Factors Influencing Suspended Sediment Flux in the Upper Gulf of California

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Few studies exist of sediment dynamics in inverse estuaries, which are characterized by hypersaline water bodies and associated gravity currents and arise in arid regions where little precipitation and runoff combine with a high evaporation. Observations of velocity, density and suspended sediment concentration profiles have been made using an acoustic Doppler current profiler, CTD, optical backscatter sensors and water sampling at a shallow water site in the Upper Gulf of California over a spring to neap tidal cycle. These revealed contrasting dynamic conditions in which gravity current events produced significant net near-bed suspended sediment fluxes of 2.5 g m\textsuperscript{-2} s\textsuperscript{-1} out of the Gulf during neap tides. Instantaneous suspended sediment fluxes exceeded 30 g m\textsuperscript{-2} s\textsuperscript{-1} during spring tides due to tidal resuspension, but net fluxes were near zero. The baroclinic gravity current is shown to be the dominant mechanism for net flux of suspended sediment toward deeper waters, at least during quiescent summer conditions. This flux is proposed to be confined within a wide, western along-Gulf channel. This is consistent with evidence that the Colorado River delta system is exporting sediments to deeper water after becoming unstable due to switching off of river discharge since 1930.

\textbf{Keywords:} suspended matter; sediment flux; inverse estuaries; gravity currents; Gulf of California

Introduction

Rivers discharge fresh water and sediments to the coastal ocean. The resulting estuarine environments become the pathways through which finer sediments may reach the open sea. Within an estuary the fine sediment particles are dispersed along paths determined by water motion. Tidal energy continually erodes, transports and deposits bed sediments. Thus, within the classic estuary the suspended particulate matter (SPM) concentration is generally high even with little new sediment input (Dyer, 1995). These low salinity water bodies respond to seasonal fluctuations of freshwater discharge. Extensive research in shelf seas has been oriented to determine the fate of the high river runoff that occurs during the wet season. In contrast, dry season estuarine dynamics has only received attention in recent years. The tropical estuaries of northern Australia, for instance, are influenced by large seasonal fluctuations in freshwater discharge (Wolanski, 1988). In arid regions where little precipitation and runoff combine with a high evaporation rate, hypersaline water bodies develop called negative estuaries or inverse estuaries. Large-scale examples of this are the Persian Gulf, the Red Sea, the Arabian Sea, the South Australian gulfs and the Gulf of California (Bowers, 1989; Nunes Vaz \textit{et al.}, 1990).

In contrast with the classic estuary model, the inverse estuary in arid regions requires a net flow of oceanic water toward its head to compensate for the freshwater loss due to evaporation. The tendency for salt accumulation inside the inverse estuary requires an opposing mechanism that removes the high salinity water. One process involves the sinking of saltier (denser) water in the shallower areas and its flow toward the open ocean boundary as a near-bed gravity current (Nunes Vaz \textit{et al.}, 1990). Gravity current events have been observed in the Australian inverse estuaries and in the Upper Gulf of California during neap tides (Laví\textup{'n} \textit{et al.}, 1998). Among the smaller-scale examples, coastal lagoons in arid regions can also exhibit inverse-estuarine behaviour when high evaporation causes a net loss of water. In these so-called anti-estuarine lagoons, the seaward flowing circulation near the bottom can carry SPM from the lagoon out to the ocean (Groen, 1967; Postma, 1967). Enhancement of the seaward flux of SPM can be expected since both gravity currents and high SPM concentration may develop close to the sea bed concurrently. Sediment transport under these conditions has not been widely documented, perhaps as a consequence of the relatively little attention given to inverse estuaries in the past. The present study reports measurements of currents and SPM concentrations at a site in the Upper Gulf of California, a shallow...
macrotidal region with inverse estuarine features. The aim of this work was to investigate the processes influencing sediment fluxes using intensive observations made for the first time in this region.

**Area of study**

The Upper Gulf of California (henceforth called the Upper Gulf) is located in the northernmost part of the Gulf of California, bounded by the arid lands of Sonora and the Baja California peninsula (Figure 1). It is one of the most dynamic shallow environments in Mexico due to its large tidal range (~7 m) and fast tidal currents (~1 m s\(^{-1}\)) during spring tides. Before 1930, the Colorado River supplied freshwater (~20 \(\times\) \(10^9\) m\(^3\) yr\(^{-1}\)) and sediments (~180 \(\times\) \(10^6\) tons yr\(^{-1}\)) to the northern end of the Upper Gulf (Thompson, 1968). Estuarine conditions may have prevailed then, before human tampering with the river drainage, as suggested by numerical modelling and recent surveys made during unusual river discharge (Carbajal et al., 1997; Lavin & Sánchez, 1999).

