9 Tidal Mixing in the Gulf of California

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9.1 INTRODUCTION

The Gulf of California is a 1500 km long narrow inlet on the west coast of Mexico. It exhibits a strong M_2 tidal response (Hendershott and Speranza, 1971) with vigorous currents, consequent frictional effects and a large dissipation of energy. The impact of this input of tidal energy ($\sim$5 GW) in stirring the water column and thus controlling its structure have been demonstrated for the relatively shallow regions of the northern gulf (Argote, Amador and Morales, 1985; Durazo, 1989) and the analogy with similar systems such as the Irish Sea have been clearly established.

What makes the Gulf of California particularly, and perhaps uniquely, interesting is the fact that its topographic configuration facilitates the operation of tidal stirring on the deep stratification of the ocean. The deep waters of the Pacific have free access into the southern gulf down to depths in excess of 2000 m, with Pacific intermediate and deep waters occupying most of the volume below 500 m south of the Guaymas Basin (Bray, 1988b). To the north of this basin the bottom depth decreases rapidly, with pronounced sills in the region of the midriff islands (Figure 9.1) separating the deep southern basin from shallow regions to the north. This shoaling, combined with the proximity to the M_2 amphidrome, is responsible for vigorous tidal flows, which are further enhanced by the presence of the islands which squeeze the tidal flow by severely reducing the channel cross-section. Direct observations of currents in the vicinity of the islands are few, but results from shipborne acoustic Doppler current profile and current meter moorings (Badan-Dangon, Hendershott and Lavin, 1991) near the sills indicate flows in excess of $1.5\,m\,s^{-1}$ at spring tides.

The impact of such strong tidal flows on the structure of the water column and the exchange flow over the sills has been little investigated, although efforts have been made to observe the operation of hydraulic control and the possible generation of hydraulic jumps and lee wave phenomena in the stratified flow over the sills (Badan-Dangon, 1989). There is good evidence from synthetic aperture radar imagery that propagating packets of internal waves do have their origin in the flow over the sills (Fu and Holt, 1984), and it has been proposed (e.g. Paden, 1990) that the mixing associated with these internal wave phenomena may operate at a much higher level of efficiency than stirring by bottom stresses, especially in the high amplitude region near the source.

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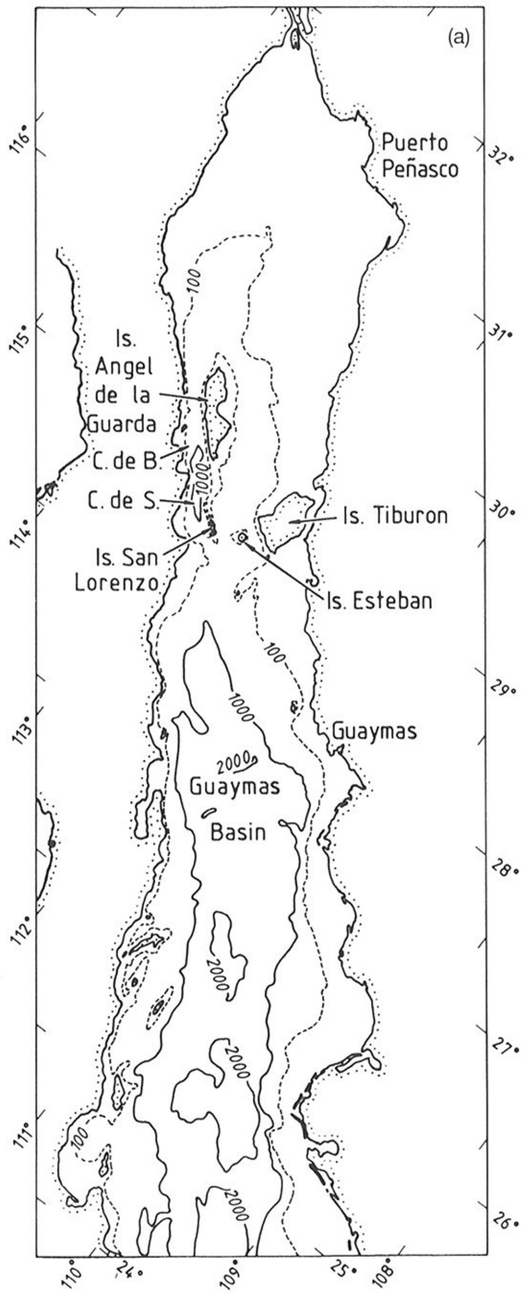


Figure 9.1 Study area in the Gulf of California. (a) Bathymetry in the region of the northern and cental Gulf of California

In an innovative study using EOF (Empirical Orthogonal Functions) techniques, Paden (1990) has analysed AVHRR (Advanced Very High Resolution Radiometer) thermal infrared data to demonstrate the influence of tidal stirring on SST (Sea Surface Temperature) distributions. This approach indicates the presence of a marked fortnightly modulation of surface temperature gradients, which is most pronounced in the vicinity of the midriff islands, where there is a significant lowering of surface temperatures with an associated frontal region.

