Lagrangian Observations of the Circulation in the Northern Gulf of California

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ABSTRACT

ARGOS drifters deployed in the Northern Gulf of California in September 1995 showed the presence of a cyclonic gyre, while a second deployment in March 1996 revealed an anticyclonic gyre. A circulation pattern consisting of a seasonally reversing gyre had been proposed before on the basis of satellite images, geostrophic calculations, and numerical models, but so far no direct observations have been made to test its existence. In September the gyre was cyclonic, baroclinic, very well defined, stable, and strong; its mean speed and rotation time were 0.3 m s^{-1} and ~7 days. In March the gyre had the same mean speed, but it was anticyclonic and displaced to the northwest of the summer position. The March gyre has barotopic and baroclinic characteristics, but the observed speeds are stronger than in numerical simulations. These data and a data bank analysis suggest that the summer gyre is a persistent summer feature, but the winter–spring situation remains ill-defined and requires further research.

1. Introduction

The Gulf of California (GC), located in the Pacific northwest of Mexico (insert, Fig. 1), boasts several unique features: it is the only large evaporative basin on the Pacific Ocean (Roden 1958) as well as the only one subjected to intense tidal mixing (Argote et al. 1995). Among elongated semienclosed seas, it is the only one lacking a sill at its point of communication with the ocean and may be the only one with a net annual heat gain through its surface (Lavín and Organista 1988), thus requiring a reverse-Mediterranean thermohaline circulation. Its dynamics and thermodynamics are strongly seasonal, owing to the marked seasonality of the forcing agents: heat and momentum exchange with the atmosphere and interaction with the seasonally changing system of currents and mass field at the connection with the Pacific Ocean (Wyrtki 1965; Castro et al. 1994; Ripa 1997). The climate over the gulf presents only two clearly differentiated seasons: a midlatitude winter lasting approximately from October to May and a subtropical summer lasting approximately from June to September (Roden 1958; Badan-Dangon et al. 1991); the transition seasons are short. The winds blow along the axis of the gulf, from the NW in winter (mean speed of ~5 m s^{-1}) and from the SE in summer (~3 m s^{-1}).

Most of the unique features of the gulf are actually found in the northern section, called the Northern Gulf of California (NGC), whose mean depth is about 200 m (Fig. 1). It has three deep basins, Delfín Basin (800 m), Tiburón Basin (500 m), and Wagner Basin (200 m), and is separated from the rest of the gulf by an archipelago that includes the two largest Mexican islands (Angel de la Guarda and Tiburón) and several sills: San Esteban Sill (~400 m deep) at its connection with the southern gulf, and the North Ballenas Sill (600 m deep) at its junction with the Ballenas–Salsipuedes Channel. This channel is an oceanographic province on its own and is connected with the southern gulf through San Lorenzo Sill (430 m deep; Fig. 1).

Until now it has been accepted that salinity and temperature distributions in the NGC are determined by heat and moisture seasonal fluxes in the presence of tidal stirring plus wind and convective mixing (in winter) (Lavín and Organista 1988; Paden et al. 1991); however, Ripa (1997) argues that most of the thermodynamic and dynamic variability at the annual frequency in the gulf is caused by a baroclinic Kelvin wave coming from the Pacific Ocean, modified inside the gulf by topography and friction, reinforced by another baroclinic Kelvin wave

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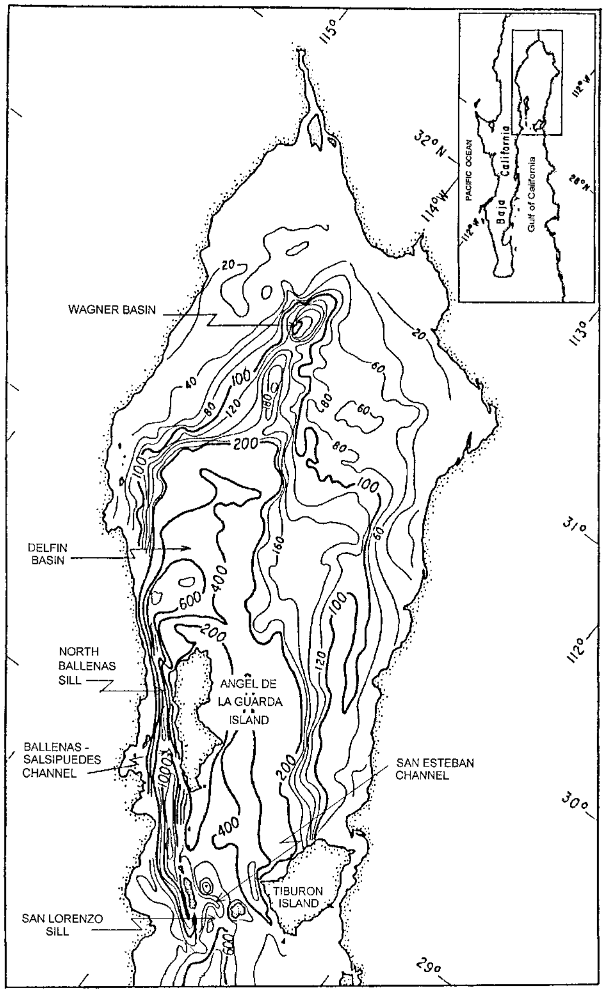


