TEMPORAL AND SPATIAL VARIABILITY OF TEMPERATURE IN TWO COASTAL LAGOONS

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ABSTRACT

With *in situ* continuous recording thermographs, year-long surface-temperature time series were generated at four points in San Quintin Bay and at three points in Estero de Punta Banda. During spring and summer, upwelling events were clearly detected at the mouth of San Quintin Bay. Upwelled waters propagate throughout San Quintin Bay by tidal currents. In both coastal lagoons, temperature increases, in general, from the mouth to the interiors, except during some winter periods when the gradient reverses. The time series have in general a semidiurnal behavior, with high temperatures corresponding with low tides and vice versa. Water residence time in the lagoons is minimal with spring tides and strong currents parallel to the coast in the adjacent oceanic area.

The Estero de Punta Banda waters are warmer than those of San Quintin Bay during summer; during winter they have similar temperatures. Time series from Estero de Punta Banda indicate that upwelling water from the area off Todos Santos Bay is being carried by coastal currents to the estero. At the mouth of San Quintin Bay, minimum temperature for the year was registered during summer and was clearly associated with an upwelling event. In both lagoons, maximum temperatures were registered at the end of September.

RESUMEN

Termógrafos colocados en cuatro lugares en Bahía San Quintín y en tres en el Estero de Punta Banda han proporcionado durante un año completo, series continuas de la temperatura del agua de superficie. En la Bahía San Quintín se aprecia claramente que en primavera y verano se producen una serie de fenómenos de surgencia, y las corrientes de marea propagan estas aguas de surgencia por todo el interior de la bahía. En estas bahias la temperatura aumenta en general, de la boca hacia el interior, excepto durante algunos períodos en invierno, cuando el gradiente se invierte. Se observa que el ciclo de la temperatura es en general semidiurno, de acuerdo con las mareas, correspondiendo temperaturas altas con mareas bajas y viceversa. La permanencia del agua en las bahías es de corta duración en períodos de mareas vivas y de corrientes fuertes paralelas a la costa en la zona oceánica adyacente. En verano, las aguas del Estero de Punta Banda son más cálidas que las de San Quintín, y en invierno ambas zonas presentan una temperatura similar. Los termogramas indican que aguas de surgencia de la zona fuera de la Bahía Todos los Santos son arrastradas hacia el estero por las corrientes costeras. En la boca de la Bahía San Quintín, la temperatura mínima se observó en verano y parecía evidentemente asociada con fenómenos de surgencia. En ambas bahías las temperaturas máximas se registraron hacia finales de septiembre.

INTRODUCTION

Since the beginning of the 1970s, there has been an increasing interest in developing aquaculture in coastal lagoons of Baja California. The main interest has been concentrated on oyster culture. Very successful experiments with *Crassostrea gigas,* the Japanese oyster, and *Ostrea edulis,* the European oyster, have been carried out in most of the coastal lagoons of the peninsula's Pacific coast (Islas-Olivares 1975; Islas-Olivares, et al. 1978). Most of the coastal lagoons are still very much in their natural state in Baja California, though very few, if any, remain unaltered by human activities in southern California. As development goes on from the two ends of the Baja California peninsula, human activities will begin to make an impact upon the ecology of the lagoons. Basic ecological studies can give the background against which future situations may be compared. Also, studies can be designed to gain useful information that might be applied to make rational decisions as mariculture is developed. For example, it is important to know the spatial and temporal ranges of such important variables as temperature and salinity, the relative food availability in different lagoons, the mechanisms responsible for greater or lesser fertility of some lagoons with respect to others and with respect to the open ocean, and the water exchange rate between the lagoons and the adjacent ocean (Lara-Lara et al. 1980).

The objectives of the work reported herein were to describe the temperature variability throughout a year

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in San Quintin Bay and Estero de Punta Banda—two coastal lagoons of northwestern Baja California; to describe associations between seawater temperature changes and oceanic and atmospheric processes in these lagoons; to study the penetration of upwelled waters into these two coastal lagoons; and to qualitatively study the variation of residence times in both lagoons. To do this, we generated one-year-long surface-water temperature time series at various locations in these lagoons.

