LAGRANGIAN OBSERVATIONS OF NEAR-SURFACE CURRENTS IN CANAL DE BALLENAS

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ABSTRACT

Radio buoys tracked at depths of 0 and 50 m in the northern portion of Canal de Ballenas, Gulf of California, in June 1982, show a current dominated by alongchannel oscillations, on which are superimposed smaller-scale turbulent eddies. Maximum displacements and velocities of the motions recorded alongchannel are 0(15 km; 3 m $\sec^{-1}$), and crosschannel they are 0(5 km; 0.5 m $\sec^{-1}$). The mean velocity was generally towards the southeast along the channel and close to two orders of magnitude smaller than the maximum instantaneous velocities observed. The eddy-like motions, which had no preferred sense of rotation, had typical scales similar to those of the crosschannel excursions and appeared to trap the buoys after these had traveled southeastward for a few hours. This suggests a spatial variation of the flow, which might be associated with the rough configuration of the channel's coastline and bottom topography. Spectral analysis of the drogue excursions about their mean positions indicated that the motions were probably related to the semidiurnal tide and, at the surface, to the strong winds that blew from the mountain passes in Baja California, and also showed a large spatial variability. Logistics and weather conditions made longer and more precise measurements impossible, and it is difficult to conclude here on the dynamics of the flow in Canal de Ballenas. These measurements, to our knowledge, represent the first direct measurements of circulation reported for this area.

RESUMEN

Un grupo de radioboyas en superficie y a 50 m, rastreadas en la parte norte de Canal de Ballenas, Golfo de California, en Junio de 1982, muestra corrientes dominadas por oscilaciones longitudinales sobre las cuales se superponen vórtices de menor escala. Los desplazamientos y velocidades máximas registradas son de 0(15 km; 3 m $\sec^{-1}$) en la dirección longitudinal y 0(5 km; 0.5 m $\sec^{-1}$) en la dirección transversal al canal, respectivamente. La velocidad media fue generalmente hacia el sureste a lo largo del canal y aproximadamente dos órdenes de magnitud menor que las velocidades instantáneas máximas observadas. Los giros turbulentos se observaron carentes de sentido preferente de rotación y con escalas típicas comparables a la de los desplazamientos transversales al canal. En apariencia, dichos giros atraparon a las boyas después de que éstas se desplazaron hacia el sureste por algunas horas. Esto sugiere una variación espacial del flujo, asociada posiblemente con la configuración irregular de la costa y del fondo del canal. El análisis espectral de la excursión de las boyas con respecto a su posición media indica una relación probable con la marea semidiurna y, en superficie, con los vientos fuertes provenientes de los pasos de las montañas de Baja California, los cuales presentaron asimismo una marcada estructura espacial. Las condiciones atmosféricas locales y logísticas no permitieron efectuar observaciones más prolongadas y precisas, por lo que es difícil concluir aquí sobre la dinámica de la corriente en Canal de Ballenas. El principal interés de nuestros resultados reside en que representan las primeras observaciones directas de la circulación dentro del canal.

INTRODUCTION

Canal de Ballenas is a complex stretch of water that, together with the eastern Tiburon Basin, connects the northern Gulf of California to its central Guaymas Basin. It is bounded on the west by the peninsula of Baja California and on the east by a long, continuous submarine ridge from which rise Angel de la Guarda, San Lorenzo, and other smaller islands (Figure 1). The bathymetry of Canal de Ballenas is poorly known, but its main depression is the Salsipuedes Basin, where depths exceed 1,600 m. The channel is about 125 km long and is bounded by sills at both ends. In the area of our study, the width varies from 15 to 25 km.

The purpose of this note is to report on drogue measurements of the near-surface currents in the northern end of Canal de Ballenas, during the Pichicuco I expedition in June 1982. No extensive analysis can be done of these series, which are fewer and shorter than could be wished in a study of such a complicated system. But they are, to our knowledge,

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[Manuscript received April 18, 1984.]

among the first direct measurements made of the circulation in this region.

Early reports of the flow in Canal de Ballenas indicated the currents can reach speeds of 3 m sec^{-1} (Hubbs and Roden 1964). Studies of the base of the shelf in Salsipuedes Basin showed exposed bedrock, suggesting that currents at depth are strong enough to scour or inhibit the deposition of sediments (Rusnak et al. 1964). On the other hand, Brown's (1965) drogue measurements of less than a day at the southern end of Salsipuedes Basin showed slow currents with a net drift to the south along the channel, believed to be the result of the combined driving influences of tides and wind.

Currents in Canal de Ballenas have been attributed mainly to the large tidal range in the northern gulf and to the narrow configuration of the channel. These motions appear to produce intense vertical mixing that brings cool water to the sea surface during most of the year (Robinson 1973; Badan-Dangon et al. in press) and generate packets of internal waves that radiate away from the sill regions, particularly during spring tides (Fu and Holt 1984). The mixing above sill depth probably causes the weakly stratified water column found beneath the thermocline in Canal de Ballenas (Roden 1964; Alvarez-Borrego 1983).