In this present chapter, we report efforts to diagnose the influence of tidal mixing by observing this spring–neap tidal modulation in the structure of the whole water column. The nature and intensity of the tidal mixing processes are not only of considerable physical interest

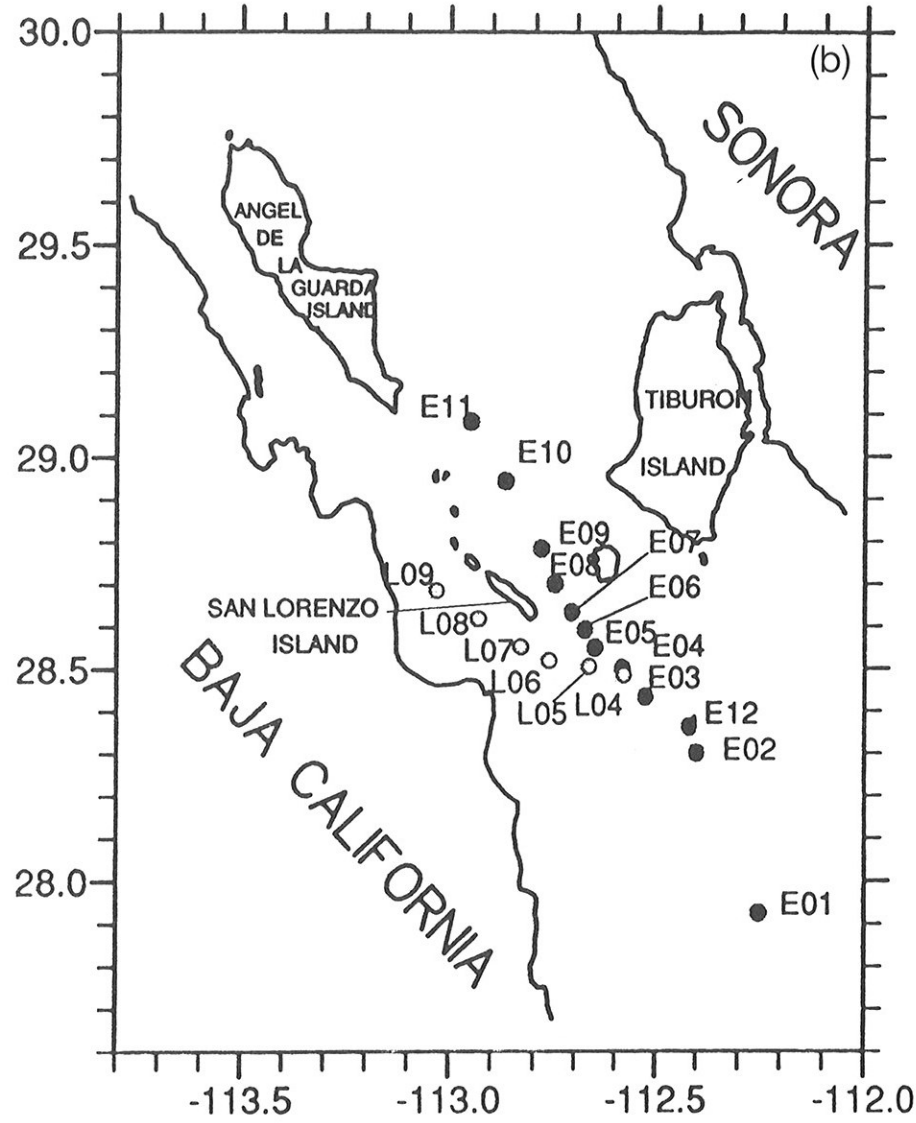


Figure 9.1 (*continued*) (b) Station positions showing line E (E1–E11) and line L (E1–L9)

in relation to the forcing of the circulation in the gulf, but they may also be the key to understanding the intensity and distribution of primary production, the unusually high levels of which are arguably supported by a supply of nutrients from deep waters.

9.2 SURVEYS

The observations were made from the USNS *De Steiguer* during the period 17–26 July 1990 as part of a collaborative programme to examine a range of physical and biological processes in the Gulf of California. The observational strategy was designed to determine the impact of tidal mixing directly, by contrasting surveys programmed to exploit the large spring–neap ratio in tidal range (Figure 9.2). As dissipation increases with u^3 (u = amplitude of the tidal velocity), the change in range means that tidal stirring is effectively switched off for a period around the neap tides. It is clear from the results of Paden and previous studies of the neap and spring cycle (Simpson and Bowers, 1981) that maximum and minimum stratification will occur, not at the neap and spring tides, but with a time lag of two to three days.

Two near-identical surveys of the key sections in the area of the midriff islands were therefore conducted over periods of 2.5 days at times as close to a three day lag from neap and spring tides as operational constraints allowed (observational periods shown in Figure 9.2). Both sections started in the deep Guaymas Basin; one section continued across the San Esteban sill (the line E in Figure 1b) and the second over the San Lorenzo sill into the Salsipuedes Channel (line L).

Measurements of the temperature and salinity profiles were made twice at each of these 18 stations using a NBIS mark III CTD (Conductivity Temperature and Depth profile). A rosette bottle sampling system attached to the CTD facilitated frequent calibration of the sensors and provided water samples for chemical analysis and estimates of plant pigment concentrations. Calibrations were consistent throughout the survey so we have confidence that all the presented data are accurate to ±0.01°C and ±0.01 psu (practical salinity units) in temperature and salinity, respectively. Satisfactory pairs of profiles were obtained for all stations except for the first profile at E1, which was lost due to initial problems with the CTD logging system. A flow-through system was also available for the continuous measurement of temperature, salinity and fluorescence of chlorophyll.