San Quintin Bay is located between 30°24'-30°30'N, and 115°57'-116°01'W on the Pacific coast of Baja California (Figure 1a). The bay is 300 km south of the Mexico-U.S. border. It is Y-shaped, with a single permanent entrance at the foot of the Y. It has a general north-south orientation, and an area of about 41.6 km^2. The lagoon is extremely shallow, and at lower low tide some portions of the bottom are exposed. There are narrow channels that rarely exceed 8 m in depth.

Estero de Punta Banda is located between 31°42'-31°47'N, and 116°37'-116°40'W, on the Pacific coast of Baja California, at the southeastern extreme of Todos Santos Bay, 13 km south from Ensenada (Figure 1b). It is L-shaped, with a single permanent entrance at the end of the longest arm. There is one channel along the main arm. Depth in this channel decreases nonuniformly from the lagoon's mouth towards the interior, from 8 to 1 m. The estero has an area of about 11.6 km^2.

San Quintin Bay and Estero de Punta Banda have water densities equal or almost equal to those of the open sea, and water movement is mostly caused by tides and wind. Tidal ranges are about 2.5 m during spring tides. There are no streams flowing into these lagoons: they are evaporation basins. However, with winter rains, sometimes there are significant inflows of fresh water. This happened with the high precipitation of the winters of 1978 through 1980.

METHODS

Identifying and interpreting the characteristic frequencies or periodicities of the ecosystems' variables should be one of the central goals of the discipline of ecology (Platt and Denman 1975). Since the work of Acosta-Ruiz and Alvarez-Borrego (1974), time series have been generated to study the variability of water properties in these two coastal lagoons. These time