FIG. 1. The Northern Gulf of California, with bathymetry and main basins.

forced by the wind regime. Tidal mixing fronts are found close to the head and over the sills in the archipelago (Argote et al. 1995). The surface mixed layer increases from about 10 m in summer to 70 m in winter (Martínez-Sepúlveda 1994). The heat loss that occurs in the NGC in autumn and winter causes mixing by vertical convection and leads to water mass formation in the shallowest areas at the head of the gulf (Lavín et al. 1995).

More than twenty years ago, a descriptive model of the circulation in the NGC was proposed by Lepley et al. (1975), based on visible, infrared, and multispectral photographs taken by GEMINI, APOLLO, and SKYLAB astronauts, and by ERS satellite: it consisted of a seasonally reversing gyre, cyclonic in summer and anticyclonic in winter. This pattern, suggested originally by the distribution of suspended sediments as seen in the photographs can sometimes be observed in infrared satellite images (Fig. 2). The mechanism proposed by Lepley et al. (1975) for the generation of this circulation system (a ''thermal engine'') was somewhat simple, but it was a good effort considering the data they had at hand.

Bray (1988a) and Ripa (1997) have shown that geostrophic calculations in a cross section of the NGC present a seasonally reversing pattern. Using a larger dataset, Carrillo-Bibriezca (1996) has shown that closed baroclinic gyres appear in the dynamic topography, concave in summer and domed in winter–spring, with the average calculated geostrophic velocities much stronger in summer (0.1 m s^{-1}) than in winter–spring (0.03 m s^{-1}).

In this article we present the first direct observations of the circulation in the NGC, using satellite-tracked drifters and hydrographic surveys. The mechanisms that may lead to the observed circulation pattern are reviewed.

2. Data

Five standard World Ocean Circulation Experiment ARGOS drifters equipped with holey socks centered at 15 m were deployed in the course of two CTD surveys made by the R/V *Francisco de Ulloa* in the NGC, one during 12–20 September 1995 and the other from 30 March to 9 April 1996. The positions of the CTD stations are shown in Figs. 3a and 5a for the September and March surveys, respectively. The CTD used was a factory-calibrated SeaBird Model 9/11. Objective mapping was used for the hydrographic distributions, and all subsequent calculations were performed on the mapped data.

The ARGOS drifters were programmed to give positions continuously for the first month and then change to a 1-day-on-2-days-off cycle. The reason for this sampling scheme was that the drifters were expected to leave the NGC soon, exit the gulf, and merge with the oceanic circulation of the eastern tropical Pacific. In fact, the drifters remained in the NGC, trapped in the gyres, and all of them were eventually recovered, initialized, and redeployed. An average of five fixes per day was obtained at the latitude of the NGC. Typical position accuracy was about 300 m.

3. Results and discussions

a. Summer

Although near the end of the summer season, we will refer to September as ''summer.'' The dynamic topography (Fig. 3a) shows a depression in the middle of the NGC, somewhat to the northeast of the deepest part of Delfín Basin. The geostrophic currents at 10 m relative to 100 m (Fig. 3b) present a clear cyclonic gyre with speeds reaching 0.4 m s^{-1}. The gyre is elongated in the direction across the gulf; it is not centered in the deepest part of Delfín Basin, but offset to the north in the center of the NGC. The currents as derived from the drifters also show the presence of an elongated gyre (Fig. 3c) with speeds very similar to the geostrophic calculations. The center of the gyre as shown by the drifters coincides with the position of the dynamic topography depression,