9.3 RESULTS

The temperature and salinity data for line L from the two surveys is presented in Figure 9.3 in the form of quasi-synoptic plots. Results for the sections L and E are closely similar except that line E does not have the deep water basin of the Salsipuedes Channel. The general picture is of a highly stable water column in deep water to the south-east, with indications of reduced stratification and lower surface temperatures in the sill region, which continues north-west of the sill into the deep Salsipuedes Channel. This reduction in stratification is noticeably more marked in the post-spring tide survey, with an increased spreading of the isotherms so that, for example, the total range of temperature over the centre of the sill decrease from 18 to 13°C after the post-spring tide survey.

To highlight the changes, we have subtracted the two temperature fields to yield the difference plot of Figure 9.4. This shows a substantial reduction in the temperature of a large volume of near-surface waters, particularly over and to the south-east of the sill. There is

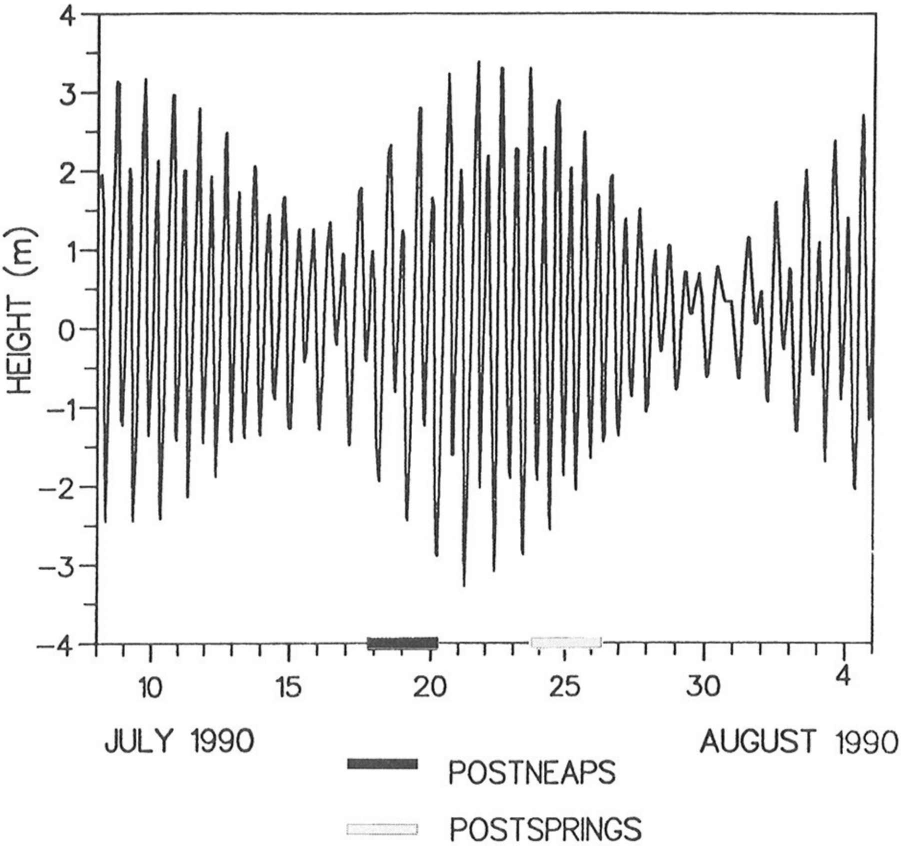


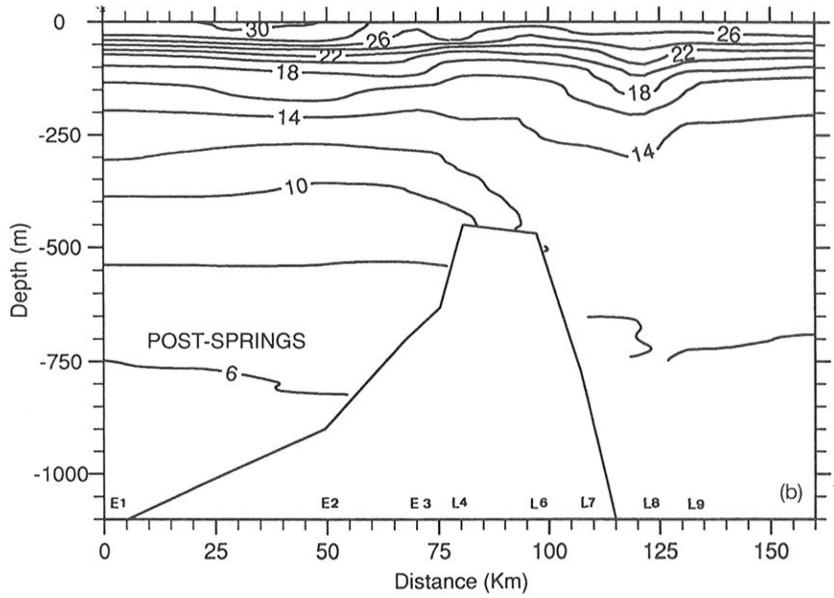
Figure 9.2 Tides at Peurto Peñasco (in the northern Gulf of California) during the observation period showing the times of the post-neap and post-spring tide surveys

a corresponding warming (by ~1°C) of the lower part of the water column over the sill and down to 500 m. On both sections E and L there is a large reduction in temperature variance (σ_T^2)

$$\sigma_T^2 = \overline{(T - \bar{T})^2}; \qquad \bar{T} = \frac{1}{h}\int_{-h}^{0} T \, dz \tag{9.1}$$

(where T = temperature, h = water depth, and z = vertical coordinate, positive upwards from the sea surface) at stations over and to the south-east of the sill, with the RMS temperature decreasing by as much as 1.4°C after the spring tide from a post-neap tide value of ~6.6°C (Figure 9.5a). To the north-west of the sill there is little change in the variance of temperature.