THE EXPERIMENT

Our measurements were made near the northern end of Canal de Ballenas, with drogues consisting of a window-shade-type drag element, with a 9-m^2 effective surface, hanging either directly beneath a surface float of 40 cm in diameter, or attached to it with a line that set the sail 50 m beneath the surface. Attached to this drogue was a radio buoy that transmitted at frequencies close to 4 MHz. The drogues, numbered consecutively, were launched in two sets from R/V *El Puma*, at positions shown in Figure 1. The first set, consisting of three surface drogues, was launched on the evening of June 17. Of these, two buoys were tracked for 14 and 27 hours, respectively. The second set, consisting of three surface and three 50-m drogues, was released near noon on June 24. Of these, two drogues transmitted for 7 and 19 hours and two others provided data for up to 74 hours. None of the drogues launched were recovered; they probably collapsed because of the extreme sea conditions that prevailed at the time.

The tracking was done from two radio direction finder (RDF) stations located 39 km apart on the western side of the channel (Figure 1). These positions

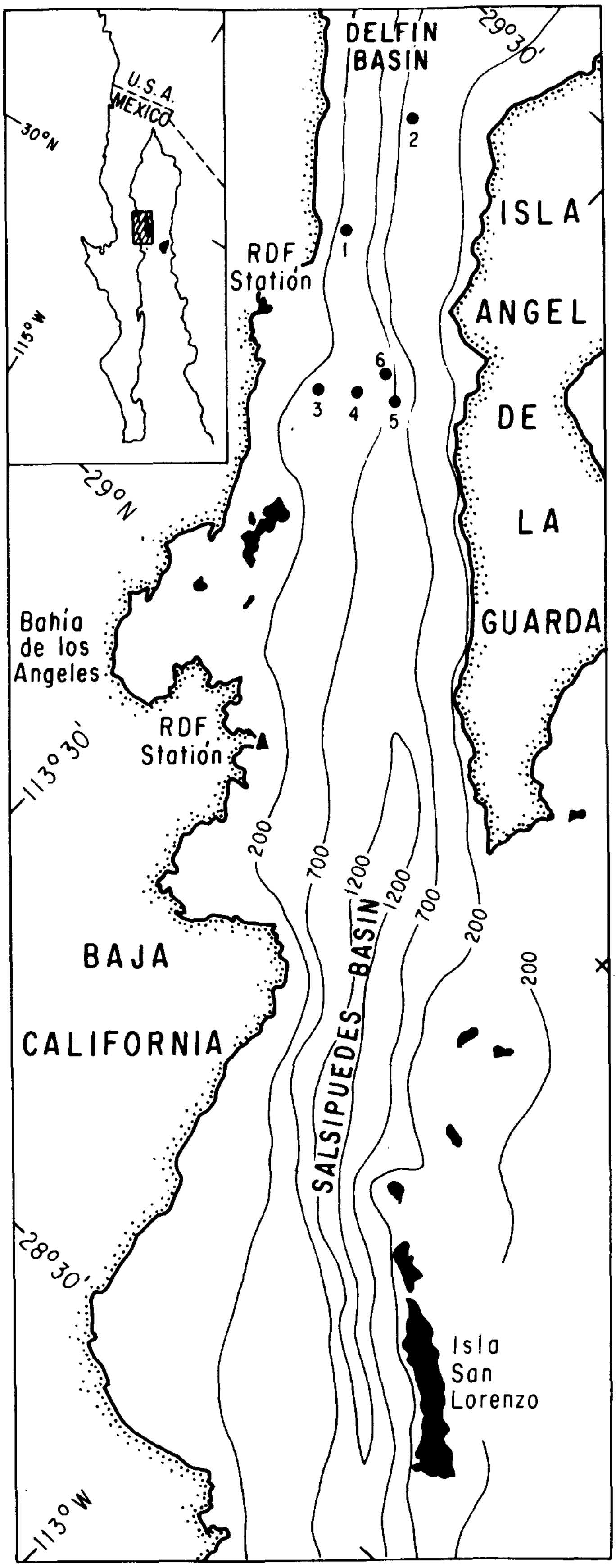

Figure 1. Location of the drogue experiment, showing the sites of the two RDF stations and the launching positions of the drogues. Depth contours are in meters and known to be approximate.

were chosen because we expected more southerly excursions of the drogues than were in fact observed. The successive positions of the buoys were obtained between every half hour to one hour by averaging twelve readings with respect to true north, to the nearest half degree, from each RDF station.

The manufacturer of the equipment (Telecommunications Enterprises Co.) reports the accuracy of each reading to be better than one degree, which is supported by the studies of Murray et al. (1975) and of Wiseman et al. (1977). In our study we found that the readings from the southern tracking station, farthest from the group of buoys, had a standard deviation close to one degree, whereas that of the northern station was closer to 2.5 degrees. Added difficulties appeared to be the echoing of the signals by the elevated terrain surrounding the channel, and radio interference that often obscured the readings, principally during the hours close to dawn. Our estimate of the average positional accuracy is reported graphically below for each drogue.

