PERGAMON

Continental Shelf Research 19 (1999) 1545–1560

CONTINENTAL SHELF
RESEARCH

On how the colorado river affected the hydrography of the upper Gulf of California

M.F. Lavín*, Salvador Sánchez

Departamento de Oceanografía Física, CICESE, Apartado Postal 2732, Ensenada, Baja California, Mexico

Received 19 October 1998; accepted 5 February 1999

Abstract

The hydrography of the shallow (< 30 m) Upper Gulf of California was mapped during a rare Colorado River fresh water discharge, which occurred during March and April, 1993. This provided (a) an opportunity to observe what may have been the hydrographic conditions before the damming of the river, and (b) a data base that can be used to calibrate numerical models with a view to simulating those conditions for ecological applications. In opposition to the now normal inverse estuarine situation, salinity and density decreased toward the head. Dilution was detectable in a coastal band flowing to the right-hand side of the river discharge, up to some 70 km from the river mouth. Tidal mixing maintained vertical homogeneity during spring tides, but stratification was established during neap tides, in an estuarine salt-wedge structure.

Keywords: Colorado River Delta; Estuarine; Stratification

1. Introduction

The Colorado River no longer discharges regularly into the Gulf of California; its fresh water is retained in dams or diverted for urban consumption and for irrigation (Fig. 1). The construction of the major dams in the Colorado River, Hoover Dam and Glen Canyon Dam, had the most drastic impact upon the amount and timing of the fresh water that reached the Gulf of California. The record of the flow of Colorado River water across the Mexico–US border (Fig. 2) shows that before 1935, when the filling of the Hoover Dam began, the large amounts of fresh water that were discharged into the Gulf of California had a seasonal modulation. The largest flows,

* Corresponding author.

0278-4343/99/$ - see front matter
PII: S0278-4343(99)00030-8

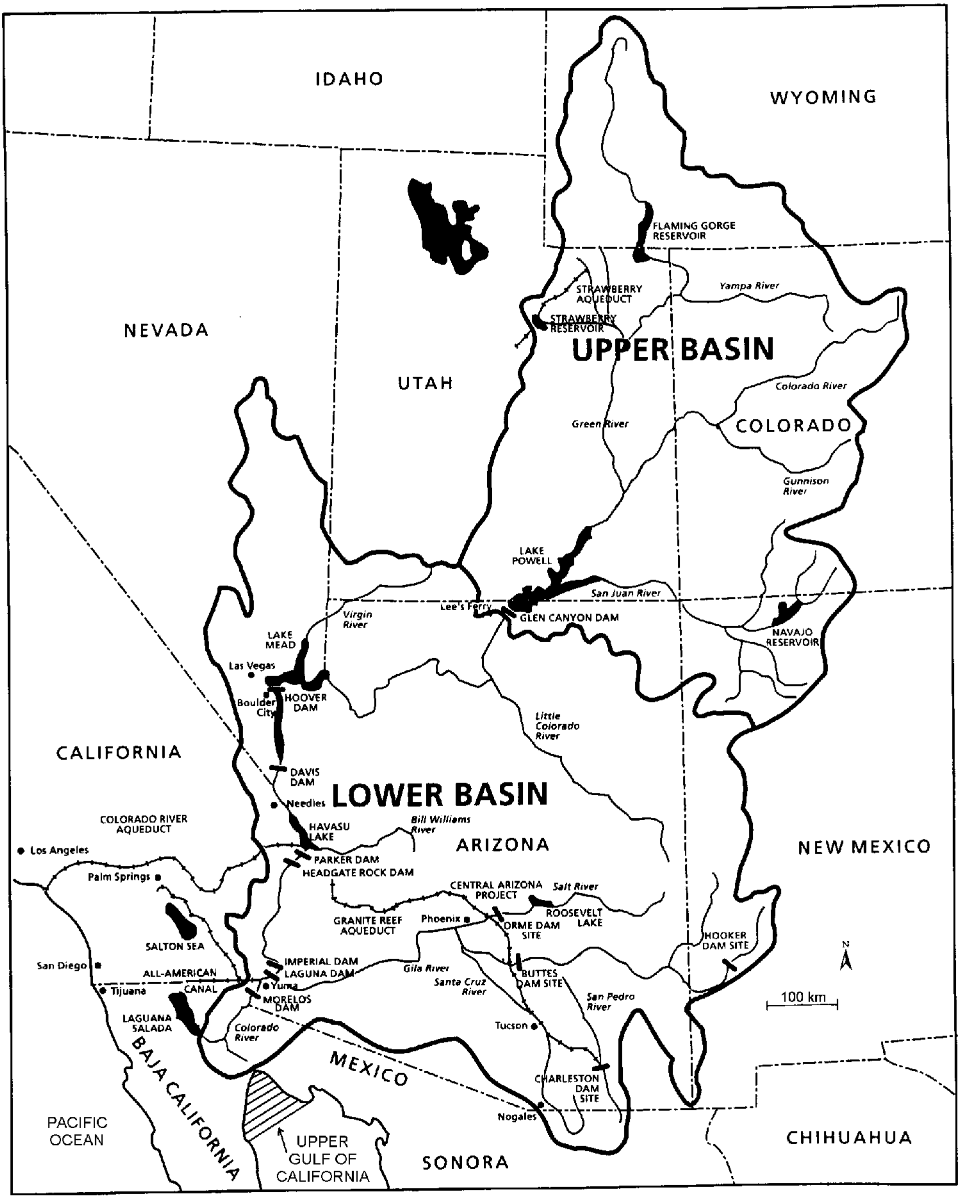

Fig. 1. Colorado River Basin, showing dams and aqueducts.

associated to snow melting and rains in the Colorado River basin, used to occur from May to July, with a peak in June (Fig. 3). After the Hoover dam was completed, the seasonal cycle was damped and man-controlled anomalies were introduced (Fig. 2). The large amount of water released in the period 1941–1960 ceased during the filling