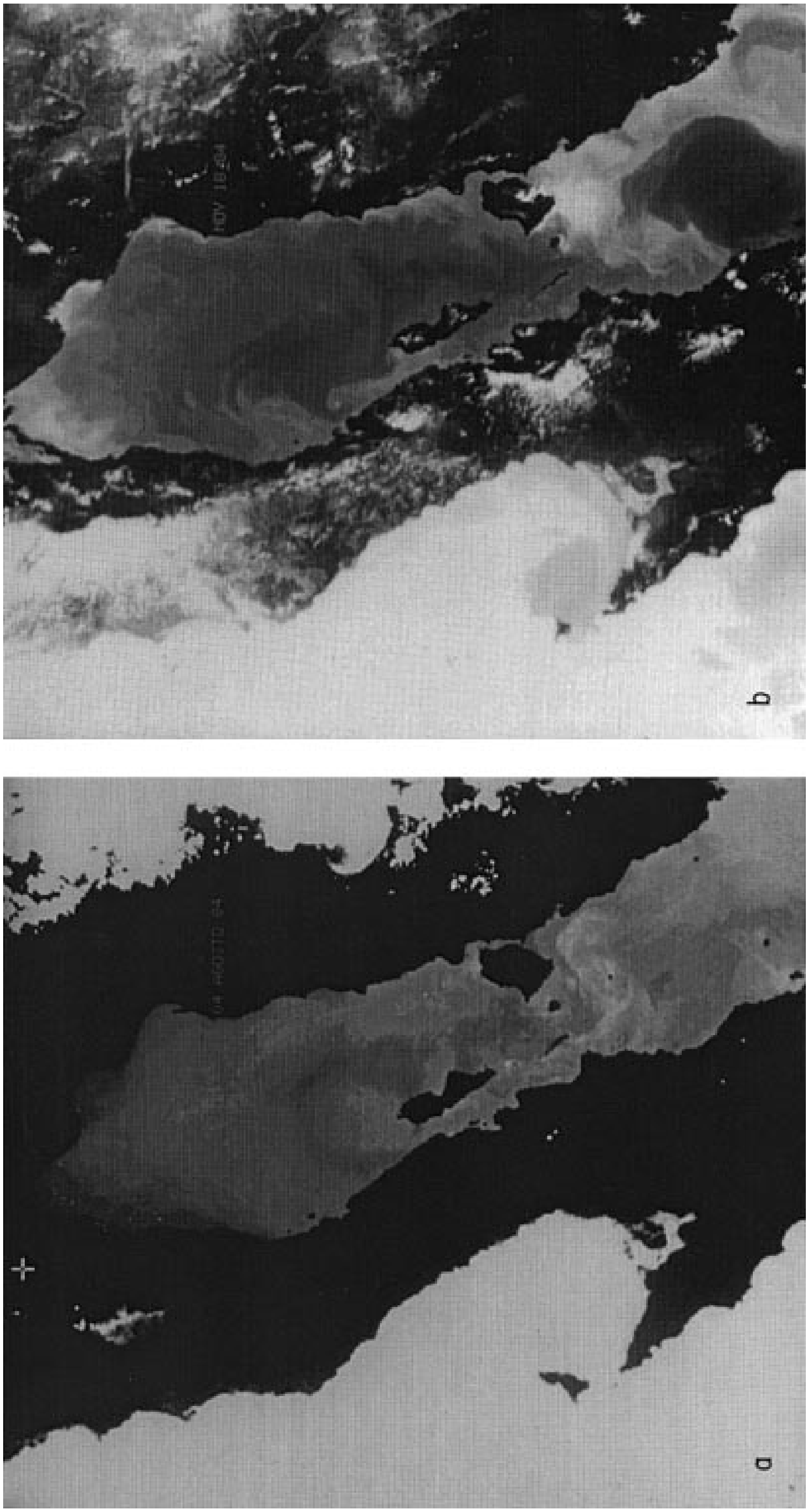
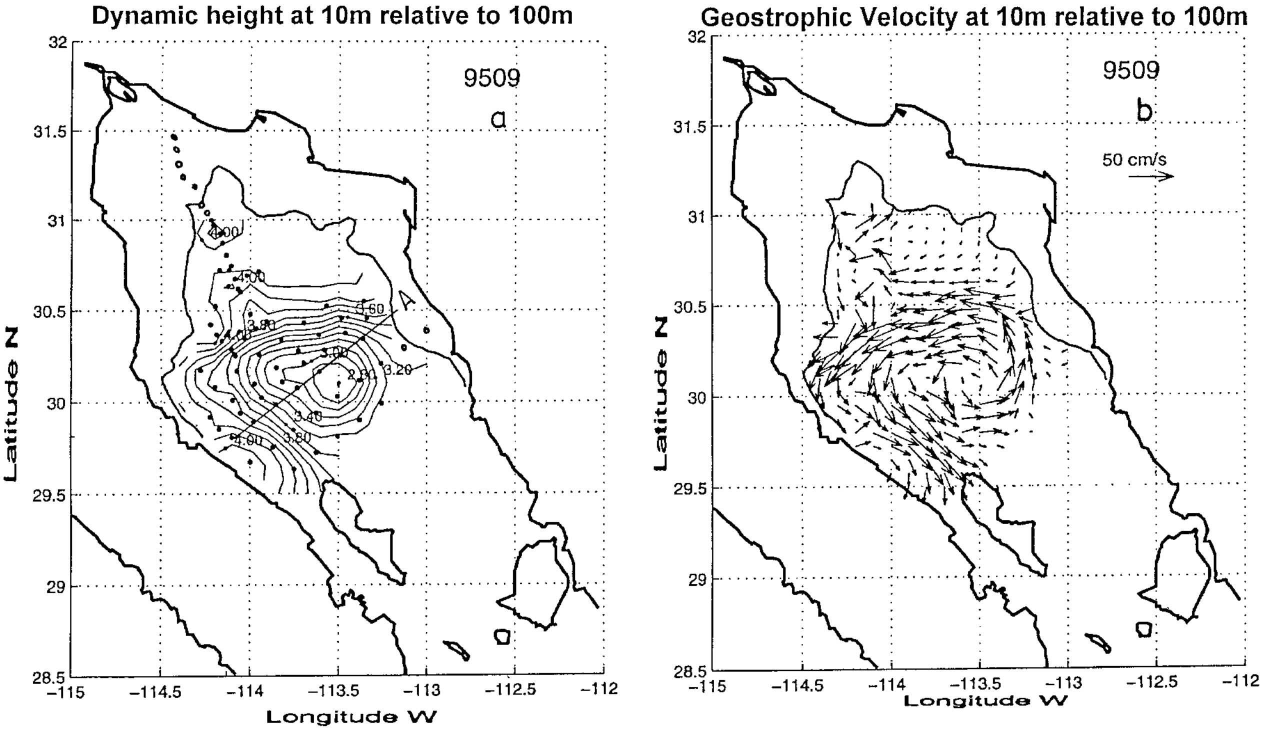