In addition to positioning the drogues, we measured winds with recording anemometers at the sites of both RDF stations for the entire period of the experiment (Figure 2). Predicted tidal elevations were obtained for Bahía de los Angeles (Figure 3). Standard hydrographic measurements with bottles were made from R/V *El Puma* (Figure 4).

RESULTS

The conditions that prevailed during the experiment are illustrated by the wind series obtained at the sites of the tracking stations (Figure 2). They show a strong sea breeze regime superimposed on a trend of weakening northerly winds as the experiment progressed. Winds were strong, often peaking above 25 m sec^{-1} at

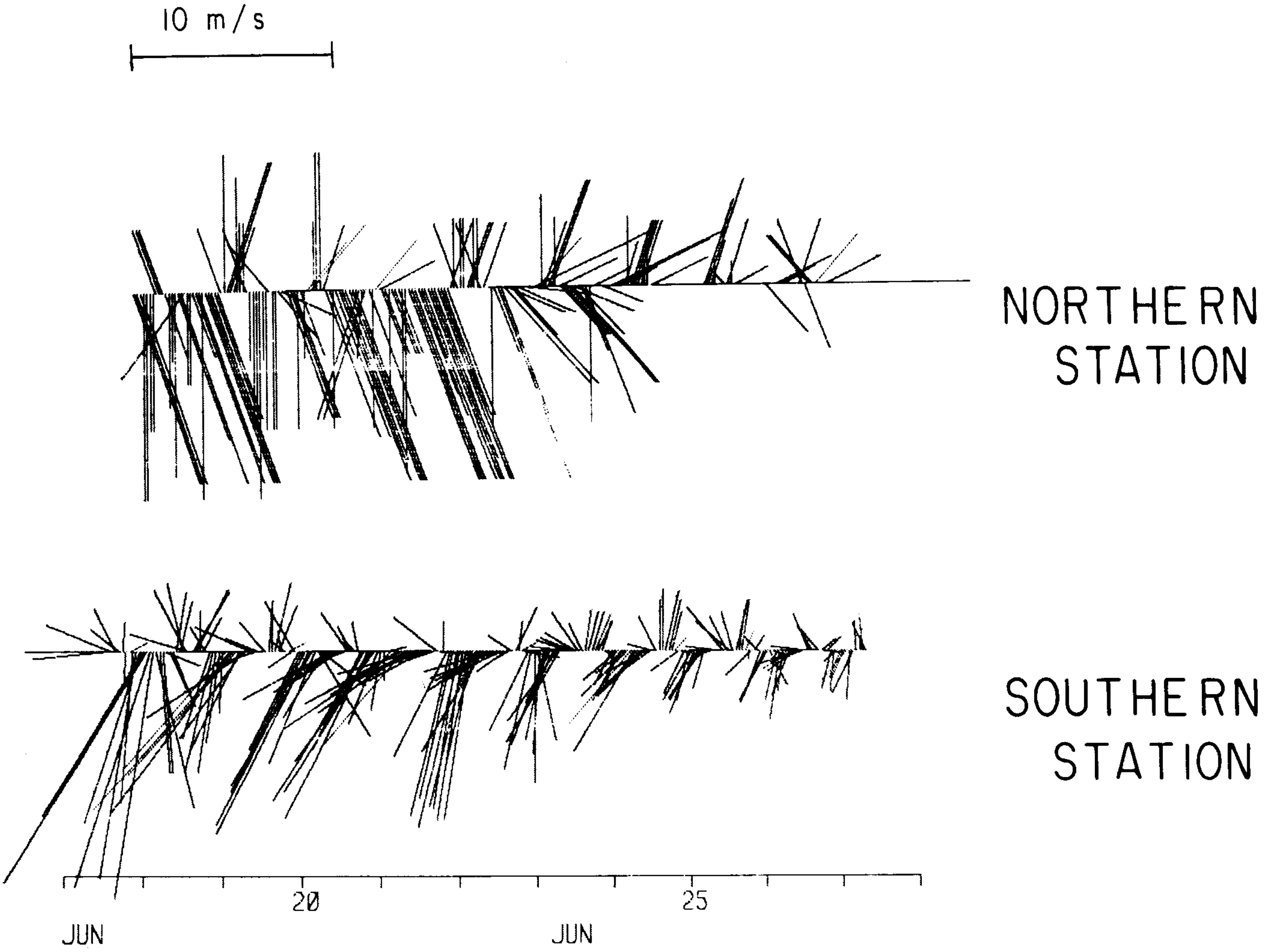

Figure 2. Wind vectors measured at the two RDF stations, rotated so the general orientation of the channel is vertical on the page.