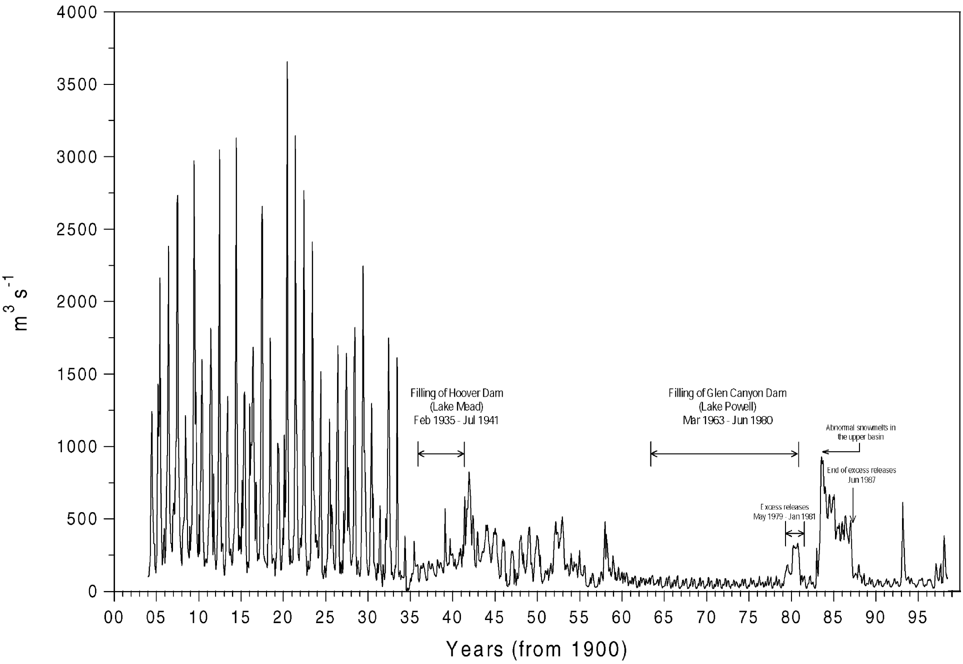

Fig. 2. Flux of water of the Colorado River across the U.S.–Mexico border. Data for 1904–1949 from Yuma (Arizona), and for 1950–1998 from Morelos Dam (Sources: Yuma, USGS; Morelos Dam, CILA-CONAGUA).

of Glen Canyon Dam, and the seasonal signal was eliminated. In the period 1980–1986, water release became necessary due to the dams reaching their capacity and to abnormal snow melts in the Upper Basin of the Colorado. Much of the released water reached the sea (Morrison et al., 1996), and hydraulic control works had to be built in Mexico (Trava, 1986).

The area where the Colorado River used to discharge is called the Upper Gulf of California (henceforth UGC, Fig. 4(a)). It is a tidal shallow sea (<30 m deep) that at present behaves like an inverse estuary (Lavín et al., 1998), with salinity increasing from its entrance (~ 35.4) to the head (39.0 in summer, 37.0 in winter). It is likely that estuarine conditions were present in the UGC before the dams were built, as suggested by the 35.2–35.7 salinity found in the area by the US Fish Commission steamer "Albatross" in 1889 (Townsend, 1901; Roden, 1958). When the first specific investigation of the hydrography of the UGC was made in 1972–1973, fresh water input from the Colorado River was null, and inverse-estuarine conditions were reported throughout the year (Alvarez-Borrego and Galindo-Bect, 1974; Alvarez-Borrego et al., 1975).

The scant knowledge about the hydrography of the UGC in the undisturbed state of the Colorado River has made impossible an assessment of the impact that the damming had on its physics and biology. It is generally acknowledged that the impact

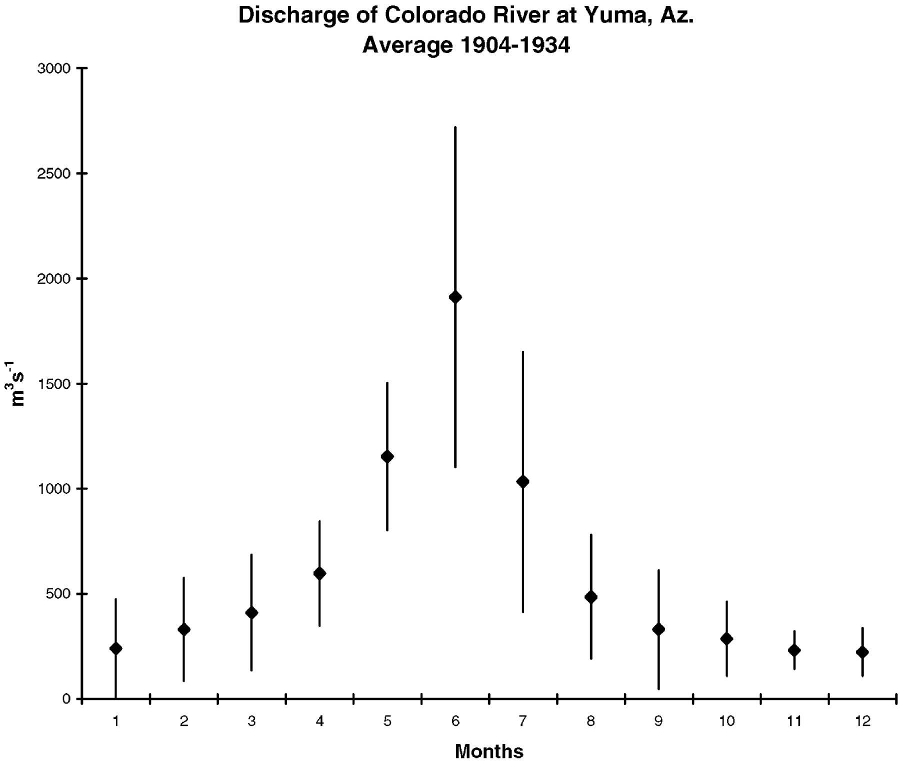

Fig. 3. Average of the monthly values of Colorado River flow at Yuma (Arizona) for 1904–1934, before the construction of Hoover Dam (Source: USGS). The bars are one standard deviation.

on the ecology was detrimental, and it has been reported that shrimp and fish catches improved during the releases of fresh water, apparent in Fig. 2 (Morrison et al., 1996). Galindo-Bect et al. (1999) find a correlation between shrimp catch and the river discharge of the previous year, and between high river flow and El Niño events.