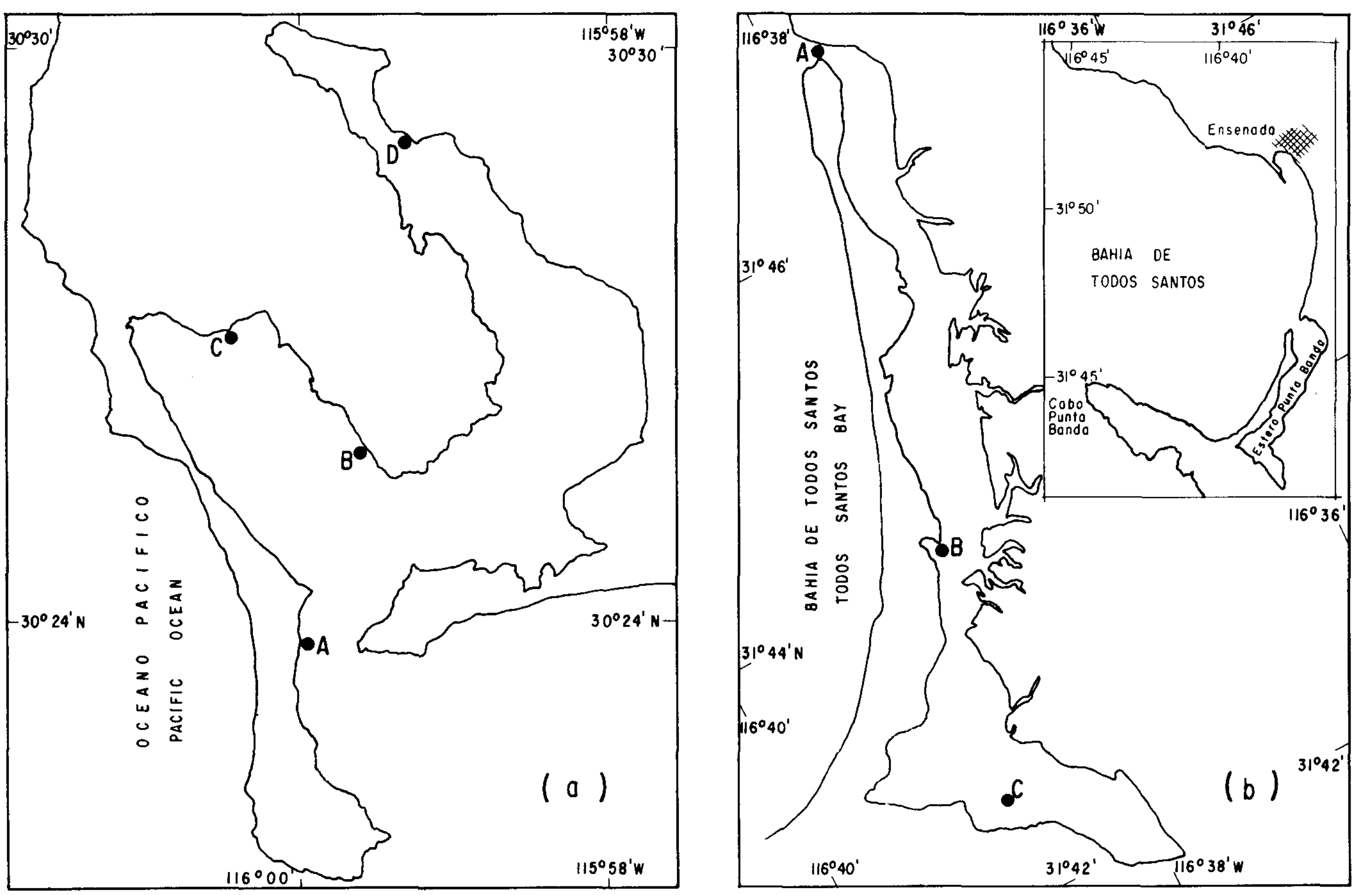


Figure 1. Location of sampling points in San Quintin Bay *(a)* and Estero de Punta Banda *(b)*.

series had been generally too short, of the order of tens of hours. Lara-Lara, Alvarez-Borrego, and Small (1980) generated 17-day time series, with sampling every hour. Ideally, time series should be at least one year long, to roughly describe seasonal changes. Usually this is not possible, because an enormous amount of samples has to be collected and analyzed manually. With relatively cheap and reliable thermographs able to automatically generate time series, it is possible to study the natural phenomena that cause temperature changes.

Temperature was measured *in situ* with Peabody Ryan thermographs, which produce an analog record on paper. The thermographs were situated at four locations in San Quintin Bay, and at three in Estero de Punta Banda (Figure 1a and b). They were located deep enough to remain under water even at the lowest spring tides. They can register without attention for as long as three months. Precision for temperature is ±0.5°C, and the maximum error in time was half an hour for a three-month period. Data were digitized manually, with readings every hour, by two independent readers. Data were then input to a Prime-400 computer.

In order to study the relationship between the factors that affect temperature in different locations, a lagged cross-correlation technique was applied to the temperature time series, and to temperature and tide series, through application of a standard algorithm (Jenkins and Watts 1968). Spectral analysis of the temperature time series was also performed. Spectral analysis of a series of data may be regarded as an analysis of variance in which the total variance of a property fluctuation is partitioned into contributions arising from processes with different characteristic time scales (Platt and Denman 1975). The spectral estimate presented here was computed with a fast Fourier transform algorithm (Jenkins and Watts 1968).

We also obtained estimates of coherence and phase spectra of the different temperature series, and between them and tide series. Coherence gives an estimate of the relationship between components of one series with those of another, and the phase spectrum gives the angular time lapse between two components of the same frequency. However, we consider that these estimations did not provide significant additional information. This type of estimate would have been more informative if we had time series of air temperature, solar irradiance, tidal currents, winds, etc.

RESULTS

San Quintin Bay

The temperature time series for San Quintin Bay were located at four points, with point A at the mouth of the bay and point D nearest the head of the bay. The time series for each point was as follows:

Point A May 17, 1979, through May 13, 1980
B July 6, 1979, through May 13, 1980
C May 17, 1979, through May 13, 1980
D May 17, 1979, through May 13, 1980

Upwelling occurs in the open ocean immediately off the mouth of the bay during spring and summer (Dawson 1951). Bakun (1973) calculated upwelling indices for the west coast of North America, and these calculations show favorable upwelling conditions throughout the year for latitudes 27°N to 33°N, with the maximum upwelling indices from March to June. Upwelling intensification events are clearly shown from the end of spring through the end of summer at point A, the mouth of the bay. These events are also evident at the other data stations because of tidal currents, but are attenuated. Upwelling intensification periods were from a week to ten days.