The region is less than 40 m deep with irregular bottom topography. Several 10 to 30 km long ridges rise 8–10 m above flat-bottomed, gentle-sloping troughs aligned parallel to the Gulf’s axis. The sea-bed sediments consist of unconsolidated deposits supplied by the Colorado River before dams were built. Textural classification of the bottom surface sediments yields three groups: silt-clay, sand-silt-clay and sand. Silt-clay predominates off Baja California, north of San Felipe and between the ridges in the intervening troughs (Thompson, 1968). Finer sediments of mean grain size \(5\rho – 7\rho\) predominate over the western half of the Upper Gulf and coarser sediments of \(2\rho – 4\rho\) are found over most of the eastern half (Carriquiry & Sánchez, 1999). Observations across the gulf by García de Ballesteros and Larroque (1974) indicated that surface SPM concentrations were higher near the river mouth with a persistent horizontal gradient to the southeast. This trend was described earlier by Thompson (1969) based on turbidity patterns. He suggested that tidal currents were the main conveyor of sediments in this region and that the slight rotary motion of these currents induced a westward drift of sediments in suspension.

A sea breeze wind regime prevails near the coast with magnitude less than 5 m s\(^{-1}\). Maximum average wind speed in mid-summer is 4 – 4.5 m s\(^{-1}\). Synoptic wind events lasting 2–5 days occur with a
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Observations

The main data set consists of velocity measurements made during a 15-day deployment of a bottom-mounted SonTek® Acoustic Doppler Profiler (ADP) in waters 25 m deep. The velocity record consists of consecutive 5-min averages from 0·5 m depth ‘bins’. In addition to currents, the sea level, near-bottom temperature and backscattered acoustic signal strength were recorded by the ADP. The site (W3) is located on the western side of the Upper Gulf, 20 km off the coast of Baja California, and 25 km northwest of San Felipe, as shown in Figure 1. The mooring was set inside an 8-km wide trough with the shallow coastal shelf on the west and a narrow ridge rising 8–10 m on the east. This long, gently sloping channel reaches Wagner Basin 40 km to the southeast of the measurement site.

Vertical profiles were obtained with a Sea-Bird CTD fitted with a Sea-Tech 10-cm path length transmissometer and a Seapoint optical backscatter sensor (OBS). Casts were made on board the R/V ‘Francisco de Ulloa’ along transects and every half an hour near the ADP (site W3) over fixed periods. These time series lasted 48 h during spring tides and only 15 h during neaps due to poor weather. Water samples from CTD-mounted bottles were used to measure SPM concentration by filtering a known volume of the water sample and by differential weighing of the dried filters. Forty-two samples were collected less than 0·9 km from the ADP site, and the directly measured SPM concentration range appeared to encompass most of the spring to neap tide variation observed in this area.

Additional CTD and OBS profiles were measured during a preliminary survey in June 1996 in the same area (site J shown in Figure 1), under spring and neap tide conditions. The hydrography and current measurements at 1 and 6 m above the sea bed have been described by Lavin et al. (1998).

Analysis of data

Velocity

After rejection of near surface ADP data due to signal reflection or signal-to-noise ratio reduction, useful velocity bins started at 1·2 m above the sea bed and extended up to 16 m. This range represents 60% of the water column at mean sea level. The velocity components were projected along the principal axes corresponding to the directions of maximum variance and its perpendicular. These directions

northwesterly direction in winter and southeasterly direction in summer. These monsoon-type winds may reach 13 – 16 m s⁻¹ in winter and 5 – 10 m s⁻¹ in summer (Gayman, 1969; Green 1969; Delgado-González et al., 1994). This wind regime generates the low, steep, short-period waves typical of the northern Gulf. Significant wave height is only 0·3 – 1·0 m with a period of 2–4 s due to limited fetch and wind duration. Southern swells may arrive 2–10 times a year, mainly in late spring, with wave height 1–1·5 m and period 4 – 7 s. These events last only 6–24 h (Gayman, 1969).