FIG. 2. Satellite infrared images of the Northern Gulf of California, suggesting the presence of gyres in Delfín Basin for (a) summer (4 Aug 1984) and (b) winter (18 Nov 1984).



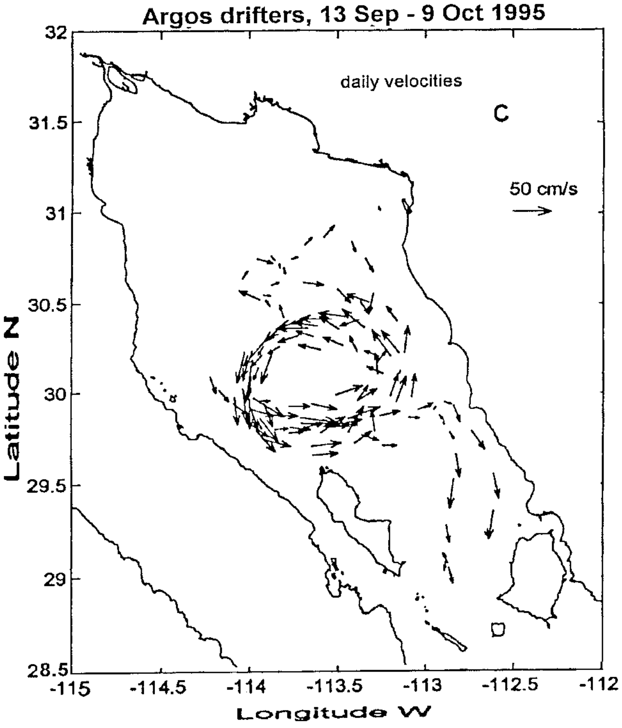


Fig. 3. Observations made in summer 1995: (a) Dynamic topography at 10 m relative to 100 m, (b) surface geostrophic velocity relative to 100 m, and (c) daily averaged velocities derived from drifters. Dots indicate CTD stations and the continuous line is the 70-m isobath.

although the drifter data were collected over a longer period of time (13 Sep to 9 Oct 1995) than the hydrography (12–20 Sep 1995). The resemblance between the geostrophic and the drifter gyres is striking and constitutes the first hard evidence of the presence of this gyre and its characteristics.