Perhaps the most striking contract between the surveys is in the surface temperatures, which were greatly modified on both sections. It is evident from Figure 9.4 that, on line L, the SST was reduced by up to 4°C. Similarly, on line E (Figure 9.6a), surface records show the post-spring tide temperature in the vicinity of E4 plunging to 25°C. At the same time it appears that the high surface gradient region south-east of the sill (a front) has intensified and moved further away from the sill. Parallel measurements of chlorophyll fluorescence



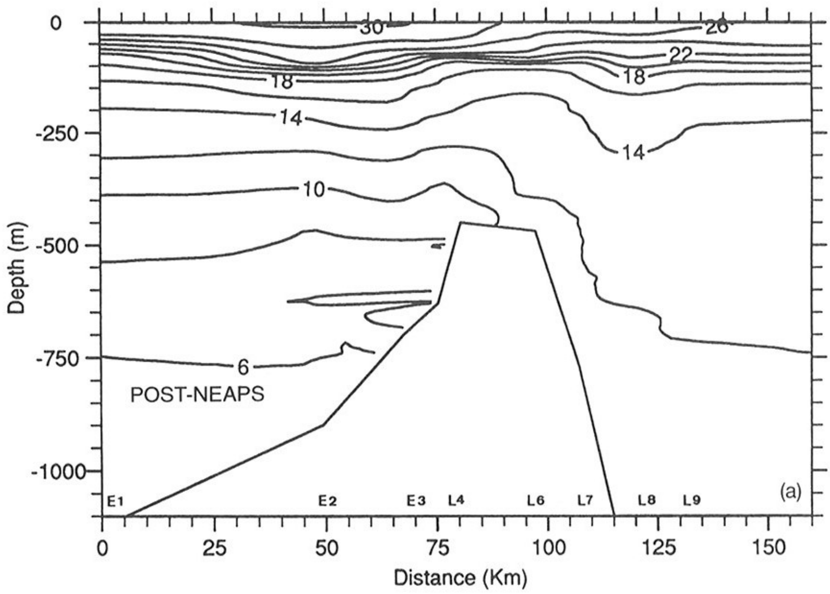


Figure 9.3 Post-neap and post-spring tide sections E1–L9. (a) Temperature variation post-neaps; (b) temperature variation post-springs

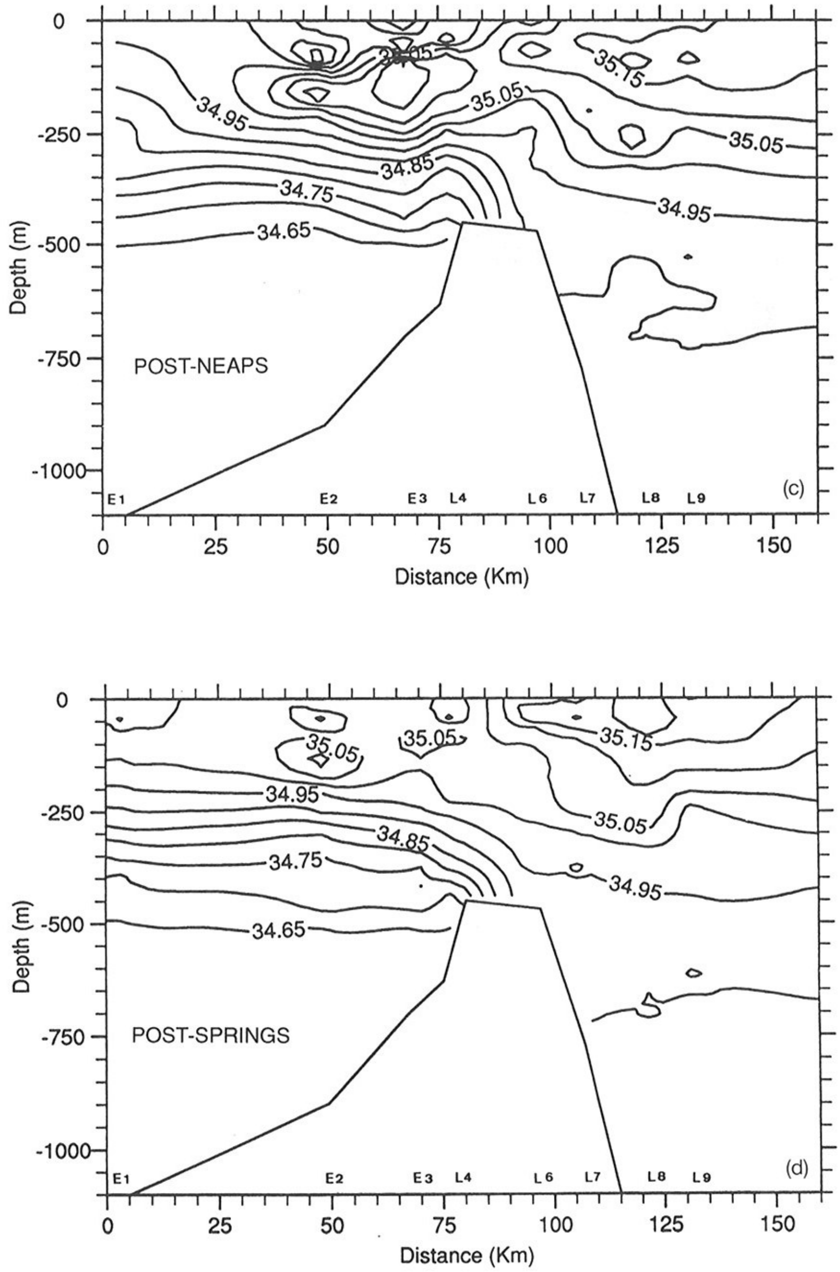


Figure 9.3 (*continued*) (c) salinity variation post-neaps; (d) temperature variation post-springs. Distance along both sections is measured north-westward from a datum at E1