The reconstruction of the former environmental conditions has to rely on numerical modeling (e.g., Carbajal et al., 1997), and on the data collected during sporadic fresh-water discharges. One such event occurred in March and April of 1993 (Fig. 2), and hydrographic data collected at that time are used here to give the first description of the hydrography of the Upper Gulf of California under the effect of fresh water discharge from the Colorado River.

2. Observations

The distribution of CTD stations is shown in Fig. 4(b), and the names of the cross sections described in the text are shown in Fig. 4(a). The CTD stations were made from the vessel *BIP-XI*, between April 4 and 13, 1993, as an addition to a fisheries survey, so the grid was not covered in a consecutive series of cross sections, which is obvious from the station numbers in Fig. 4(b). A total of 143 CTD stations were occupied, the first 90 during spring tides (marked + in Fig. 4(b)) and the rest during neap tides (marked • in Fig. 4(b)). A Neil-Brown Smart CTD was used, whose field and

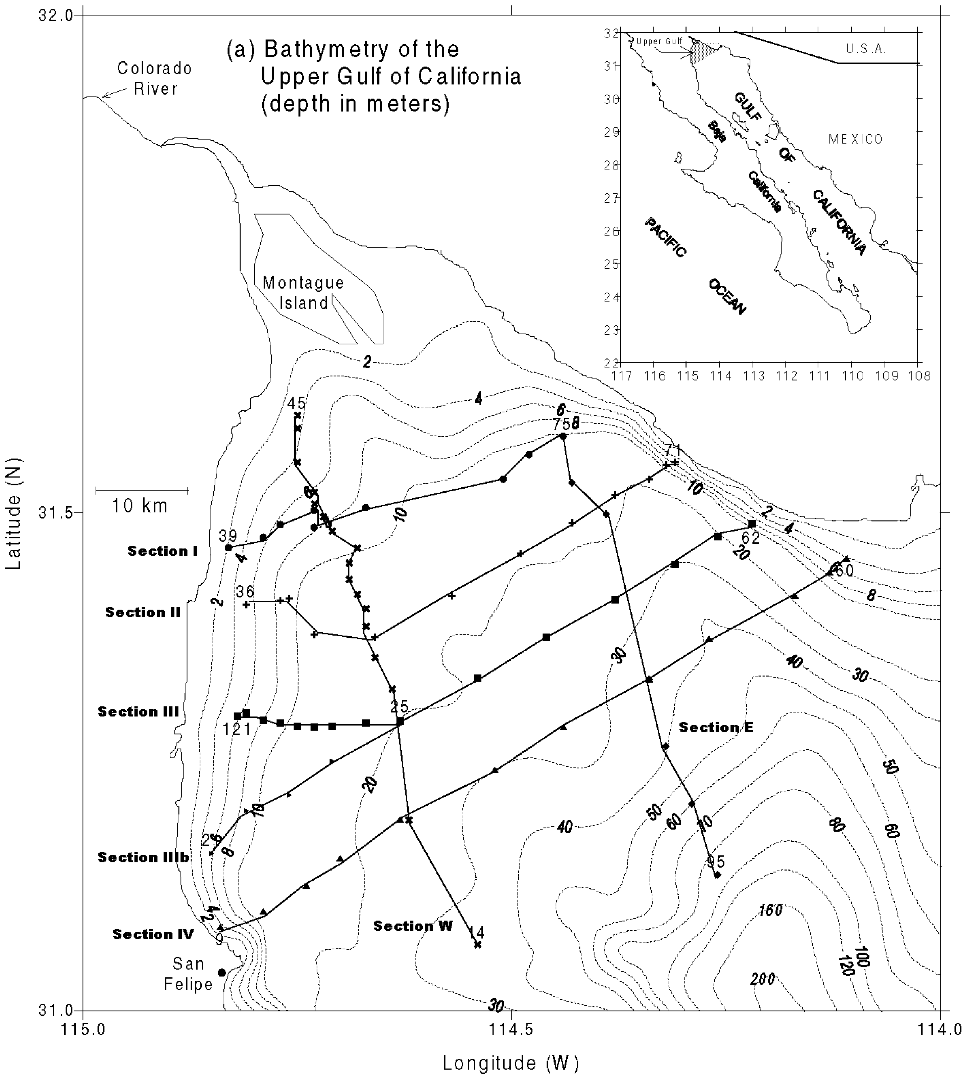

Fig. 4. The Upper Gulf of California (UGC): (a) bathymetry and lines of CTD stations dicussed in the text; (b) sequential number of CTD stations: + indicates stations made during spring tides, and those marked • were made during neaps.