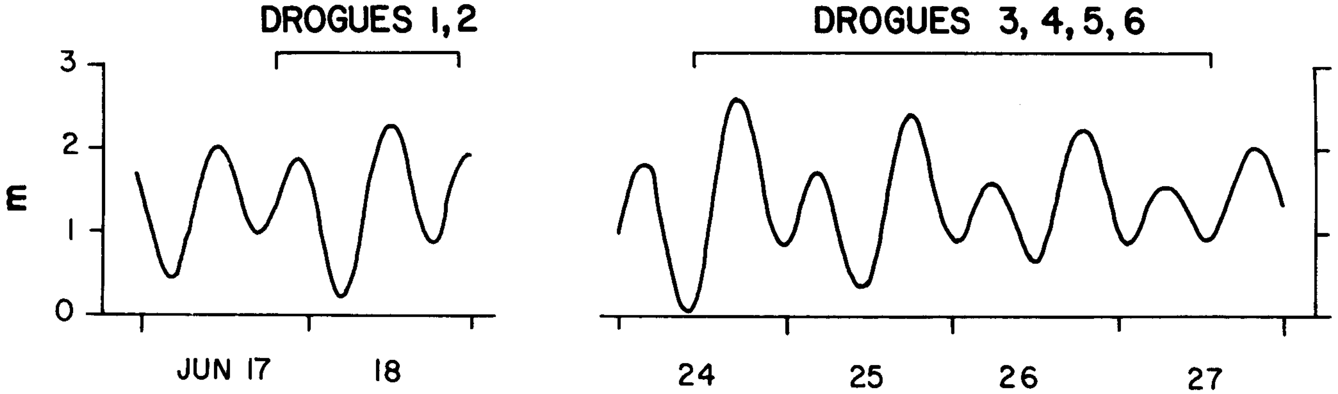

Figure 3. Predicted tidal elevations at Bahía de los Angeles for the duration of each set of measurements.

the beginning of the experiment, and caused heavy local seas that made tracking the buoys difficult and caused several of them to fail. The series confirm the marked spatial variability of winds that may be expected in the region. This variability was manifested during the experiment by widely differing local sea states.

Figure 3 shows the predicted sea-surface elevations at Bahía de los Angeles for the time of the two sets of measurements. The character of the tide is dominated