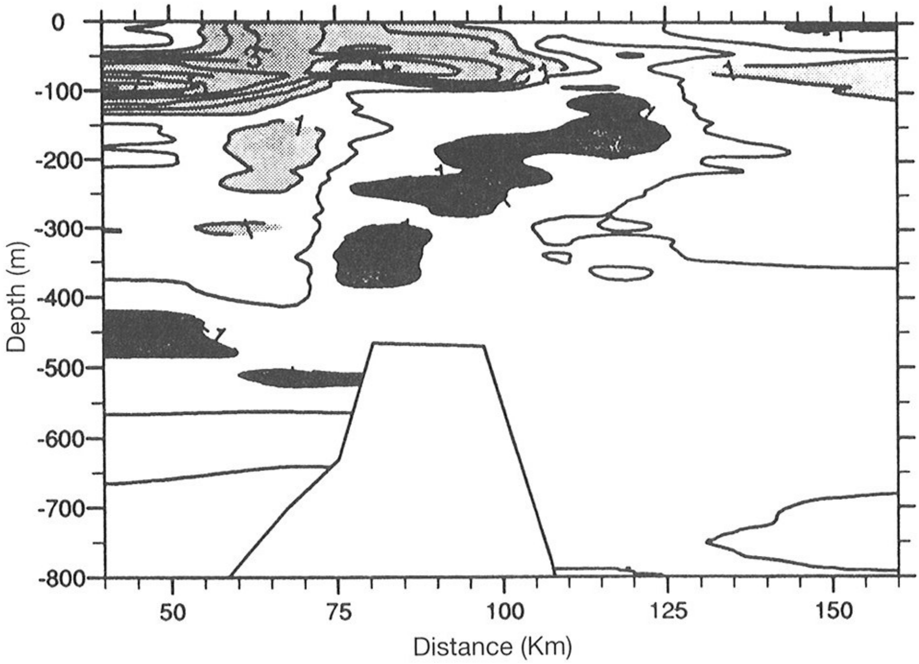


Figure 9.4 Plots of the temperature difference between post-spring and post-neap tide surveys. Black areas indicate warming of more than 1 °C; light shading corresponds to cooling of more than 1 °C. Distance is measured north-westward from E1

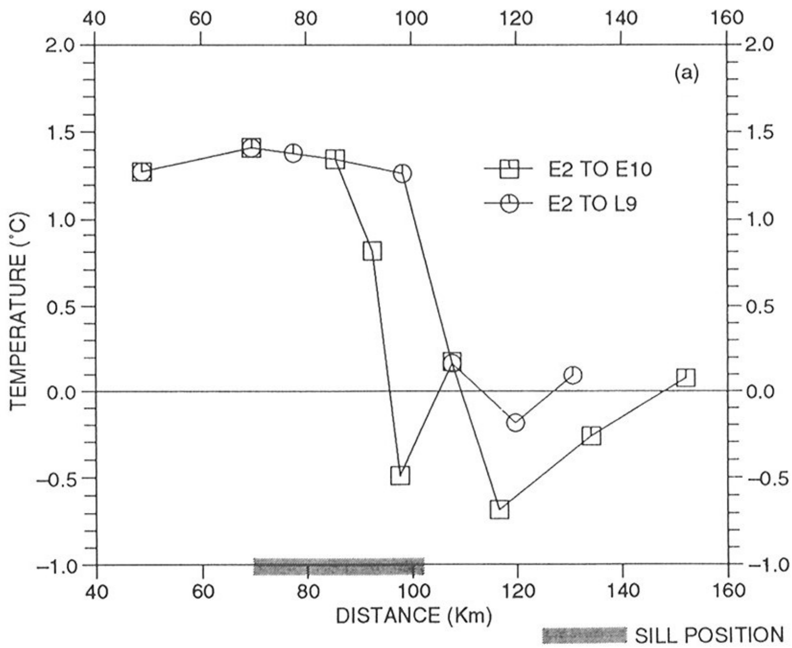
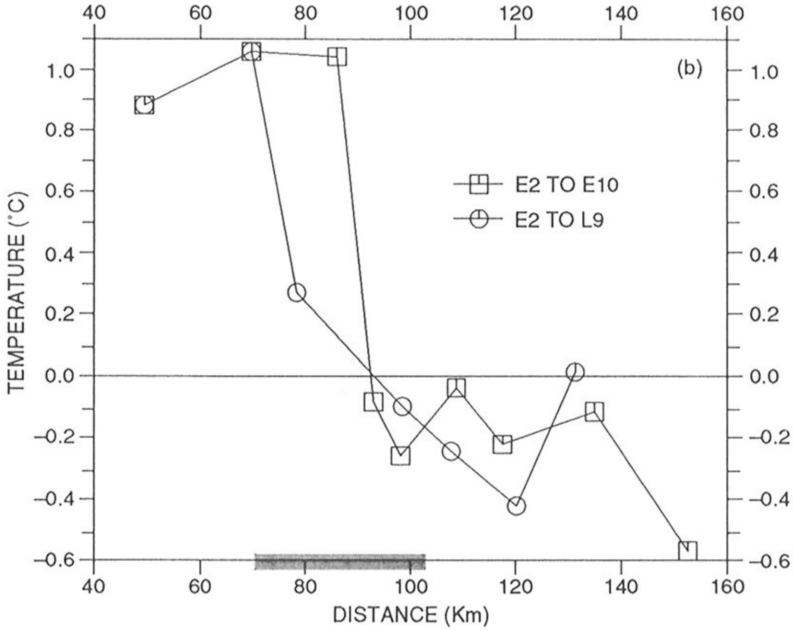