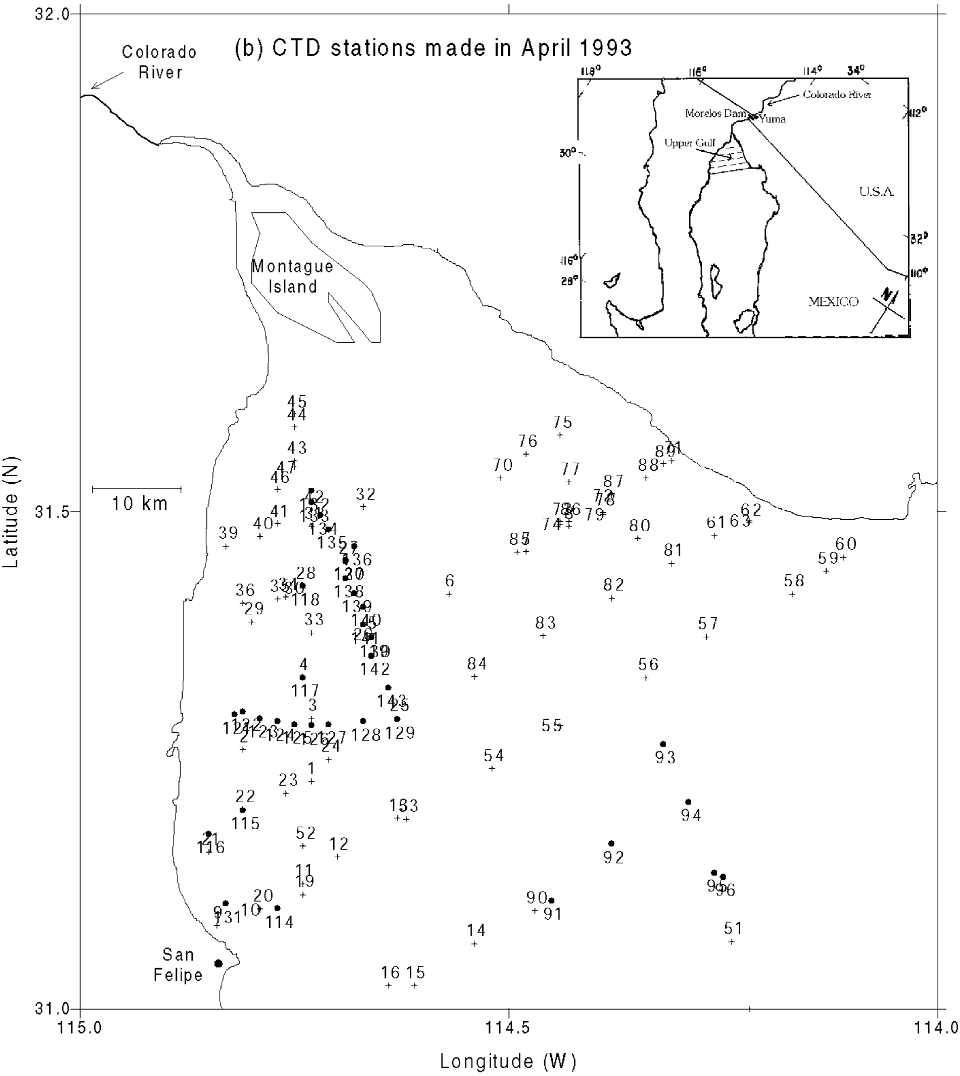

Fig. 4. (*Continued.*)

laboratory calibrations can be found in Godínez et al. (1995). Calm winds prevailed for most of the survey.

The surface salinity (Fig. 5(a)) shows the important diluting effect that the Colorado River had upon most of the UGC. Salinity decreases from the usual value of 35.4 at the entrance to as low as 32.0 to the SW of Montague island. Normally, the salinity increases over the same distance from 35.4 to about 37.00 at this time of the year (Lavín et al., 1998), therefore salinity to the SW of the island fell by at least 5 psu. This

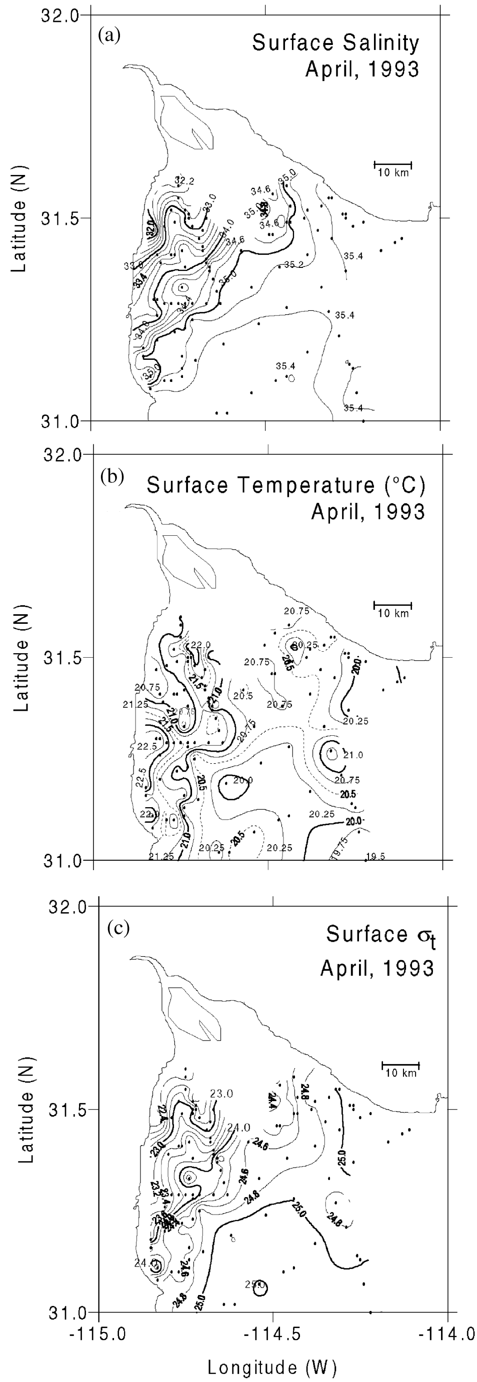

Fig. 5. Horizontal distribution of the hydrographic variables, in April 1993. (a) Surface salinity, (b) Surface temperature, (c) Surface σ_t.

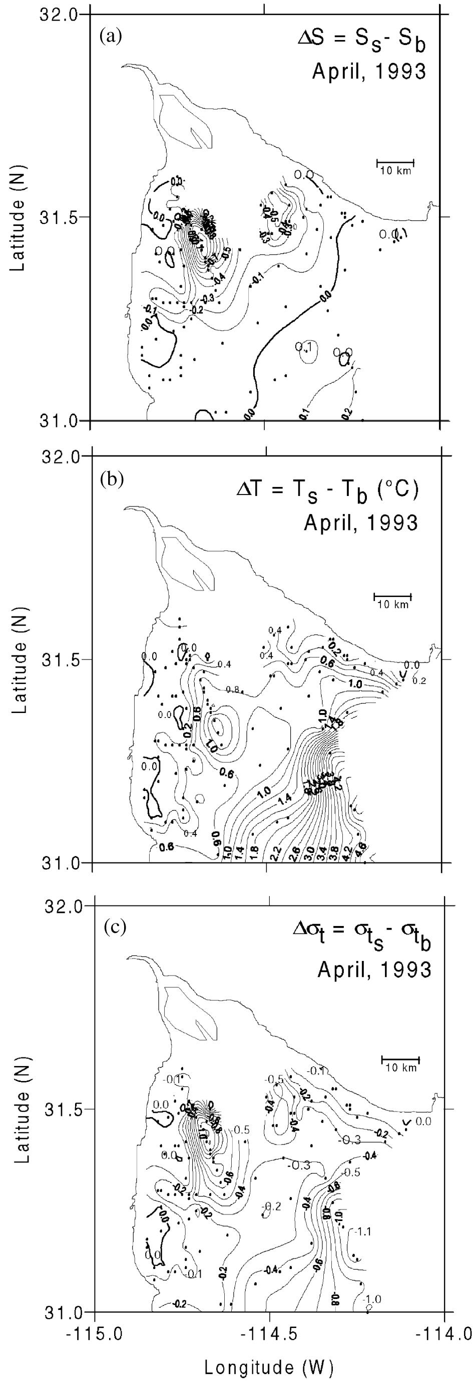

Fig. 6. Horizontal distribution of the surface-to-bottom differences of the hydrographic variables, in April 1993. (a) Salinity, (b) Temperature, (c) σ_t.