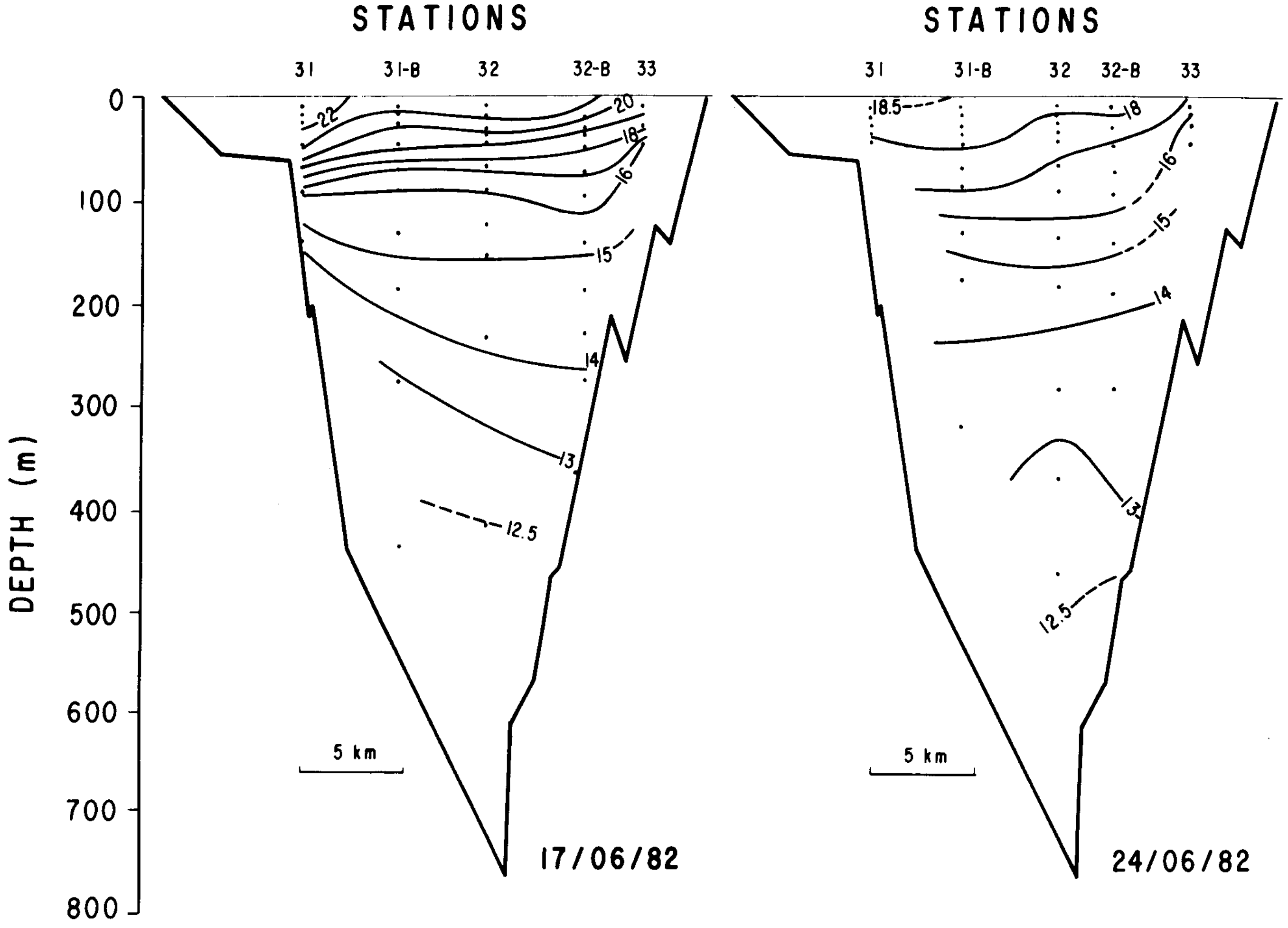

Figure 4. Temperature sections (in degrees C) made across the wider, central portion of Canal de Ballenas at the times the drogues were launched.

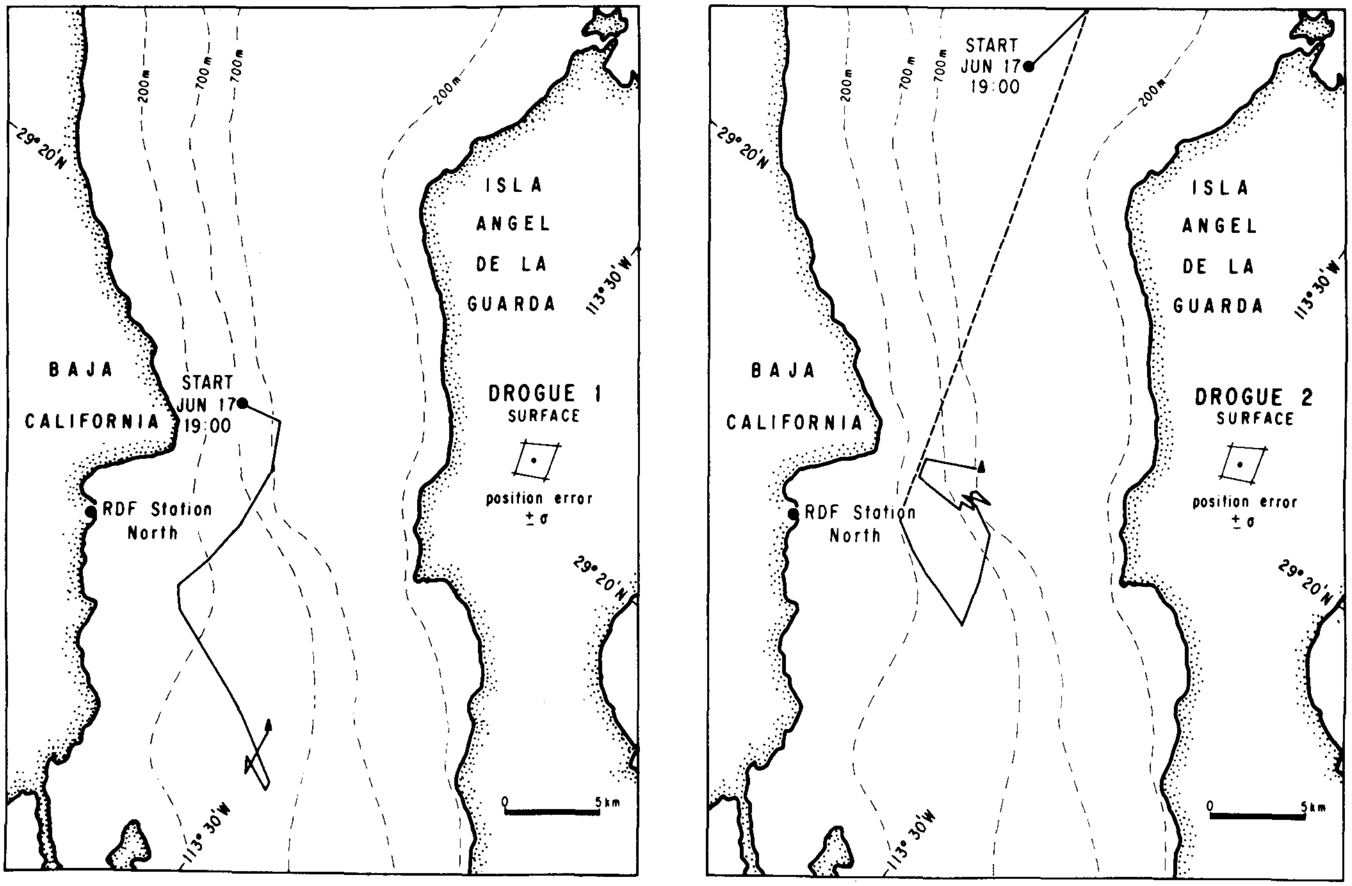

Figure 5. Tracks of the drogues launched in the first set. Launching time, depth of drogue, and estimated average position error is indicated.