Numerical modelling studies, supported by hydrographic observations indicate that tidal mixing is responsible for the generally vertically homogeneous character in the shallow areas of the Upper Gulf (Argote et al., 1995). The vertically mixed waters extend southeast to depths between 30 and 60 m where a thermal front has been regarded as the boundary (Durazo-Arvizu, 1989; Argote et al., 1998).

Indirect evidence suggests that a cyclonic residual circulation is generated in the Upper Gulf (Hendrickson, 1973; Hernández-Ayon et al., 1993). A similar pattern was reported by Marinone (1997), through numerical modelling of the tidal residual currents, and also by Carriquiry and Sánchez (1999), based on calculated sediment transport pathways. The patterns of suspended sediment plumes observed in satellite images have been attributed to the effect of this residual circulation. Carbajal et al., (1997) have speculated that the transport of sediments to deeper basins takes place through the mechanism of residual currents.

Hydrographic surveys and current measurements reported by Lavin et al. (1998) have revealed that the Upper Gulf normally behaves like an inverse estuary, in which salinity and density increase toward the head throughout the year, despite reversal of the temperature gradient from summer to winter. As in other inverse estuaries, the horizontal density gradients in the shallow coastal areas of the Upper Gulf are sustained by intense vertical mixing during spring tides. During neap tides the decrease in mixing allows, given the horizontal contrast of density, the onset of gravity currents: the warmer but saltier and denser water (Δσ)>0·2) in the shallow, well-mixed regions flows underneath the colder, fresher and lighter offshore water with a down-slope component and just near the bed. The same authors reported that the velocity at 1 and 6 m above the bed was to the southeast, flowing out of the Upper Gulf at ~0·1 m s⁻¹, similar to geostrophically adjusted speeds of gravity currents observed in Australian Gulfs (Nunes & Lennon, 1987).
coincide with the along-Gulf and across-Gulf orientations, respectively.

**Optical backscatter**

The voltage \( V \) of the CTD-mounted OBS was converted to SPM concentration \( C \) (mg l\(^{-1}\)) by calibration against filtered water samples. These samples were obtained throughout the Upper Gulf in the August 1997 intensive cruise. During the preliminary cruise in June 1996, a near-bottom water sample was brought on board for calibrating the OBS under laboratory conditions. Results of the least squares fits are given in Table 1. Time series of the vertical profiles of SPM concentrations were then obtained every half-hour at sites W3 and J during spring and neap tides.

**Acoustic signal strength**

The ADP stored the raw acoustic signal strength backscattered from particulate matter in the water. After conversion to decibels, the signal strength was corrected for water sound absorption and geometric spreading of the acoustic beams (SonTek Technical Notes, 1997). The corrected signal strength from the three beams was averaged and normalized by the minimum value of the data set. Corrected signal strength from selected range cells between 3 and 15 m above the transducers was extracted at suitable times. These values were compared to SPM concentrations measured from water samples collected at corresponding times and depths. A linear regression procedure yielded the calibration curve:

\[
\log_{10} C = 1.1186 + 0.0245 A,
\]

where \( C \) is the concentration of SPM in mg l\(^{-1}\) and \( A \) is the corrected return signal strength in decibels. The regression parameters are given with 95% confidence intervals. Figure 2 shows the SPM concentration values and the regression line that accounted for 80% of the variance in the data.

Close to the transducers, within the so-called near-field range, a complex acoustic beam pattern develops. It deviates from the spherical spreading of the far-field, in which the acoustic signal strength is inversely proportional to the range \( r \) from the transducers. The boundary between the near-field and the far-field backscatter regions is at a distance \( r = \pi a^2/\lambda \) (SonTek Technical Notes, 1998), where \( a \) is the transducer radius and \( \lambda \) is the acoustic wavelength. For the ADP used, \( r \) is 1.25 m. Thorne et al. (1996) have applied a factor of 2 which in our case yielded the first three bins within the near-field. Since the suspended sediment samples for calibration were collected in the far-field region, only signal strength values measured 2.7 m from the sea-bed and above were used for estimating SPM concentrations and fluxes. Instantaneous horizontal fluxes between 2.7 and 10.7 m above the sea-bed were obtained as the product of velocity times SPM concentration \( \nu C \) at 0.5 m increments. Vertically integrated instantaneous fluxes were calculated by numerically integrating \( \int_{z_1}^{z_2} \nu C dz \), where \( z_1 = 2.7 \) m and \( z_2 = 10.7 \) m above the sea-bed, with 0.5 m increments. Further calculations yielded instantaneous and time averages of along-gulf (principal axis) and across-gulf fluxes during spring and neap tides and over the full fortnightly cycle.