The temperature minimum, maximum, and yearly mean are shown below:

Location	Minimum		Maximum		Yearly
	Date	°C	Date	°C	mean (°C)
A	12 July	11.0	19 Sept.	21.5	15.2
B	22 Nov.	12.9	20 Sept.	23.5	16.7
C	24 Dec.	13.3	20 Sept.	25.3	18.4
D	23 Nov.	13.0	19 Sept.	27.3	19.0

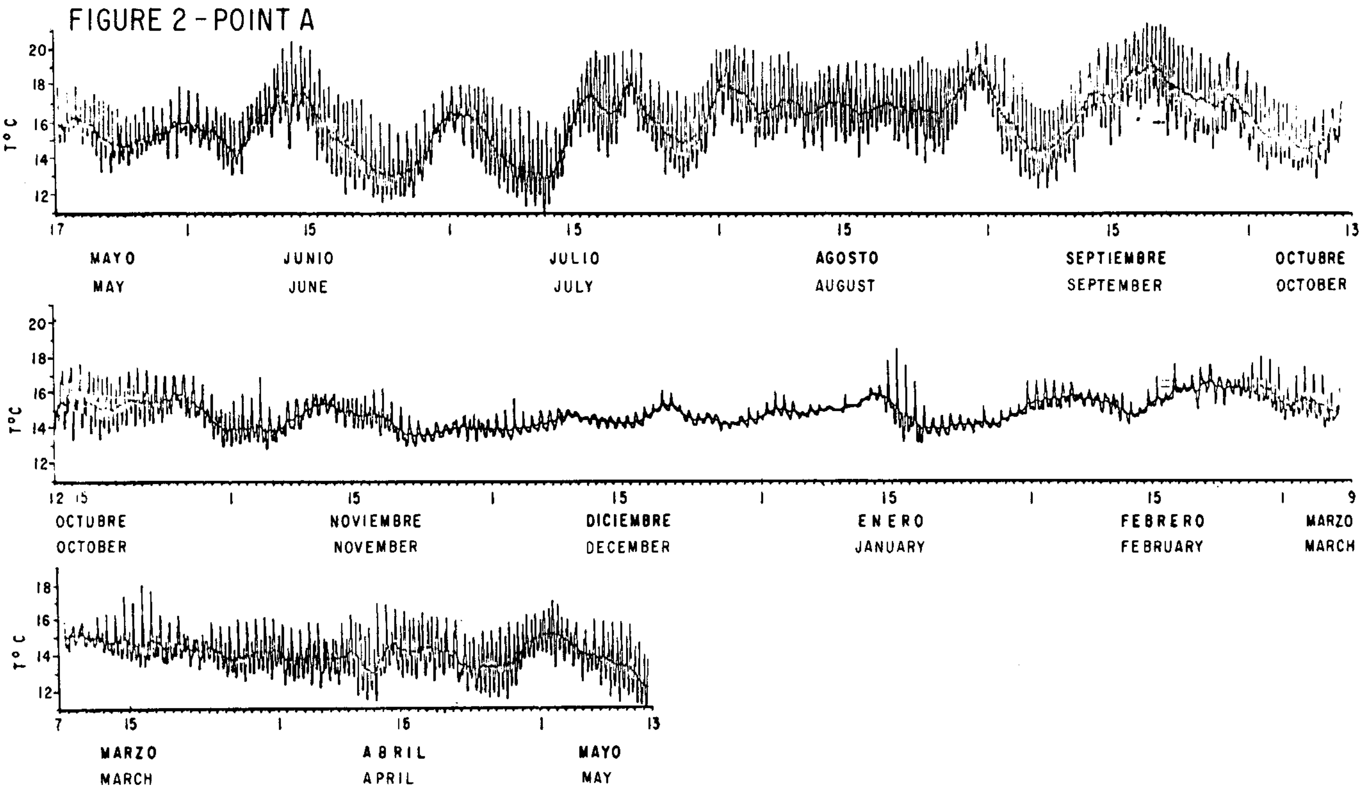
All stations show a semidiurnal behavior in relationship to the tides, with the highest amplitudes at point A. Flash floods at point B caused the thermograph to be buried in sediments from January 8-27. This burial acted as a physical filter for the high-frequency temperature changes. Spring and neap tides are clearly evident at each station.