by the semidiurnal components, with maximum ranges close to 3 m. Unfortunately, logistics prevented us from launching buoys during the peak of the spring tides that occurred between the two sets of measurements and probably would have resulted in more rapid displacements of the drogues than documented here. Two hydrographic lines were made across the wide section of the channel after launching the two sets of drogues (Figure 4). They show the water column consisting of an initially well-stratified, 100-m-thick near-surface layer overlying the weakly stratified water typical of this region. Although the hydrographic structure in the channel is known to be extremely variable in short time scales, all of our drogue measurements were clearly made within the near-surface layer, as defined by the 16°C isotherm.

The first set of drogues was released in the northern end of the channel, close to where its narrowest cross section (4.5 km^2) separates the Salsipuedes Basin from the southern extension of the Delfin Basin. The second set was released 10 km farther south, where the channel widens to 9.7 km^2 (Figure 1). Trajectories of interpolated hourly positions were obtained for each drogue by fitting a cubic spline to the original series of averaged positions (Figures 5 and 6). All drogues, with the exception of drogue 3, show large alongchannel excursions, apparently in response to reversals of the tidal flow through the channel. These alongchannel displacements appear larger in the narrow northern end of the channel than in the wider central portion. This is shown more clearly in Figure 7, where successive alongchannel departures from their mean positions were computed for drogues 3 and 4. Drogue 3, a surface buoy, remained in the southern part of the study area and had limited excursions of less than 5 km for all 74 hours. During the first 24 hours of that same period, drogue 4, a 50-m buoy, showed excursions close to 15 km as it traveled in the narrow section of the channel. It then moved south, where it had excursions comparable to those of buoy 3 for the remaining 48 hours. The qualitative impression provided by the trajectories is that the buoys moved rapidly alongchannel until they were caught in complicated eddylike motions in the wider part of the channel. As a result, it appears that motions are more rapid alongchannel in the narrow northern channel than in

