisms that may cause the high primary productivity of the system. The first mechanism was related to a persistent flow into the gulf through the deepest part of Boca Grande (the equatorward facing entrance to the embayment). This poleward flow was cool and had low dissolved oxygen, characteristic of the upwelled water in the region. The poleward flow was likely part of a double gyre (Figure 15) that caused flow divergence in the southern end of the gulf and allowed the cool upwelled water to surface in that southern portion of the gulf. A portion of this upwelled flux was recirculated in and out of the gulf through the same area of Boca Grande and also through a westward opening at Boca Chica. The second mechanism

was not as evident with our observations but has to do with the diurnal variability in heat (from air-sea interactions) and horizontal momentum (from wind stress) fluxes. This diurnal forcing causes oscillations of the pycnocline with ranges of  $\sim 10$  m that may propagate poleward along the coast, emulating a Kelvin wave. These oscillations may break down in the shallow portions ( $< 20$  m) of Boca Chica, hindering the wave from further propagation and allowing the mixing of properties in the water column. These two mechanisms should be responsible for the high productivity of the gulf, and both are located in the southern end of the gulf, where color images suggest maxima in concentrations of chlorophyll (e.g., Figure 1).

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