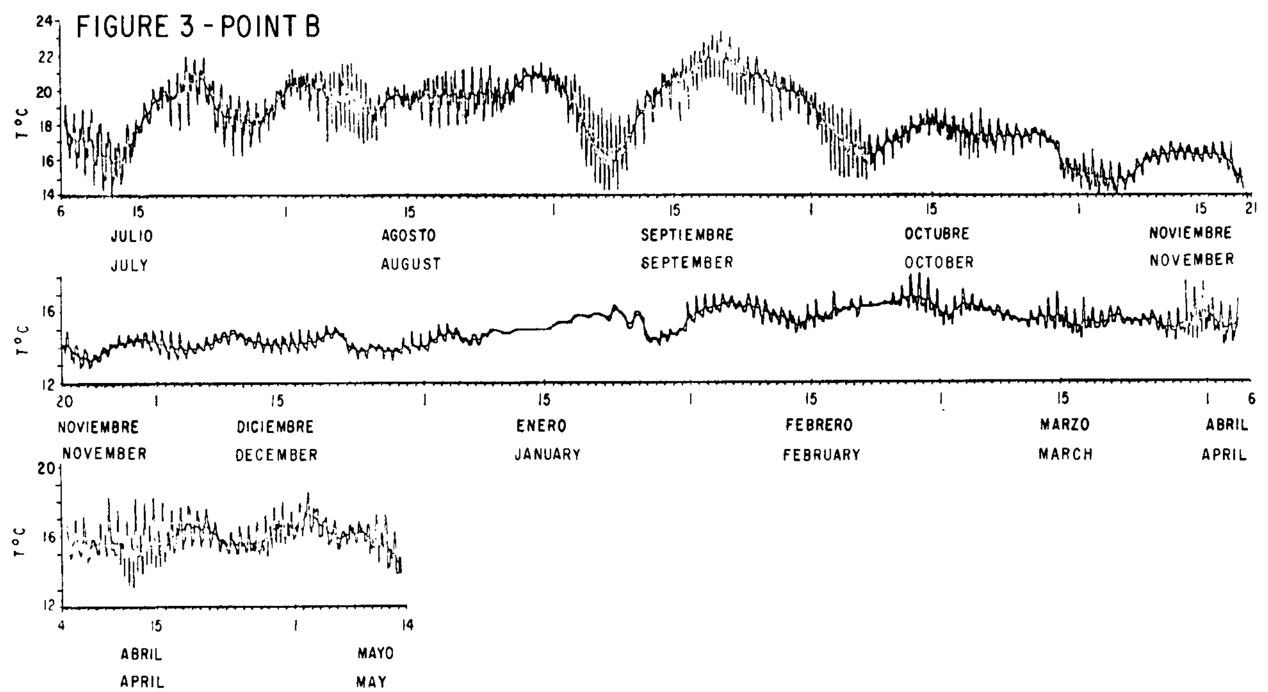
During spring, summer, and the beginning of fall, the short-period temperature variability was smaller at points C and D than at points A and B (Figures 2-5). However, towards the end of fall and during winter, there was a greater low-frequency variability (periods of one to two weeks) in points C and D than in A and B. This was possibly due to changes of atmospheric temperature, solar irradiance, and winds during the rainy winter season. These atmospheric changes have more effect on the waters at points C and D because of their shallow depth.