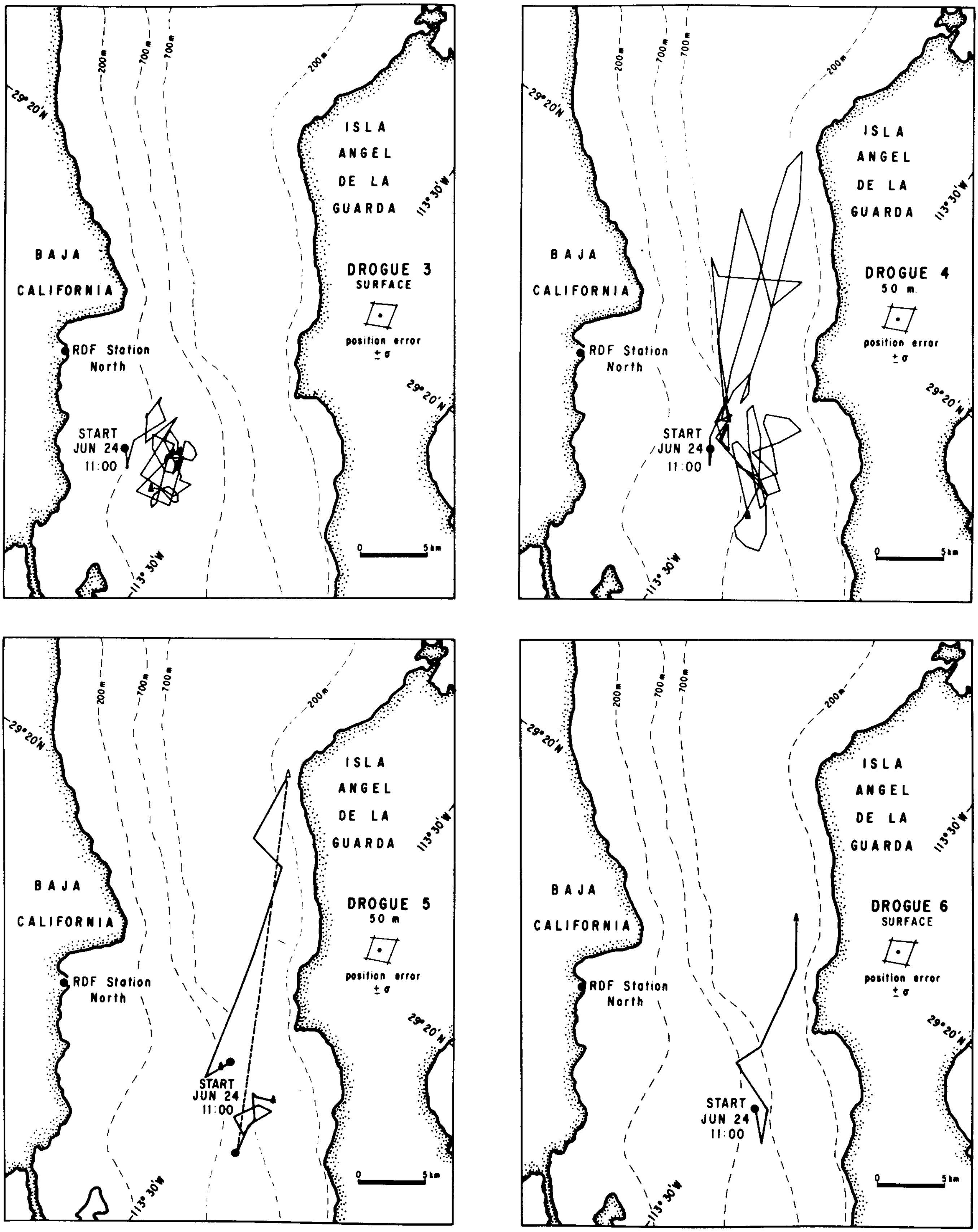

Figure 6. Same as Figure 4, for the second set.

TABLE 1
Basic Statistics of the Velocity Components Computed from Hourly Positions of the Drogues

Drogue Number		1 (sfc.)	2 (sfc.)	3 (sfc.)	4 (50 m)	5 (50 m)	6 (sfc.)
Tracking time		14 hrs	27 hrs	74 hrs	73 hrs	19 hrs	7 hrs
Alongchannel velocity (m•s^{-1})	Mean	−0.34	−0.19	−0.01	−0.02	−0.39	0.57
	St. dev.	0.45	0.63	0.28	0.71	0.72	0.69
	Max.	0.57	0.84	0.72	2.76	2.35	1.26
	Min.	−0.97	−1.94	−0.96	−2.03	−0.39	−0.68
Crosschannel velocity (m•s^{-1})	Mean	0.03	0.04	0.00	0.00	0.04	0.08
	St. dev.	0.36	0.50	0.24	0.45	0.56	0.53
	Max.	0.49	1.25	0.79	1.56	1.15	0.74
	Min.	−0.51	−1.48	−0.84	−1.28	−0.82	−0.74

its central part, by a factor close to the inverse proportion of the corresponding cross-sectional areas. This suggests that the rough configuration of the channel's coastline and bottom topography is important in determining spatial variations of the flow. In contrast, transverse excursions were everywhere of the same magnitude, about two to three times smaller than the alongchannel excursions in the narrow part of the channel.

The net flow, inferred from buoys 3 and 4 after six tidal cycles, appears to be towards the southeast along the channel and about two orders of magnitude smaller than the maximum velocities observed. The remaining drogues, with the exception of drogue 6, also had net southward displacements, but their series were too short to suppose this to be a real indication of net flow.

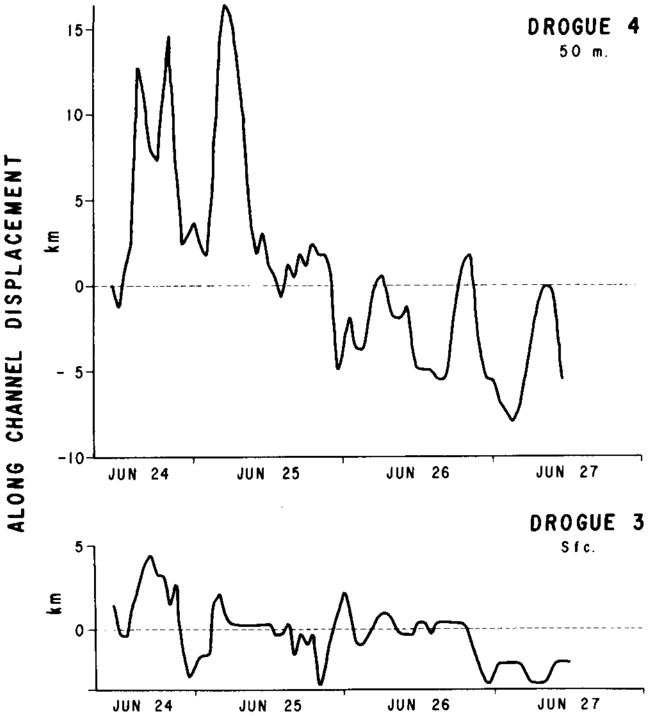

Figure 7. Hourly alongchannel displacements about their mean positions for drogues 3 and 4.

In the same way, buoy 6 suggests a flow to the north close to Angel de la Guarda Island, where less violent winds were observed and the surface layer is also less deep (Figure 4). However, this northward flow was also observed with other buoys that later returned southward (e.g., buoy 5), and buoy 6 was lost after only 7 hours of measurements, so it is difficult to attach much significance to a possible counterflow on that side of the channel.