### Results

Variable winds less than 6 m s\(^{-1}\) prevailed during the 15-day deployment period (12–27 August, 1997). Direction changed from NW to SE within a few hours but the most frequent were southerly winds, blowing over 80% of the time. Moderate southerly wind events

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**Table 1.** Calibration of the optical backscatter sensors against filtered SPM samples. \( C \) (mg l\(^{-1}\)), \( V \) (volts)

<table>
<thead>
<tr>
<th>Date</th>
<th>Linear fit equation</th>
<th>( R^2 )</th>
<th>Data points</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 1996</td>
<td>( C = 0.72 + 92.00 ) ( V )</td>
<td>0.99</td>
<td>5</td>
</tr>
<tr>
<td>August 1997</td>
<td>( C = 3.44 + 16.03 ) ( V )</td>
<td>0.92</td>
<td>371</td>
</tr>
</tbody>
</table>

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**Figure 2.** Measured SPM concentration vs ADP signal strength (circles). The regression line (solid line) is shown with the 68% confidence interval (dotted lines).
6–10 m $s^{-1}$, lasting $\sim$ 1 day, occurred during neap tides on 12 August, and again on 14, 23 and 24 August. Maximum period and wave height, visually estimated, were 4–5 s and $\sim$ 1 m respectively, during these events.

**Hydrographic setting**

Spring-tide time series of temperature, salinity and sigma-t profiles are shown in Figure 3 which only displays a 15 h interval. The temperature, salinity and density variation is small (30.2–30.8 °C, 36.2–36.4, and 22.3–22.7 sigma-t units, respectively). The nearly vertical isolines indicate that well mixed conditions prevailed from near the bottom to near the surface. Slight stratification involving a vertical temperature rise of 0.5 °C was observed close to the surface during most of the daylight hours, possibly the effect of solar heating. This increase in temperature reflects a transient buoyant layer near the surface, as revealed by the sigma-t structure.

The neap-tide time series, despite being limited to 15 h, shows contrasting patterns especially close to the sea bed (Figure 4). A denser near-bottom layer 5–8 m thick was overlaid by an almost homogeneous less dense water. The near-bed water was up to 0.5 °C warmer and 0.6 more saline than the upper layer. The density changed 0.2–0.3 sigma-t units across a 2-m thick interface that displayed a wave-like pattern. At the end of the series the interface spread upward over most of the water column. The weakening of the vertical density gradient at the end coincided with the onset of strong southerly winds and rough seas that prevented longer observations.

**SPM concentration**

High SPM concentrations were found near the sea-bed, decreasing upwards, as shown in Figures 3 and 4. This indicates that the source of SPM was the sea-bed sediment resuspended by the tidal currents. The maximum concentration during spring tides reached 85 mg l$^{-1}$ close to the sea-bed (Figure 3), while near surface values were $\sim$ 5 mg l$^{-1}$. The highest near-bed concentrations were only 25 mg l$^{-1}$ during neap tides (Figure 4). The spring-tide time series show a clear tidal resuspension signal in which periodic concentration peaks coinciding with maximum flow extended over most of the water column. A different pattern is evident in the 15-h time series during neap tides: the high SPM concentration layer was constrained to a near-bottom layer, 5–8 m thick, showing only a weak resuspension signal. Similar conditions prevailed during the 2-day long neap tide SPM observations of June 1996, at site J (Figure 5). The high concentrations were observed within 6 m from the sea bed, with a 20 mg l$^{-1}$ maximum near the bed. A weak resuspension is evident when currents were stronger, flowing out from the Upper Gulf.

**CTD transects**

Figure 1 shows the location of two CTD along-gulf transects made in this area, 1 to 2 days after the neap tides. Transect A was made along the depression in which the time series were obtained. Transect B was made along the next depression further East, to depths of about 100 m, at the edge of Wagner Basin. Salinity, sigma-t and SPM distributions are given in Figure 6. These transects were made at different stages of the tide. However, both transects show higher values toward the shallow depths in the head of the Upper Gulf. Denser, more saline and turbid water remained close to the sea-bed. At a depth of 50 m this water left the bottom and intruded into the ambient fluid, with a sigma-t value near 22.4, as shown in Figure 6(b). The high salinity and turbid water that became detached from the sea-bed could be traced as a subsurface maximum to at least 10 km away from the point of detachment.