The vertical distributions of temperature, salinity, and density across the gyre (Figs. 4a–c) show a slightly domed structure, with the sharpest downward tilt of the isolines at the site where they touch the sloping bottom, above ~150 m. This is not the tidal-mixing front described by Argote et al. (1995) separating well-mixed

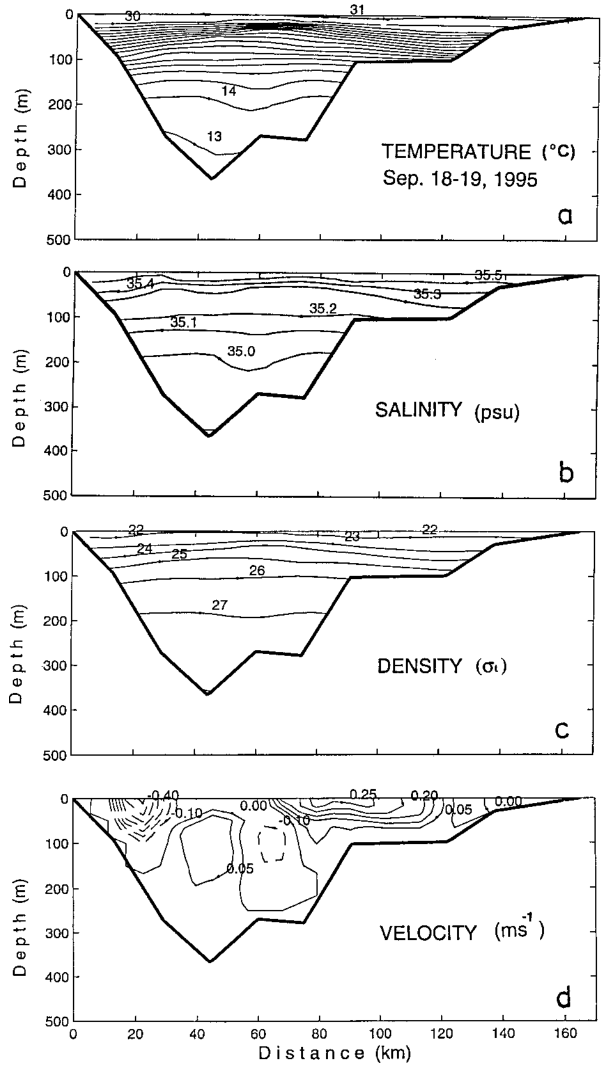


FIG. 4. Vertical distribution of temperature (a), salinity (b), density (c), and geostrophic velocity relative to the bottom (d) for the across-gulf line marked **A** in Fig. 3a. Positive velocities are into the page (toward the northwest).

and stratified water in the shallower area (~30 m), which was not sampled. The geostrophic velocity referred to the bottom (Fig. 4d) shows the strongest speeds near the surface, over the sloping bottom area intersected by the isolines. Figure 4d clearly shows that the gyre is not located in the center of Delfín Basin, but somewhat to the north; half of the gyre is located outside the basin.

Some features of the gyre are reminiscent of the isolated, geostrophic, cyclonic eddies described by Hill (1993), which are generated by the trapping of cold bottom water in topographic depressions surrounded by tidal mixing fronts. Hill et al. (1994) made Lagrangian measurements in a gyre of this kind in the Irish Sea and found it to be an order of magnitude slower (0.05 m s^{-1}) than that in the NGC. A difference between the two areas is that tidal mixing is weaker and stratification stronger in the latter. Also, in the NGC there is tidal mixing only in half of the periphery of the gyre. Although tidal mixing is a possible cause for the tilting of the isolines in the NGC, other mechanisms need to be considered. Barotropic residuals induced by tidal rectification in the NGC can be dismissed because they are very weak (~0.01 m s^{-1}; Argote et al. 1997, manuscript submitted to *Atmósfera*).

The next likely mechanism must be wind driving. A vertically integrated numerical model (Argote et al. 1997, manuscript submitted to *Atmósfera*, hereafter ALA) driven by mean southeast winds predicts a cyclonic circulation in the NGC, with the strongest currents along the northwest edge of Delfín Basin and in the shallow area along the mainland coast. However, the predicted circulation pattern is not a closed gyre, and the velocities are too weak (~0.05 m s^{-1}); there is a clear need to take stratification into account since the baroclinic mode is more easily affected by the wind than the barotropic mode.