Table 1 summarizes some basic statistics of the velocity components computed from the successive positions of the drogues. In all cases the mean is only a few centimeters per second and smaller than the standard deviations, suggesting that the net flow through the channel is much smaller than the instantaneous transports. The mean alongchannel velocities are generally larger than the mean crosschannel velocities. However, the standard deviations of both components are comparable, with the alongchannel only slightly higher than the crosschannel. The maximum velocities reach between 2 and 3 m sec^{-1}, confirming the estimates reported by Hubbs and Roden (1964). The largest velocities in both components were shown by buoy 4, generally located closer to the center of the channel and at 50-m depth. Hence, during this experiment, the flow in the channel had large oscillations and a smaller net flow, generally to the south, except possibly very close to the eastern edge of the channel. Since the buoys stayed for the most part in the wider part of the channel, the standard deviation of the two horizontal velocity components is similar, suggesting a dominance in this region of turbulent eddy motions with typical horizontal scales of about 5 to 7 km.

In an attempt to investigate the character of the alongchannel motions, we computed maximum entropy spectra of the two longest series, provided by buoys 3 and 4. These show rather different compositions (Figure 8). The spectrum for the surface drogue shows peaks close to the semidiurnal and diurnal frequencies and smaller peaks at higher frequencies. The spectrum for the 50-m drogue shows a well-defined peak at the semidiurnal frequency and a smaller sec-

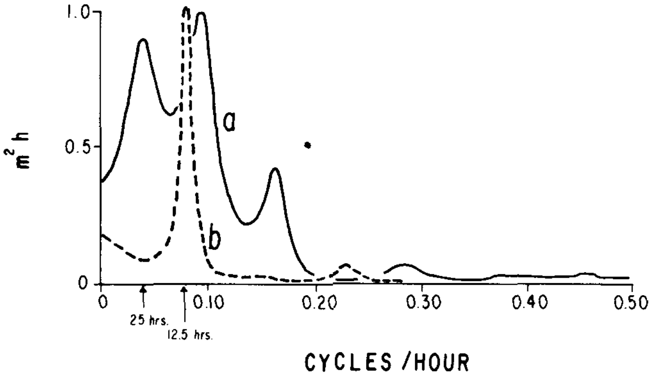

Figure 8. Normalized MEM spectra of alongchannel displacement for surface drogue 3 (a) and 50-m drogue 4 (b). These were computed from series of 73 hourly data points, with a 15-element predictor error filter.

ondary peak. The diurnal peak is absent from the 50-m spectrum. The peak at the semidiurnal frequency is probably associated with the strong tidal forcing by the M2 component, which is prominent in the gulf (Filloux 1973), whereas the diurnal peak exhibited by the spectrum of the surface drogue might be associated with the diurnal sea breeze, which we have shown to be very strong during the experiment. We have no satisfactory explanation for the smaller peaks at higher frequencies, since they do not correspond to any of the higher-order tidal components. If real, these may represent the frequencies of the turbulent eddies that appear dominant in the central part of the channel, or they could have been induced by our sampling and interpolating schemes.

CONCLUSIONS

The extreme conditions that prevailed in Ballenas Channel during our field experiment made it impossible to obtain longer and more accurate series of measurements with the drogues. It is therefore difficult to provide more quantitative results about the kinematics, or strong conclusions about the dynamics of the flow through the channel. Qualitatively, the data support the notion that the flow is forced by the semidiurnal tide. At the surface, the intense winds can play an important role, and thus their strong spatial variability contributes to the complexity of the flow patterns. The flow is predominantly in the alongchannel direction, with typical excursions of about 15 km. Nonetheless, crosschannel motions are not negligible, and in the wider, central part of the channel, motions appear dominated by eddylike patterns with typical scales close to 5 km. Thus, spatial variability of the flow is large, and it is to be expected that the dynamics of the flow are strongly nonlinear in this region.

Because the tidal range in the channel can account for but a fraction of the instantaneous volume transport, and the motion is turbulent, it appears that although no large net flow takes place through the channel, a considerable amount of water may be exchanged through eddy processes over several tidal cycles. Moreover, the magnitude of the velocities observed and the general configuration of the flow support the idea that the region is able to sustain the efficient mixing suggested by other investigators. More extensive conclusions about the net flow through the channel should await longer series of measurements, which must include a sampling of the motions of the deeper, weakly stratified layer beneath the thermocline.

ACKNOWLEDGMENTS

Thoughtful comments by several colleagues, especially H.G. Peña, and a reviewer substantially improved our manuscript. We also wish to acknowledge the numerous people who helped collect the data under very difficult field conditions, and we thank the crew of R/V *El Puma,* Captain Fernando Ramirez commanding. José M. Domínguez did the illustrations, and Maricela González assisted in preparing the manuscript. This work was supported by a grant from the Consejo Nacional de Ciencia y Tecnología of México.

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