Figure 9.5 Summary of changes on the two sections E and L. (a) Station difference of temperature standard deviation



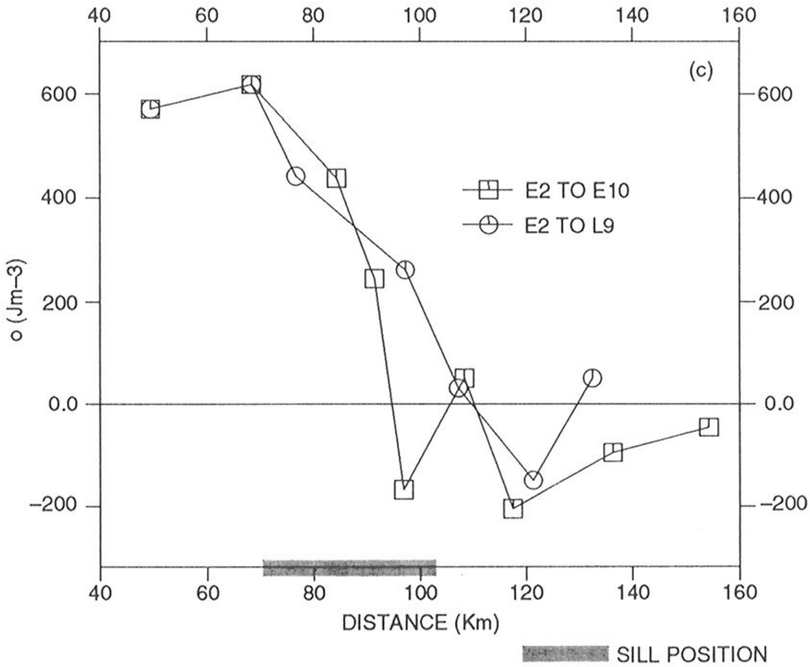


Figure 9.5 (*continued*) (b) Station difference of depth-mean temperatures. (c) Potential energy anomaly difference ϕ. In all cases, the difference is the neaps value minus the springs value

(Figure 9.6b) show a pronounced increase in the post-spring tide survey. The enhancement of fluorescence is by as much as a factor of three over an area coinciding with the region of strongest temperature reduction.

Pronounced changes are also apparent in the salinity fields. The strong salinity maximum extending south-westwards from the northern gulf at about 150 m in the post-neap tide sections (Figure 9.3c) is much lower in intensity after the spring tides (Figure 9.3d), especially in the vicinity of the sill. As with temperature, there is a marked reduction in the variance of salinity after spring tides at stations over and to the south-east of the sill. For example, at station E3 the standard deviation of salinity decreased from 0.205 to 0.160 psu between the two surveys, representing a 20% reduction in variability.

9.4 INTERPRETATION

The contrast in the surveys described here is strongly suggestive of the operation of vertical mixing brought about by intensified tidal stirring during the spring tide period. The reduced variability of water properties over the sills and to the south-east, with warming of the deep layers and cooling near the surface, point to the impact of large vertical fluxes driven by stirring. The magnitude of these fluxes is greatly in excess of the surface exchange, as is clear from the strong surface temperature reduction. This reinforcement of the SST minimum in the vicinity of the islands at a time of steady surface heating seems to be particularly clear and unambiguous evidence for the operation of enhanced vertical mixing. The area of reduced SST is consistent with that observed in infra-red data (Paden, 1990), and correlates closely with the observed strong increase in chlorophyll fluorescence. The introduction of nutrients to the surface layers by vertical mixing may be expected to stimulate production in the vicinity of the temperature minimum. Surface chlorophyll levels may also increase as a result of the upward mixing of plankton previously confined to lower layers in the photic zone.

Interpreting all the changes as being due to the effects of vertical mixing, we could use the changes in density [calculated by the UNESCO (1981) equation] distribution to calculate the change in potential energy anomaly (ϕ)

$$\phi = \frac{1}{h}\int_{-h}^{0} (\bar{\rho} - \rho)\, gz\, dz; \; \bar{\rho} = \frac{1}{h}\int_{-h}^{0} \rho\, dz \tag{9.2}$$

(where ρ = water density, and g = gravitational acceleration) due to the episode of spring tide mixing. A large decrease in ϕ of up to $500\,J\,m^{-3}$, apparent on both sections (Figure 9.5c) over and to the south-east of the sills, is a quantitative indication of the amount of work performed by stirring processes over the interval between the surveys. This large decrease in stability contrasts with indications of a slight increase in stratification on the north-western side of the sills in both basins.