reversal of the salinity gradient suggests that the surface layer of the entire UGC was affected in some measure by the fresh water. The effect is more pronounced on the western side, where the most diluted water is found, almost reaching San Felipe, ~70 km from the river mouth. Although the extreme NE was not sampled because of its shallowness, the trend of the isohalines clearly suggests that the dilution occurred mostly along the western side. The surface temperature (Fig. 5(b)) is normal for the time of year; the freshest water was also the warmest (~22.5°C vs. ~20.0°C offshore), and a thermal front meandered approximately N–S parallel to the western coast, bordering the freshest water. The surface density distribution (Fig. 5(c)), which at this time of the year normally increases from ~25.4 at the entrance to ~26.2 at the head (Lavín et al., 1998), now decreases from 25.0 to 22.4.

The surface-to-bottom differences (Fig. 6) show that the coastal water affected by dilution was found in a coastal band about 10–20 km wide adjacent to the western shore. This water was vertically well mixed in all the variables. Outside this region, slight stratification in all the variables is apparent ($\Delta S \approx -0.1$–0.3; $\Delta T \approx 0.5$°C, $\Delta\sigma \approx -0.3$), with values similar to those of the inverse-estuarine conditions; the difference is that in the estuarine conditions the surface water is less salty due to the fresh water, while in the normal conditions the bottom water is more salty due to water-mass formation in the coastal zone and its subsequent movement offshore as a bottom gravity current (Lavín et al., 1998).

Also apparent in Fig. 6 are the two elongated nuclei of high stratification ($\Delta S \approx -1.1$; $\Delta T \approx 1.1$°C, $\Delta\sigma \approx -1.0$), close to the western coast. These are caused by the data collected during neap tides along the western side of Section 3 and along Section W (see positions in Fig. 4(a)), which are described below.

Since Sections 1 and 2 were made during spring tides and were vertically well mixed, the vertical sections are not shown. Their more relevant features, which can be seen in the surface distributions (Fig. 5), are: (a) the contrast between the fresher western side (minimum salinity 32.0) and the eastern side that has a salinity (35.4) typical of the surface mixed layer just outside the UGC, and (b) the thermohaline fronts delimiting the water affected by the fresh water. More importantly, it is clear that in this area, tidal mixing during spring tides was capable of overcoming the stratifying influence of the river buoyancy input.

The western side of Section 3 (Fig. 7) was made during neap tides, while the eastern one was made during springs. The minimum salinity on the west had increased to 34.2, while the eastern side showed no sign of dilution. The western side has a wedge structure with linear gradients in all the variables. This wedge was not found in this area when Section 3(b) (see position in Fig. 1(a); data not shown) was made during spring tides; well mixed water of 35.3 salinity was found in a 25 km-wide coastal zone, to a bottom depth of 25 m.

The last line of stations of the survey, Section W (see position in Fig. 4(a)), which was made in neap tides but in the along-gulf direction (Fig. 8) shows even more strikingly that the three distributions are dominated by a typical estuarine wedge structure, with tilted surface-to-bottom haline, thermal and density fronts separating offshore water ($T \approx 19.5$°C, $S \approx 35.5$, $\sigma_t \approx 25.2$) from very diluted coastal water ($T \approx 21$°C, $S \approx 32.5$, $\sigma_t \approx 22.5$).

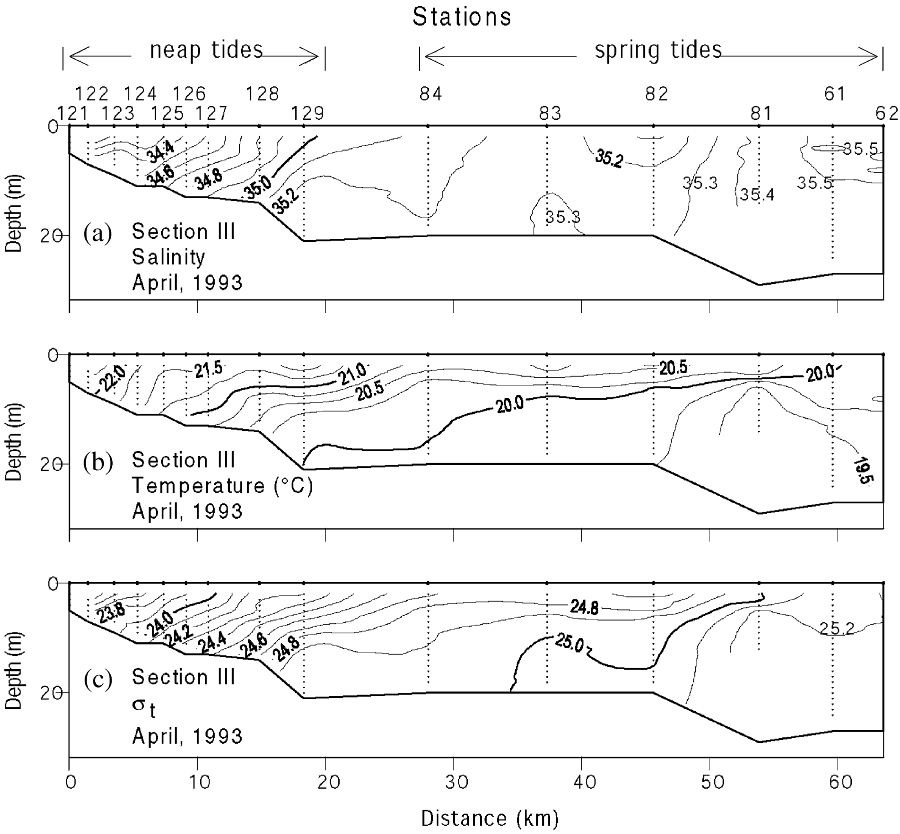

Fig. 7. Vertical distributions at Section 3: (a) Salinity, (b) Temperature, (c) σ_t.