This has been done by Beier (1997), using a two-dimensional two-layer linear model with real bathymetry and a surface layer 70 m deep. The model is driven by seasonally variable winds, surface heat flux, and forcing at the mouth; the latter is needed to achieve a seasonal heat balance and, in fact, it is the main component of the seasonal signal of stored heat (Castro et al. 1994; Ripa 1997). The model is limited in that it lacks surface moisture flux and vertical mixing. In the f plane, both wind stress and forcing at the mouth generate a cyclonic, but not closed, circulation in the NGC during summer. This is explained by means of a baroclinic wave trapped within an internal Rossby radius (30 km) from the intersection of the pycnocline with the bottom. When β effects and diffusion are included, a cyclonic gyre is formed in the NGC, located like the observed gyre (Fig. 3c) just to the northwest of Angel de la Guarda Island, not in the center of Delfín Basin. Associated with this gyre the model predicts a surface depression of 3 cm and a doming of the pycnocline. The strongest currents (~0.7 m s^{-1}) occur in August, so they are closer to the observations than those of the barotropic model and they are found in deeper water. Like the observations, the modeled currents are concentrated in a ring with the width of an internal Rossby radius. Therefore, the three mechanisms—tidal mixing, wind driving, and forcing at the mouth by the Pacific Ocean—may be partly responsible for the summer gyre, but their relative importance is as yet unknown. Although the drifter data are only from summer 1995, a strong gyre is clearly present in the dynamic topography of the NGC for all summers for which hydrographic data are available (Carrillo-Bibriezca 1996); therefore the summer gyre is probably a persistent feature.

b. Winter

Strictly speaking, these data were collected at the end of winter and the beginning of spring, but we will refer

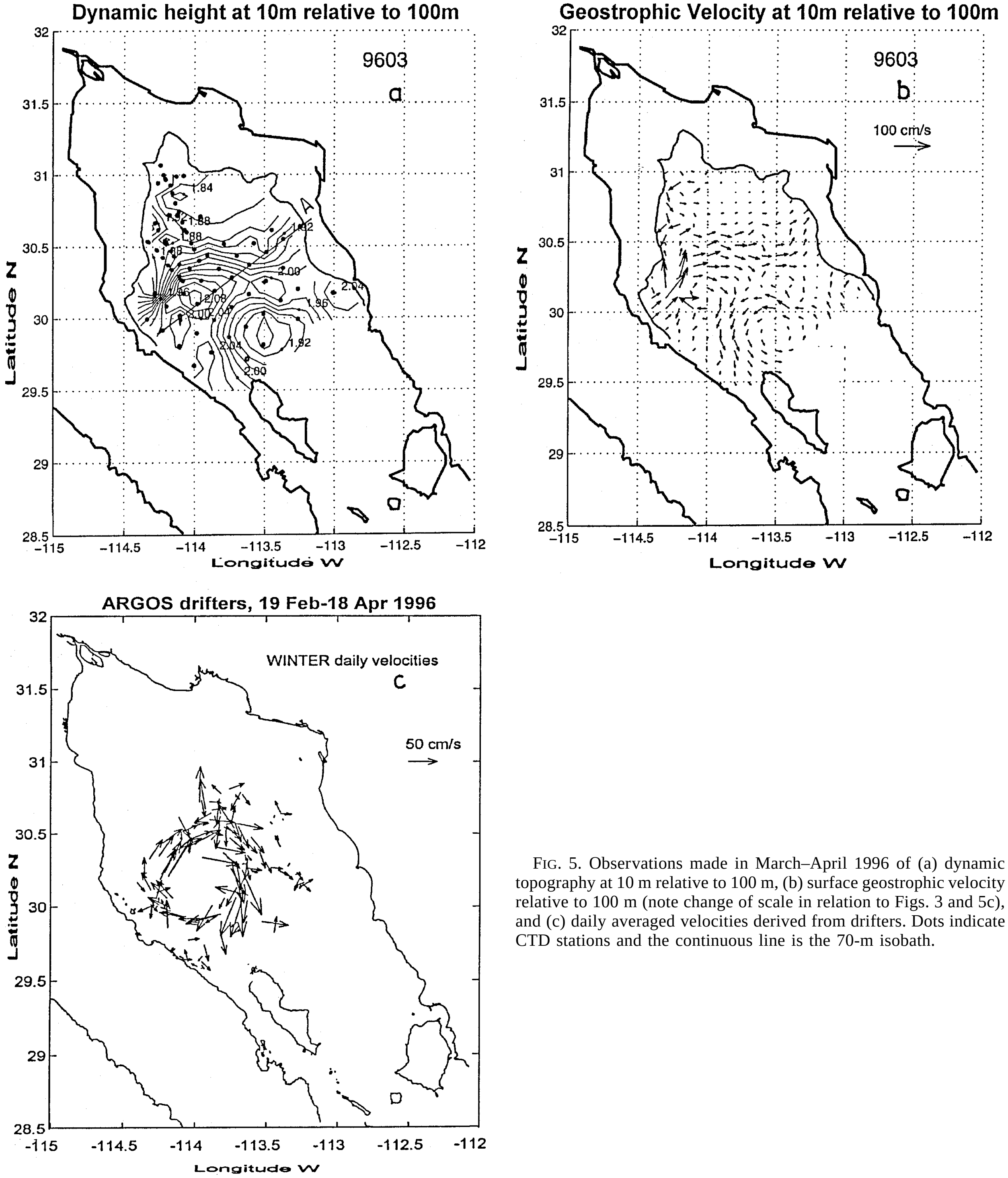


Fig. 5. Observations made in March–April 1996 of (a) dynamic topography at 10 m relative to 100 m, (b) surface geostrophic velocity relative to 100 m (note change of scale in relation to Figs. 3 and 5c), and (c) daily averaged velocities derived from drifters. Dots indicate CTD stations and the continuous line is the 70-m isobath.