If we ascribe these changes in the density field to mixing, then the apparent efficiency at stations in the region of greatest change of ϕ can be estimated from

$$\epsilon = \frac{h\Delta\phi}{k\rho\overline{u^3}\Delta t} \tag{9.3}$$

where $k = 0.0025$ is the bottom drag coefficient, u is the tidal stream speed and $\Delta\phi$ is the change in ϕ over a time interval Δt (Simpson, 1981). For $u \simeq 1$ m/s, we have $\epsilon \sim 0.1$, an estimate which is at least an order of magnitude greater than the values usually associated

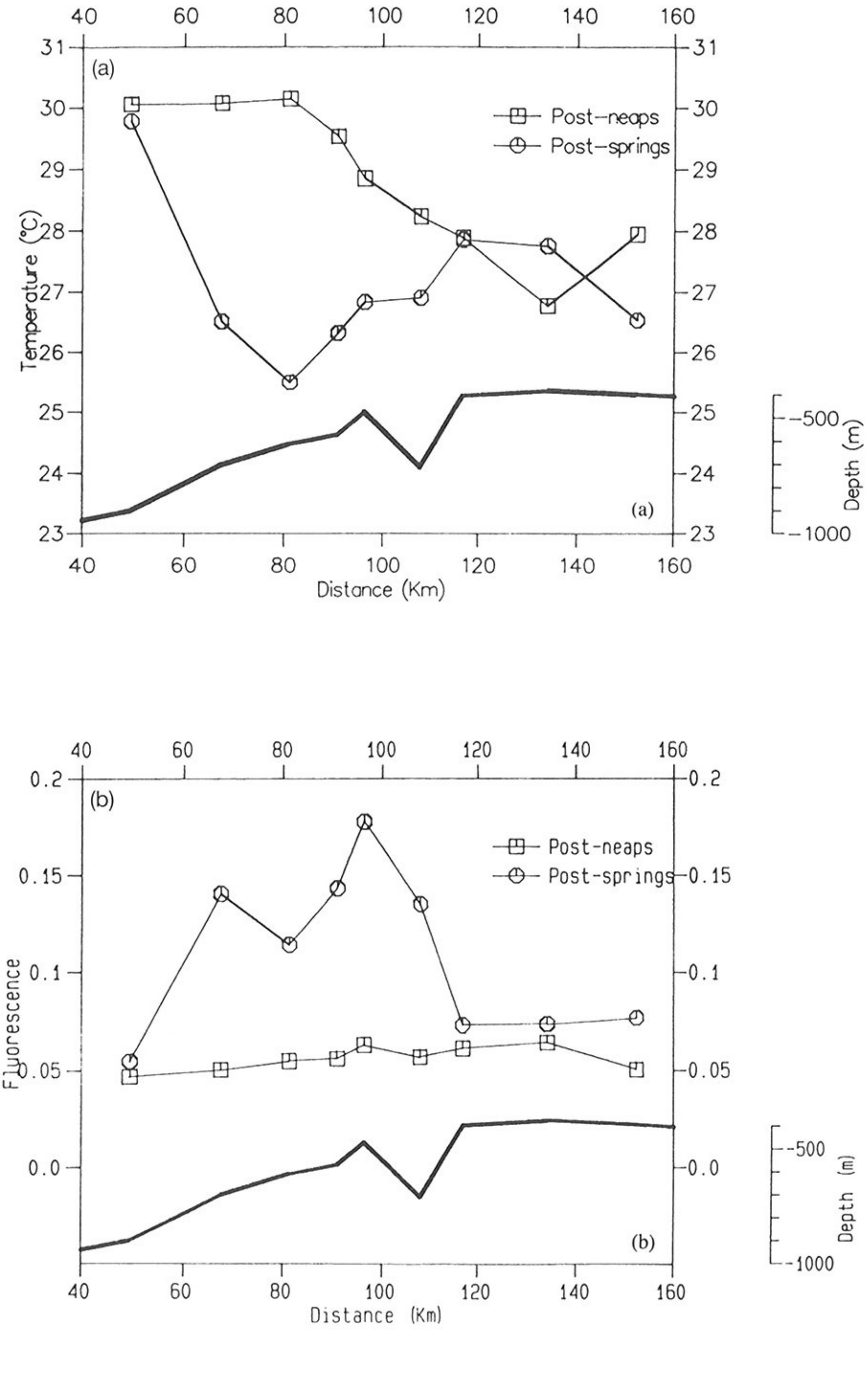


Figure 9.6 Surface measurements on line E. (a) Temperature; (b) chlorophyll fluorescence

with bottom stress stirring. The inference must be that another mixing mechanism is operating and the most likely candidate seems to be the action of hydraulic jumps and lee waves, as suggested by Badan-Dangon (1989).

This simple interpretation assumes that all the observed changes are due to vertical mixing. If this is true, then all the depth mean properties would be preserved. This is clearly not the case as there are significant changes in the column mean temperature (Figure 9.5b) at the stations in the south-east of the survey region where T increases by up to 1 °C, with indications of a slight temperature increase at the north-west end of the sections. The asymmetry of the net cooling of the near-surface waters suggests the operation of advection away from the sill to the south-east. Without such a flow it is difficult to account for strong cooling in deep water 50 km from the sills. The configuration of the subsurface salinity maximum (Figure 9.3c and 9.3d) also seems to support the idea of a near-surface flow away from the sill transporting the high salinity core, which originates in the northern gulf, to the south-east.