**Currents**

Currents were mainly tidal, semidiurnal and nearly unidirectional, with the principal axis trending NW to SE. Velocity was modulated fortnightly, reaching amplitudes of 0.8 m $s^{-1}$ during spring tides, and decreasing to $\sim$ 0.1 m $s^{-1}$ during neap tides. The velocity gradually decreased toward the sea-bed within an oscillatory bottom boundary layer. The tidal current reversal nearly vanished during neap tides at the beginning and again at the end of the fortnight cycle. The outcome was net outflow from the Upper Gulf (negative velocity) within a layer 7–8 m thick, next to the sea-bed. This outstanding feature of the flow was due to a gravity current flowing along-channel with its core centred 4–5 m above the bottom. The speed at the core varied between near zero and $\sim$ 0.2 m $s^{-1}$ over at least four semidiurnal cycles.

**SPM fluxes**

At levels between 2.7 and 10.7 m above the sea-bed, instantaneous along-gulf SPM fluxes based on the ADP backscattered signal reached $\sim$ 30 g m$^{-2}$ s$^{-1}$ during spring tides and $\sim$ 6 g m$^{-2}$ s$^{-1}$ during neap tides. The time series of instantaneous SPM fluxes display a marked spring–neap modulation at all the
Figure 3. Temperature, salinity, sigma-t and SPM concentration fields measured at site W3, in August 1997, during spring tides. Along-gulf velocity vectors drawn in the lower frame are at 1.2 m and 15 m above the sea-bed. Arrows pointing to the left indicate outflow from the Upper Gulf. Casts were made every half-hour.
Figure 4. Temperature, salinity, sigma-t and SPM concentration fields measured at site W3, in August 1997, during neap tides. Along-gulf velocity vectors drawn in the lower frame are at 1·2 m and 15 m above the sea-bed. Arrows pointing to the left indicate outflow from the Upper Gulf. Casts were made every half-hour.
measurement levels. This modulation can be seen in the time series of instantaneous fluxes measured 5·2 m above the sea-bed, at the level of the maximum gravity current flow (Figure 7). Spring tide fluxes were nearly symmetric about zero, except during neap tides, when fluxes were predominantly out of the Upper Gulf, reaching up to 6 g m$^{-2}$ s$^{-1}$. Vertically integrated instantaneous fluxes yielded maximum transport per unit width near $-4$ g m$^{-1}$ s$^{-1}$ during neap tides, $\pm 290$ g m$^{-1}$ s$^{-1}$ during spring tides, and an average of $-12$ g m$^{-1}$ s$^{-1}$ over the full fortnightly cycle.

In addition to the ADP time series, calibrated OBS profiles from site W3 have provided independent SPM concentrations and instantaneous flux calculations for two short periods during spring and neap tides. Fluxes estimated from both ADP and OBS measurements are in good agreement, as shown in Figure 8, which shows time series of fluxes at 5·2 m above the bed. Along-gulf fluxes during the 15-h neap-tide series show maximum near $-6$ g m$^{-2}$ s$^{-1}$. These figures are also similar to the neap-tide maximum flux ($-5$ g m$^{-2}$ s$^{-1}$) measured 6 m above the sea-bed at site J during the two-day preliminary survey in June, 1996.

Figure 9 shows time-averaged instantaneous flux profiles. The average over a spring–neap cycle (14·7 days) yielded a residual flux out of the Upper Gulf, as shown in Figure 9(b). This residual flux is one order of magnitude smaller than the maximum instantaneous fluxes. The remarkable contrast between spring- and neap-tide fluxes is better shown by averaging the fluxes under each tide condition. Since the neap-tide outflow events lasted around three days, the average over six semidiurnal cycles was obtained for each tide condition. It was found that near-zero residual SPM fluxes prevailed during spring tides [Figure 9(c)], while during neap tides they reached $-2·5$ g m$^{-2}$ s$^{-1}$ [Figure 9(a)]. The average fluxes during spring tides show only a very weak vertical structure. In contrast, the average fluxes during neap tides display a significant maximum at 4 m above the sea-bed, which is the same level as the maximum velocity of the gravity current.