to this period as "winter." The dynamic topography (Fig. 5a) shows an elevation to the northwest of the position of the summer depression, close to the 100-m isobath. An even weaker cyclonic depression is suggested close to the north of Angel de la Guarda Island, but the data are not enough to resolve if it is really closed. Now the gradients are less strong so that the geostrophic velocities at 10 m relative to 100 m (Fig. 5b) are weaker than in summer (<0.1 m s^{-1}); an anticyclonic gyre is clearly suggested, as well as half of an even weaker cyclone. The drifters (Fig. 5c) seem to follow the dynamic topography anticyclonically around

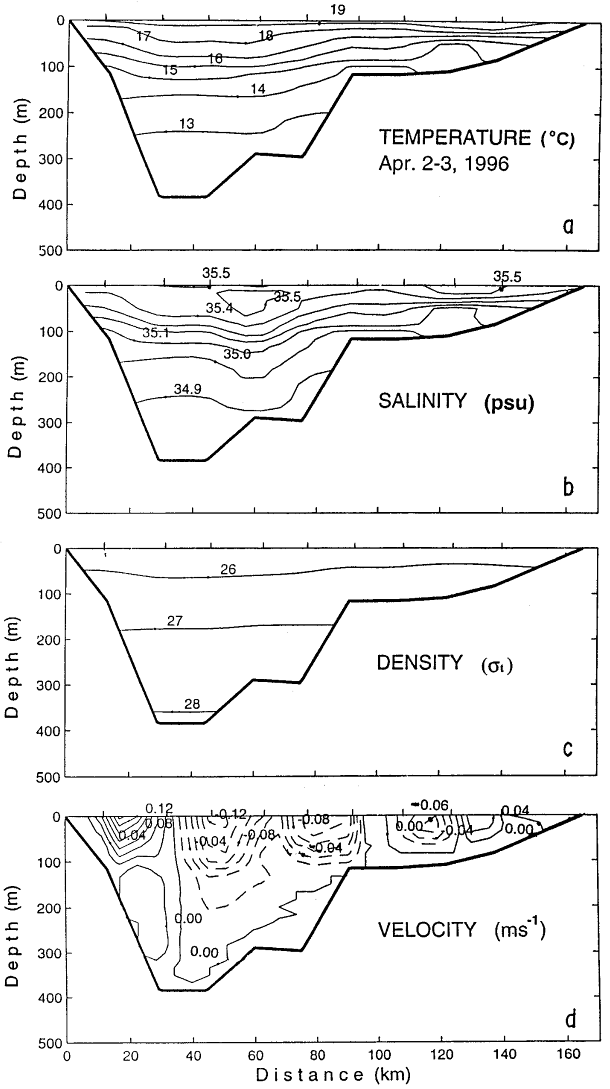


FIG. 6. Vertical distribution of temperature (a), salinity (b), density (c), and geostrophic velocity relative to the bottom (d) for the across-gulf line marked **A** in Fig. 5a. Positive velocities are into the page (toward the NW).

the elevation, but their speeds are now much stronger than the velocity calculated by geostrophy (Fig. 5b). The drifter velocities reach higher values (>0.5 m s^{-1} than in summer, although in the mean they are of the same order (0.3 m s^{-1}). Therefore, there is an anticyclonic winter circulation in the NGC, but it does not seem to be completely baroclinic.

Vertical sections of temperature, salinity, and density across the gyre (Figs. 6a–c) show the stratification to be much weaker than in the summer and the isolines to be concave upward. The weakened winter stratification is due to the combination of lower solar radiation plus increased surface mixing due to stronger winds and vertical convection brought about by surface cooling. The tilt of the isolines is less pronounced than in summer, causing weak geostrophic currents (Figs. 5b and 6d): the strongest currents (0.1 m s^{-1}) are found at the surface over the bottom slope northwest of Delfín Basin.