9.5 DISCUSSION AND CONCLUSIONS

Before attempting to draw conclusions from our results it is important to recognize the limitations of our strategy of contrasting post-neap and post-spring tide situations. The obvious attraction of this approach is that in the springs–neaps cycle, nature offers us something approaching a controlled experiment in which the modulation of tidal stirring should highlight its impact in terms of the mixing effects produced. To make an unambiguous interpretation of differences, however, we need to be able to assume that other processes remain sensibly steady during the interval between surveys. In the case of air–sea exchanges of heat, water and momentum, this is probably a reasonable assumption as meteorological conditions were consistent throughout the survey period and are characteristic of the summer regime in this part of the Gulf of California. The interpretation could, however, be complicated by advective effects in the form of large-scale internal adjustments of the structure within the gulf. The change in depth-mean temperature strongly suggests that some movement of this kind has occurred. Whether this is simply reactive to the intensified mixing, or is due to external forcing, is not clear from the present observations.

A further limitation lies in the fact that the surveys cannot be made in a truly synoptic manner, so that corresponding station surveys are generally not observed at the same phase of the tide. This means that there may be differences between profiles arising from horizontal displacements or from the effects of the internal tide. The former is probably not important in the present context, where horizontal differences on the scale of the tidal excursion are mostly small. A comparison of profile pairs, taken at well matched and opposing tidal phases, does not suggest any systematic influence of the internal tide. Its influence, and that of other internal waves, although they are probably small, cannot be ruled out without further observations.

Notwithstanding these caveats, the strategy of contrasting post-neap and post-spring tide surveys has yielded direct evidence of the operation of tidal mixing and indications of its role in this region. The conceptual picture that emerges (Figure 9.7) is of vigorous stirring in the vicinity of the sill promoting the mixing of the saline northern gulf water with underlying waters, including a component of the cold, low salinity Pacific intermediate water which is present just below the sill depth (Bray, 1988b). A slow northward flow of this intermediate water is needed to supply demand by sill mixing and a component of it will be carried over the sill in the flow to compensate for the outflow of water from the northern Gulf of California.

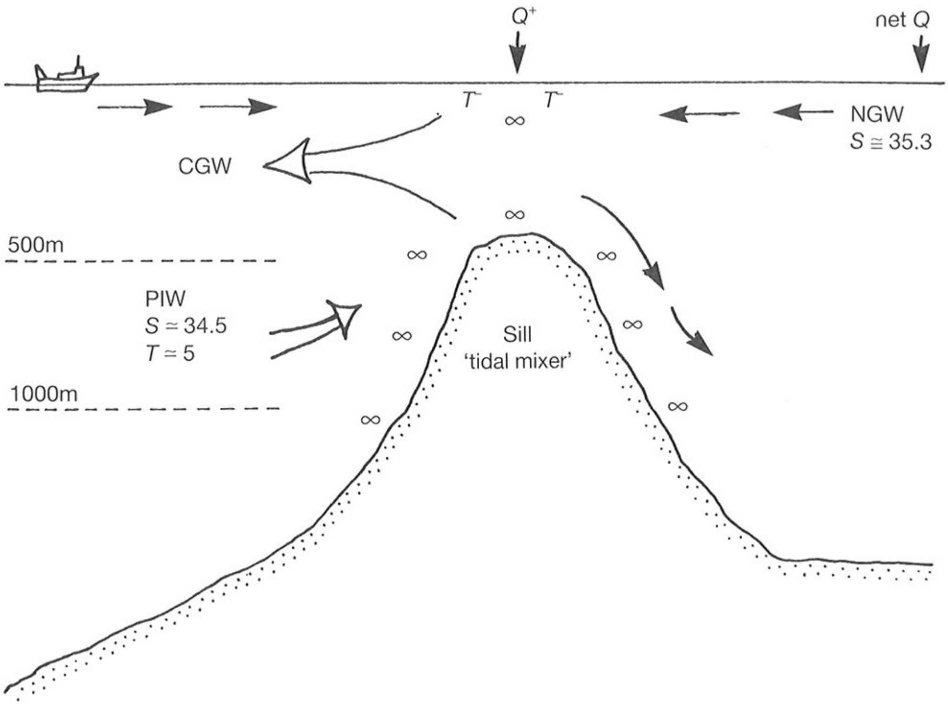


Figure 9.7 Schematic diagram of mixing and circulation in the Gulf of California. Strong stirring over the sills acts to mix Pacific intermediate water (PIW) with northern gulf water (NGW) to produce central gulf water (CGW)

Some surface water is also recruited from the south-east into the mixing process as in the three-layer circulation observed in laboratory mixing experiments (Hachey, 1934).

It has been shown (e.g. Lavin and Organista, 1988) that, although there is strong net evaporation in the northern gulf of about 1 m/year, the effect of this water loss on density is less than that of the net heat gain, so that the gulf system tends to circulate as a 'thermal estuary', with lighter water flowing out near the surface. Tidal mixing around the islands modifies this pattern and is responsible for the production of the central gulf water, which flows south-eastwards 100 m or more below the surface.

This combination of a thermal 'estuarine' circulation with circulation induced by deep mixing at the sills is consistent with the previous results of Bray (1988a) based on water mass analysis and inferences derived from the heat budget of the northern gulf (Lavin and Organista, 1988). Our results, moreover, strongly suggest that we are dealing with a system which experiences marked fortnightly modulation due to spring–neap tide variations in the activity of the sill mixing engine. We expect this to lead to corresponding pulsations in the circulation and structure over a wide area and there seems to be a good case for a campaign of observations by moored instruments on the south-east side of the sills to test this notion.

By lowering the surface temperature in the island region and also in the shallower regions further north, tidal stirring is acting to increase the input of heat to the gulf and at the same time reduce evaporation. This may contribute significantly to the predominant influence of heat on buoyancy which distinguishes the gulf from other evaporative basins such as the Mediterranean and the Red Sea, which have an outflow of denser water.

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