Section 4 (Fig. 9), made during springs, is at the entrance to the UGC, and shows only a little influence of the fresh water: there is a salinity minimum (35.2) at Station 11 (Fig. 9(a)), with salinity increasing to 35.3 toward the western coast; some salinity over 35.5 is found to the east of Station 11 and on the eastern side of the section. Most of the water in this section had a salinity of 35.4. Temperature and density stratification were present on the deeper ($\sim$30 m) eastern side (Figs. 9(b) and (c)), but this stratification is outside the regime of the UGC.

The two hydrographic regimes in the region are apparent in the along-gulf Section E (see position in Fig. 4(a)), which was made during spring tides (Fig. 10). Inshore of the 30 m isobath is the UGC regime, which is separated from the Wagner Basin regime by a bottom thermal front. This tidal mixing front is at a bottom depth of 35–40 m (Fig. 10(b); Stns. 56, 93 and 94), which agrees with the depth range predicted for the front by the h/U^3 criterion (Argote et al., 1995). As is normal, salinity of 35.4 occupies the upper layers of the offshore regime. In the UGC regime, slightly diluted

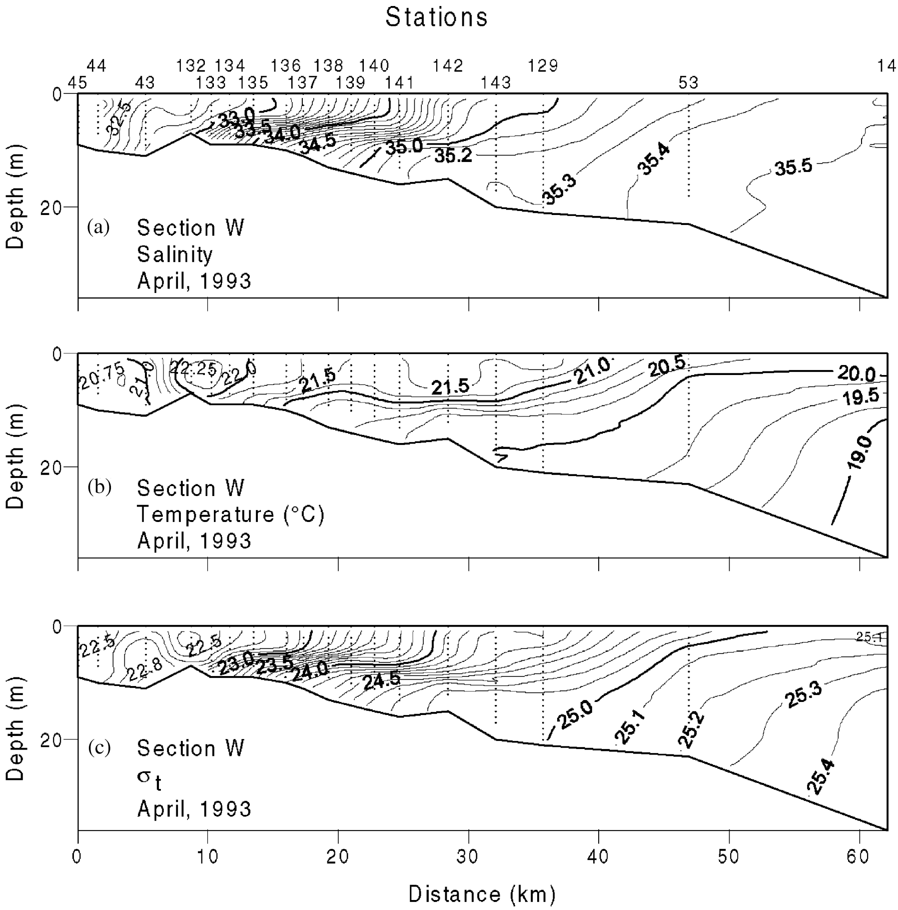

Fig. 8. Vertical distributions at Section E: (a) Salinity, (b) Temperature, (c) σ_t.

water of salinity $\sim$35.1 overlies water from the offshore regime (salinity $\sim$35.4) that is found close to the bottom (Fig. 10(a); Stations 77 and 78). The distribution of density (Fig. 10(c)) reflects the main features of the distributions of temperature and salinity, especially the fronts.

3. Discussion and conclusions

The evidence presented here establishes that the Colorado River affected in some measure the hydrography of the entire UGC. In our observations, the most diluted water was found in a shallow vertically mixed, 10–20 km wide coastal band on the western side of the UGC. The springs-neaps modulation of tidal mixing had a