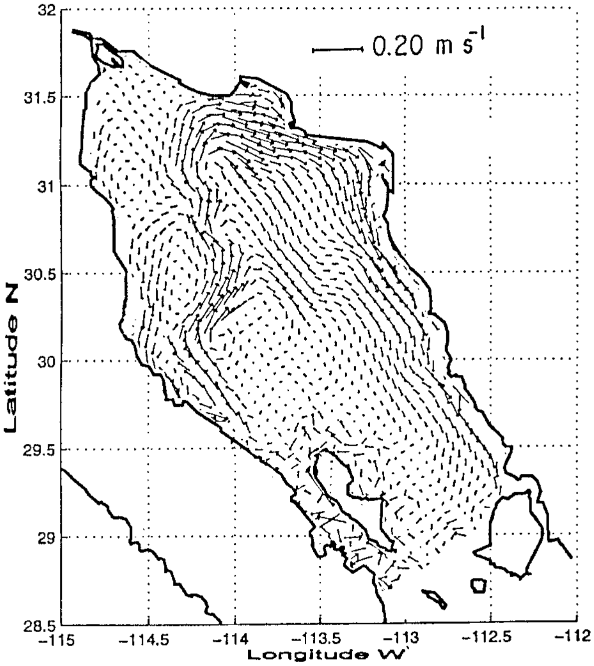


FIG. 7. Wind-driven vertically integrated residual currents in the NGC obtained with the 2D model of ALA, using a 10 m s^{-1} NW wind.

As mentioned before, the modeled barotropic, tidally induced circulation is also anticyclonic, but much slower (0.01 m s^{-1}). The first mechanism that comes to mind to explain the winter gyre is driving by the wind, which in this season tends to be from the northwest and is stronger than in summer. A two-dimensional model of the wind-induced circulation in the GC was presented by ALA; a comparison of their simulations for winter conditions against moored current-meter measurements revealed that the pattern was correct but the speeds were too slow by a factor of about 3; ALA suggest that baroclinic effects may be the cause of this discrepancy. This simulated barotropic wind-driven flow for winter in the NGC (Fig. 7) has an anticyclonic pattern, centered in exactly the same position as the gyre depicted by the drifters in Fig. 5c. However, once again the predicted speeds are slower than those measured by the drifters (maxima of 0.1 m s^{-1} vs 0.5 m s^{-1}), and a closed gyre is not formed. The difference in speed could be partly due to the fact that the model predicts the vertically averaged current, while the drifters sample the top 20 m, but it is more likely due to the presence of stratification. For winter, the baroclinic model of Beier (1997) predicts a doming surface, a concave pycnoline, an anticyclonic gyre, and, more importantly, stronger currents (maxima of ~0.7 m s^{-1} in February) than the barotropic model. However, this model predicts the winter gyre in the same position as the summer gyre, which is at variance with the drifter data. Therefore, the winter gyre has some features of the barotropic model of ALA and some of the baroclinic model of Beier (1997).

A clear geostrophic cyclonic gyre was reported in the NGC (Bray 1988b) in March 1985, which has lead to the general acceptance of the presence of the winter gyre. However, in a study of the circulation of the NGC using the historical hydrographic data, Carrillo-Bibriezca (1996) has found that the geostrophic winter circulation is always weaker than in summer, that sometimes a gyre is found in the same area as shown in Figs. 5a–b, and that such gyres are better defined around December. However, by March and throughout the spring, only a circulation vaguely anticyclonic is found, which is highly variable from year to year, with even a case (March of 1973) of cyclonic circulation. In addition, smaller cyclonic and anticyclonic eddies are often found in winter and spring (Carrillo-Bibriezca 1996); this is also found in the three-dimensional model of the circulation in the NGC of López (1997). In view of this conflicting background, it is therefore not possible to be certain that the circulation sampled in March–April of 1996 by the drifters is a permanent winter feature of the NGC.

4. Conclusions

We have tried to test, by direct observations with ARGOS drifters, the proposition that the circulation in the Northern Gulf of California consists of a seasonally reversing gyre, cyclonic in summer and anticyclonic in winter. This pattern was actually observed, in September–August of 1996 and March–April of 1996. Both gyres had mean speeds of about 0.3 m s^{-1} near the edge. However, the character of the gyre is different in the two seasons. In summer, the gyre is persistent and clearly baroclinic; the forcing agents provoking the distribution of density that gives rise to the gyre appear to be the wind, tidal mixing, and forcing through the mouth. In winter, the situation is less clear: The gyre appears to be a mixture of barotropic and baroclinic, and to be highly variable from year to year. The observed circulation suggests that neutrally buoyant substances and organisms may get trapped for extended periods in the NGC; this may be the cause of the very low chlorophyll concentrations in the position of the gyre observed in CZCS images (Santamaría-del Angel et al. 1994). A closer study of the gyres and of the mechanisms proposed as causing the observed circulation is currently under way, both by modeling and observation.

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