**Discussion**

There has been considerable interest recently in converting acoustic signal strength measured by acoustic Doppler current profilers to SPM concentration (Jones et al., 1994; Thorne et al., 1996; Holdaway et al., 1999). The calibration methods adopted have ranged from obtaining simple height dependent calibration coefficients to full consideration of particle size dependence and attenuation of the signal received from a given layer by SPM in the intervening layers. Most studies have concluded that the technique is sensitive to variations in particle size, and it has been shown that SPM attenuation can act to increase apparent concentrations by up to 26% in high concentration environments (Holdaway et al., 1999). This study considers spreading and attenuation by water but not by SPM; nevertheless, a
convincing calibration has been found using samples from a range of heights above the bed.

At short ranges (~1.5 m) and low concentrations (<1000 mg l\(^{-1}\)), the attenuation of the acoustic signal by suspended fine sand is only slight. This effect can be neglected in estuarine sediment suspensions if concentrations are less than 100 mg l\(^{-1}\) (Thorne et al., 1993). In our measurements, the range was longer and the concentrations were lower: maximum spring tide concentrations 1 m above the sea-bed
reached 85 mg l\(^{-1}\) only during short time intervals. Farther up, near the top of the water column analysed, concentrations were \(~50\%\) lower. Hence, attenuation by suspended particles was assumed to be small. However, uncertainties introduced by changes in the particle size may be important in natural environments. Since bed sediments of the Upper Gulf are poorly sorted, changes in the bed stress due to the oscillatory tidal current are likely to change the size distribution of suspended sediments. Moreover, the presence of fine silts and clays is expected to cause flocculation and therefore increase the effective particle size. Our measurements were not sufficient for a detailed evaluation of these effects; however, a comparison with earlier studies has provided bounds for the expected uncertainties in concentration. Thorne et al. (1991) have accounted for the effect of variable particle size by introducing a constant \(k_0\) that incorporates the scattering properties of the particles in suspension. In their study, the particle size varied from 55 to 210 \(\mu\)m and the detection range was up to 1 m using a 3 MHz system. A change in particle size by a factor of four produced \(~20\%\) change in \(k_0\). It was also estimated that a 10\% uncertainty in \(k_0\) translated into a 20\% uncertainty in concentration values. During our observations the median particle size near the bed varied within a factor of four (40 to 180 \(\mu\)m) throughout the spring-neap cycle (Jones et al., in preparation). Therefore we can expect that uncertainties in the acoustically estimated concentration were less than 50\% in the lower levels of the concentration profiles, and it can be assumed that the effects of variable particle size and attenuation by suspended sediment have introduced uncertainties having magnitude similar to the error of the regression equation. Conversion of ADP signal strength to SPM concentration has therefore allowed the estimation of instantaneous and time-averaged horizontal fluxes of SPM between 2·7 and 10·7 m above the bed under contrasting flow and SPM concentration conditions during a fortnightly cycle. A more detailed calibration may be needed before finer details of the temporal and vertical variation of flux profiles can be relied upon.

Figure 7. Instantaneous horizontal SPM fluxes derived from ADP data, 5·2 m above the sea-bed (the level of the gravity current core), at site W3. Along-gulf (solid line) and across-gulf (dotted line) fluxes are 5-min averages.
The near-bed region could not be calibrated using the method described as no concentration samples were collected in this near-field region of the transducers. This region may contribute significantly to depth-integrated fluxes as measured concentration profiles often indicate sharp increases toward the bed. However, currents decrease rapidly in this region and the flux profiles during periods of high flux indicate a maximum at 4 m above the bed, well above the limit of measurement. Therefore, it is likely that the main features of near-bed flux have been measured in this study.

It is unlikely that the short-crested waves observed during the survey contributed significantly to the resuspension and transport of sea bed sediments 25 m deep. Linear theory predicts that the maximum orbital velocity due to 1·5 m waves at 5 s intervals is less than 0·02 m s$^{-1}$ at this depth. According to Gayman (1969), the prevailing sea breeze waves probably do not stir up sea-bed sediments in water depths more than ½ wavelength. The wave action of a 4 s wave is limited to a depth of 6 m. Waves of longer periods are rare.