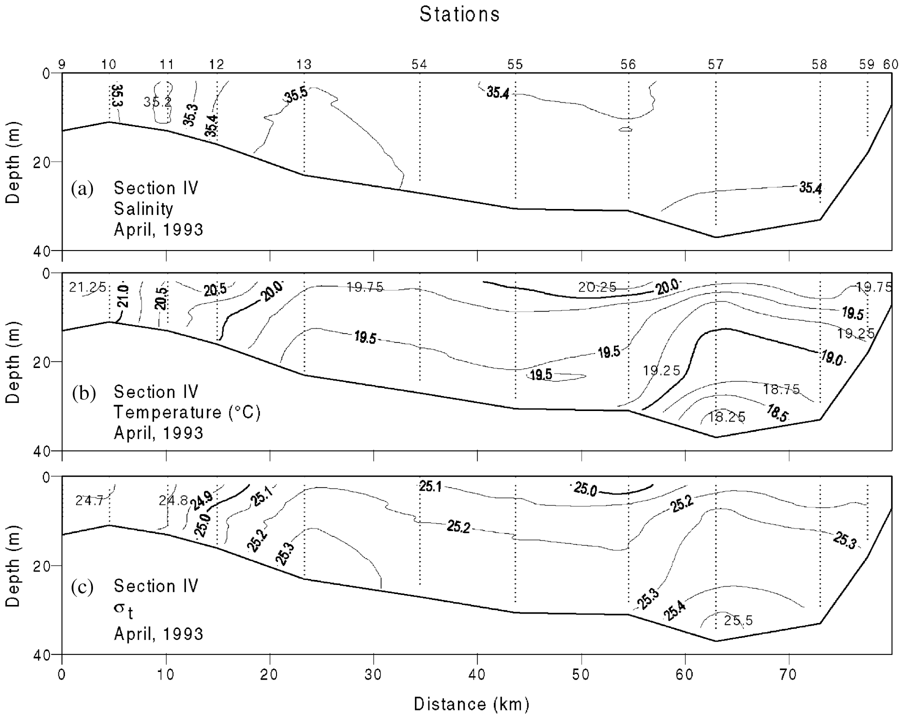

Fig. 9. Vertical distributions at Section 4: (a) Salinity, (b) Temperature, (c) σ_t.

pronounced effect, with stratification and classical estuarine salt wedges occurring during neap tides. It seems that tidal mixing was capable of keeping well-mixed conditions in the presence of fresh water inflow from the river only during spring tides, while in neap tides the stratifying tendency due to the buoyancy input by the river imposed an advective regime: the fresh surface layer flows over the denser lower layer, like a surface gravity current. This fortnightly modulation of tidal mixing affects in a similar way the formation of bottom gravity currents when the UGC is in the inverse-estuarine mode (Lavín et al., 1998).

A zero-order criterion for the formation of stratification in the presence of estuarine circulation and tidal mixing is given by (Simpson et al., 1990)

$$q = \frac{\dfrac{g^2 h^4 (\partial \rho / \partial x)^2}{320 \rho N_z}}{4 \varepsilon k_h \rho U^3 / 3\pi h} > 1,$$

where $g = 9.81$ m s^{-1} is the gravitational acceleration, h is the bottom depth, ρ is the density, $\varepsilon = 0.004$ is the flux Richardson number for tidal mixing, $k_b = 0.0025$ is the

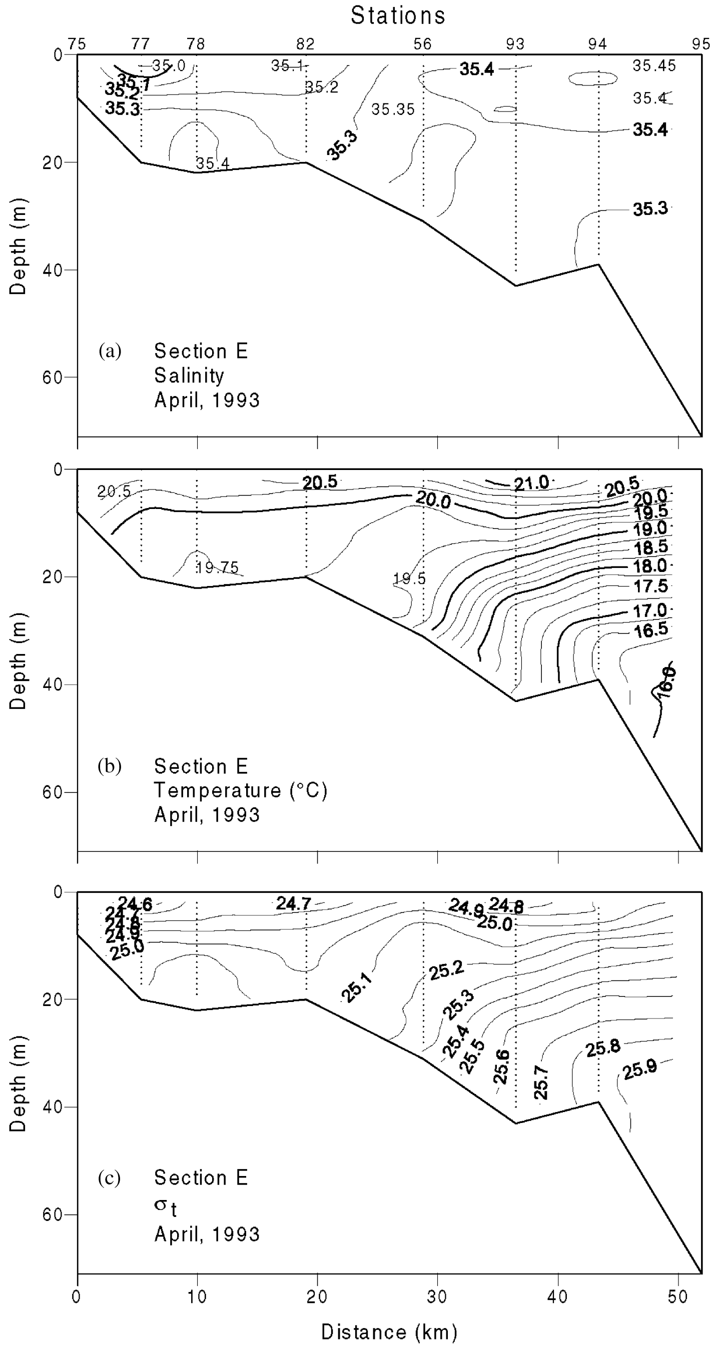

Fig. 10. Vertical distributions at Section W: (a) Salinity, (b) Temperature, (c) σ_t.

bottom drag coefficient, U is the amplitude of the major axis of the tidal ellipse, and N_z is the vertical eddy diffusivity, which can be parameterized as (Bowden and Hamilton, 1975)

$$N_z = 3.3 \times 10^{-3} Uh.$$

Using the horizontal density gradient from the data presented here ($\sim$0.5 kg m^{-3}/5 km),

$$q = 2.054 \times 10^{-10} (h/U)^4.$$

Estimates of U from observations (Argote et al., 1995; Marinone and Lavín, 1997; Lavín et al., 1998) and numerical models (Argote et al., 1995; Carbajal et al., 1997) are $\sim$0.6 m s^{-1} in springs and $\sim$0.1 m s^{-1} in neaps. The criterion predicts vertical mixing for depths typical of the UGC during spring tides. During neaps, it predicts that stratification would occur for $h > 26$ m. But the currents in the very shallow area are not known, and they are almost certainly smaller than 0.1 m s^{-1} in neaps. If $U = 0.05$ m s^{-1} at neaps in that area, stratification would occur at $h > 13$ m. Carbajal et al. (1997) reached similar conclusions using their numerical predictions. However, as Figs. 7 and 8 show, stratification occurred at depths shallower than those predicted by the criterion; this suggests that the bulk criterion is too simple for the UGC scenario, and that more elaborate considerations and more complete observations are necessary. As a next step, one-dimensional turbulent closure models can be tried, as suggested by Nunes-Vaz and Simpson (1994), before resorting to 3D models. And of course, it is necessary to obtain current measurements close to the river mouth.