The large range of the barotropic tide in the Upper Gulf generates fast currents and large horizontal tidal excursions that, during spring tides, reach 10 km near the surface. However, according to numerical models, tidal residual flows of barotropic character in the Upper Gulf are $\sim 0·01$ m s$^{-1}$. (Carbajal, 1993; Argote et al., 1998; Marinone, 1997). Therefore, residual displacement of a particle due to tides is less than 0·5 km in one semidiurnal period and SPM fluxes produced by this mechanism are approximately 0·3 g m$^{-2}$ s$^{-1}$. Gravity currents, first observed in this region by Lavin et al. (1998), are shown here to produce near-bed fluxes which, despite their short duration, are one order of magnitude larger than those induced by tidal residual currents, at least

Figure 8. Instantaneous SPM fluxes measured 5·2 m above the bed at site W3, obtained from OBS (dotted line) and ADP backscatter (solid line): (a), (b) are across-gulf and along-gulf during neap tides; (c), (d) are across-gulf and along-gulf during spring tides. The vertical axis scale in (d) is twice as large as in the first three.
During summer, therefore, the gravity current can be expected to be the main cause of SPM flux during each neap tide, and hence to contribute significantly to net fluxes during summer. Furthermore, the salinity observed in Wagner Basin has been explained in terms of water mass formation occurring throughout the year, in the shallow areas. The dense, high salinity water mass flows downslope toward the basin as sporadic gravity current pulses (Lavín et al., 1998).

Thus, sediment fluxes induced by the near-bottom gravity current may occur not only during summer, but all through the year. The present study has revealed that a net transport of fine sediments is occurring out of the Upper Gulf as sporadic gravity current pulses (Lavín et al., 1998). Therefore, the gravity current can be expected to be the main cause of SPM flux during each neap tide, and hence to contribute significantly to net fluxes during summer. Furthermore, the salinity observed in Wagner Basin has been explained in terms of water mass formation occurring throughout the year, in the shallow areas. The dense, high salinity water mass flows downslope toward the basin as sporadic gravity current pulses (Lavín et al., 1998).

The bathymetry shows several narrow along-gulf submarine ridges up to 40 km long and 15 m high. The ridges off Baja California form 5 to 10 km wide channels having an asymmetric cross section with gentler slopes on the western side (Figure 1). By joining the head of the Upper Gulf with the Wagner Basin, these channels must play an important role in along- and across-gulf exchange processes, especially in those that take place near the bed. As suggested in Figure 6(b), sediments in suspension seem to be conveyed through the channels to the deeper waters of Wagner Basin. The transect made along the second channel off Baja California revealed a down-channel decrease of SPM concentration, in support of this idea. The horizontal intrusion of turbid water at 50 m depth indicates that part of the suspended sediment load reached the edge of the Wagner Basin, while another fraction seems to have settled along the current path. If sediments are settling mainly on the western side of the channel, an asymmetric cross-section would develop in the long term. This process could also explain the seaward growth of the shallow western shelf, in agreement with the suggestion by Carriquiry and Sánchez (1999) that this shelf is a slowly prograding feature.

One can speculate on an asymmetric sediment deposition based on rotation effects. The earth’s rotation constrains a gravity current to flow along the western boundary of a channel (in the Northern Hemisphere) if time and space scales are sufficiently large. A crude estimate can be made to test whether the conditions in the Upper Gulf would allow for this adjustment: The shallow head and western side of the Upper Gulf are the sources of heavier water which is 0.2 sigma-t units denser than the water found further offshore (Lavín et al., 1998). By taking a 10 m water depth, the internal Rossby radius of deformation gives a cross-flow scale of less than 4 km, which is about half the width of the channels and about one tenth their length. Since the time scale for geostrophic adjustment is ~1 day (2π/ƒ) and the gravity current event lasts at least 3 days, then this current could evolve into a flow along the western boundary of the channels. This type of buoyancy driven flow along a boundary has been observed in laboratory rotating tanks by Wadhams et al. (1979) and Griffiths and Hopfinger (1983), among others. Thus, a plausible explanation for the eastward progradation of the western boundary of the channels involves the settling of suspended load that the gravity current transports mainly along the western side of the wide along-gulf depressions. More observations at adequate scales are needed before a precise evaluation of this concept can be made.

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Figure 9. Profiles of time-averaged instantaneous along-gulf SPM fluxes measured at site W3 in August 1997: (a) averaged over six semidiurnal cycles in neap tides, (b) averaged over 14-7 days, and (c) averaged over six semidiurnal cycles in spring tides. Negative values indicate fluxes out of the Upper Gulf and the dashed lines indicate the 68% confidence interval.
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