The horizontal and vertical distributions of the isohalines are similar to those of the numerical predictions of the effect of the Colorado River made by Carbajal et al. (1997), taking into account that they used a constant river flux of 2000 m^3 s^{-1}, which is typical of the historical spring peak, but larger than in March–April 1993 (see Figs. 2 and 3). With the data presented here it is now possible to fine-tune a three-dimensional numerical model and use it to re-create the conditions in the past, using as inputs the historical records of Colorado River discharges (Fig. 2) and predicted tides.

In addition to the numerical investigation of the seasonal and spring-neaps cycles, which were not included by Carbajal et al. (1997), it will be interesting to investigate the effect of the fresh water on the formation of the gravity currents of high-salinity bottom water, which has been observed to occur throughout the year (Lavín et al., 1998), and has been modeled numerically only for winter in the present conditions (López, 1997). Although the unperturbed fresh water input (Fig. 3) was not maximum at the time when the most important gravity currents occur (late winter and early spring), some water flowed into the UGC even in those months. The summer bottom gravity currents almost certainly were eliminated.

The amount of fresh water that reached the UGC in March and April of 1993 was much less than that during 1983–1987 (Fig. 2). Therefore, it can be assumed that the UGC had estuarine conditions all year round in those years. No research was conducted at those periods, but as Fig. 2 shows, water-release events like the one studied here have occurred recently and are likely to occur in the future. Most of these events are controlled and advanced warning given, so they can be used for a more complete investigation.

Acknowledgements

This work was funded by CICESE, and by CONACYT through Contracts No. 25555-T9712 and 026PÑ-1297. This paper was mostly written during a sabbatical stay at School of Geography and Oceanography, ADFA, University of New South Wales, Canberra, Australia, with support from CONACYT, CICESE and ADFA. We would like to thank Oscar Pedrín for allowing us to take part in his cruise. The Colorado River water flow at Morelos Dam were provided by the Comisión Internacional de Límites y Aguas (CILA). Technical support by C. Flores and V. Godínez. Internet data hunting and computer graphics by Carlos Cabrera. This paper benefited from comments by R. Nunes-Vaz, A. Badan and G. Marinone.

References

Alvarez Borrego, S., Galindo Bect, L.A., 1974. Hidrología del Alto Golfo de California-I. Condiciones durante otoño. Ciencias Marinas 1, 46–64.

Alvarez Borrego, S., Flores Báez, B.P., Galindo Bect, L.A., 1975. Hidrología del Alto Golfo de California II. Condiciones durante invierno primavera y verano. Ciencias Marinas 2, 21–36.

Argote, M.L., Amador, A., Lavín, M.F., Hunter, J.R., 1995. Tidal dissipation and stratification in the Gulf of California. Journal of Geophysical Research 100, 16103–16118.

Bowden, K.F., Hamilton, P., 1975. Some experiments with a numerical model of circulation and mixing in a tidal estuary. Estuarine, Coastal and Marine Science 3, 281–301.

Carbajal, N., Souza, A., Durazo, R., 1997. A numerical study of the ex-ROFI of the Colorado River. Journal of Marine Systems 12, 17–33.

Galindo-Bect, M.S., Glenn. E.P., Page, H.M., Galindo-Bect, L.A., Hernández-Ayón, J.M., Petty, R.L., García-Hernández, J., 1999. Analysis of the Penaeid shrimp catch in the Northern Gulf of California in relation to Colorado River discharge. Fishery Bulletin in press.

Godínez, V.M., Lavín, M.F., Sánchez Mancilla, S., 1995. Calibración del CTD Smart en laboratorio y campo. Comunicaciones Académicas, Serie Oceanografia Física No. CTOFT9511. CICESE, Ensenada, México, 14 pp.

Lavín, M.F., Godínez, V.M., Alvarez, L.G., 1998. Inverse-estuarine features of the Upper Gulf of California. Estuarine, Coastal and Shelf Science 47, 769–795.

López, M., 1997. A numerical simulation of water mass formation in the northern Gulf of California during winter. Continental Shelf Research 17, 1581–1607.

Marinone, S.G., Lavín, M.F., 1997. Mareas y corrientes residuales en el Golfo de California. In: Lavín, M.F. (Ed.), Contribuciones a la Oceanografía Física en México. Monografía No. 3, Unión Geofísica Mexicana, 1997, pp. 113–139.

Morrison, J.I., Postel, S.L., Gleick, P.H., 1996. The sustainable use of water in the Lower Colorado River Basin. Pacific Institute for Studies in Development, Environment, and Security, Oakland, CA, USA, 77 pp.

Nunes-Vaz, R., Simpson, J.H., 1994. Turbulent Closure modeling of estuarine stratification. Journal of Geophysical Research 99, 16143–16160.

Simpson, J.H., Brown, J., Matthews, J.P., Allen, G., 1990. Tidal staining, density currents and stirring in the control of estuarine stratification. Estuaries 12, 125–132.

Townsend, C.H., 1901. Dredging and other records of the US Fish Commission Steamer "Albatross" with bibliography relative to the work of the vessel. US Fish Commission Report for 1900, pp. 387–562.

Trava, J.L., 1986. Río Colorado: los excedentes de 1980. Centro de Estudios Fronterizos del Norte de México. Tijuana, Baja California, México, 66 pp.