Estero de Punta Banda

The temperature time series for Estero de Punta Banda were located at three points, with point A at the mouth of the estero and point C near its head. The time series for each point was as follows:

Point A May 29, 1979, through Dec. 12, 1979

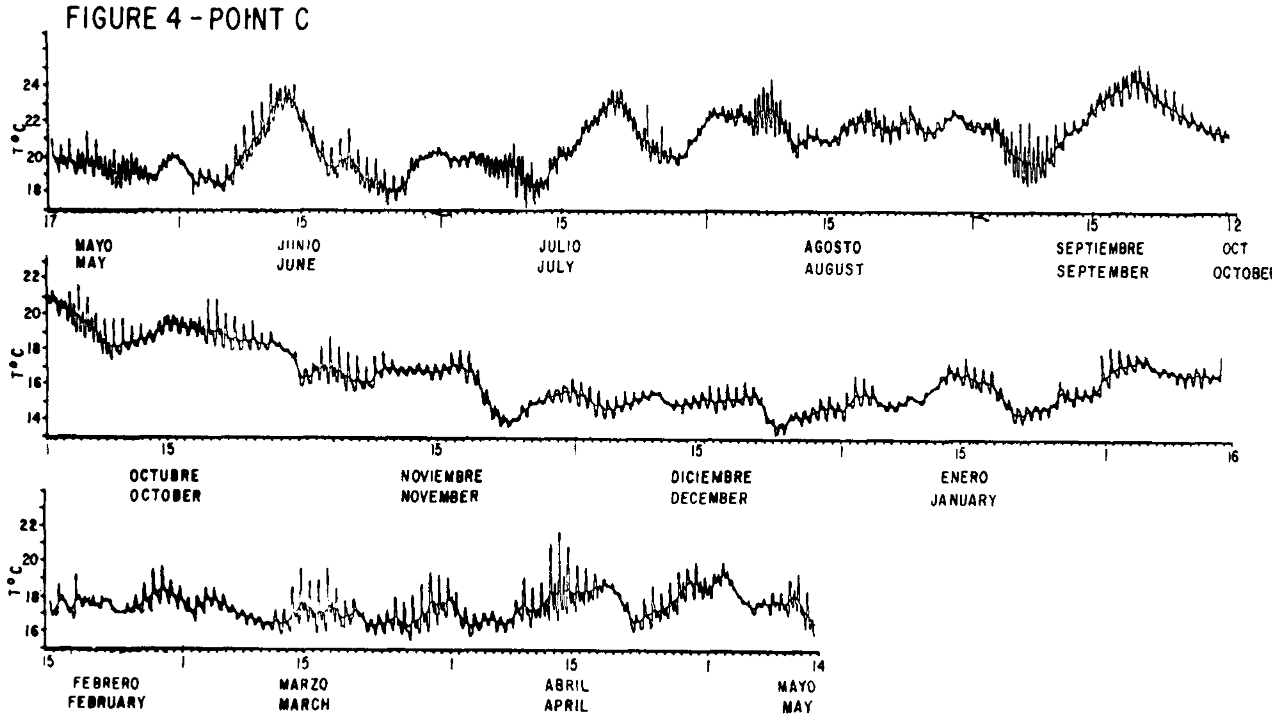


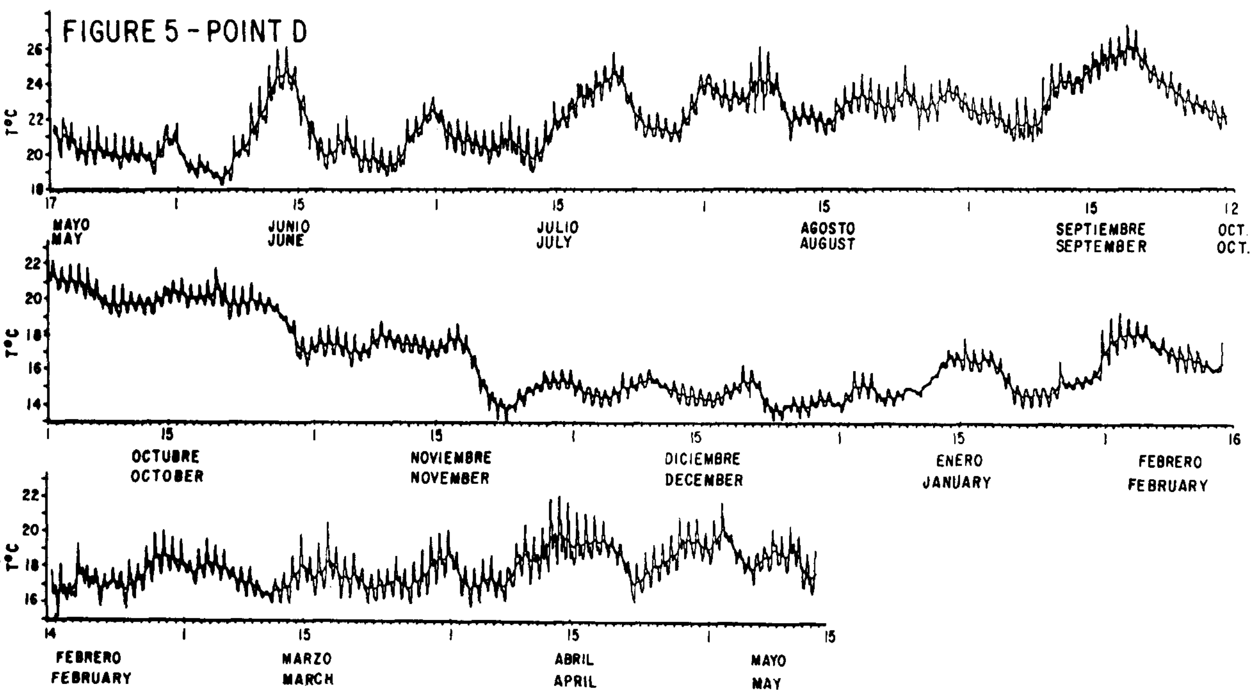


Figures 2 and 3. Thermograms from points A and B of San Quintin Bay. Marks on the horizontal axis are midnights. Numbers are dates.

Apr. 16, 1980, through May 20, 1980
B May 29, 1979, through Oct. 1, 1979
Oct. 16, 1979, through Oct. 28, 1979
Dec. 14, 1979, through Mar. 6, 1980
C May 29, 1979, through May 20, 1980

The interruption at point A was caused by the loss of the thermograph during strong winter rains. At point B the thermograph was inoperative during several periods; thus it was necessary to make three separate time series.





Figures 4 and 5. Thermograms from points C and D of San Quintin Bay. Marks on the horizontal axis are midnights. Numbers are dates.

The temperature minimum, maximum, and yearly mean are shown below:

Location	Minimum		Maximum		Yearly
	Date	°C	Date	°C	mean (°C)
A	8 Dec.	12.7	23 Sept.	25.3	19.2
B	11 Feb.	14.1	16 Sept.	26.4	19.8
C	21 Nov.	12.1	9 Aug.	28.0	19.7
			16 Aug.	28.0	
			19 Sept.	28.0	

An almost constant temperature was recorded during nine days at the beginning of the series at all three stations. This was possibly due to the combination of neap tides and a horizontal surface temperature gradient of almost zero. Between May 29 and June 2, temperature in the estero showed a horizontal gradient, with values increasing from the mouth (18-19°C) towards the extreme (20-21°C), but the following four days all the estero showed the same temperature of 19°C, which is exceptional.

In the estero, the sequence of spring and neap tides is also clearly shown in the diurnal temperature ranges at all three sampling points (Figures 6-8). Temperature semidiurnal variability in the estero was in general greater during spring, summer, and beginning of fall than during the end of fall and winter, with rare exceptions such as that registered at the end of May and beginning of June 1979. This greater semidiurnal variability is due to greater horizontal temperature gradients during spring, summer, and beginning of fall than during the rest of the year.

At the end of spring and during summer, the temperature time series from point B and the estero's entrance had a similar behavior. Some colleagues have indicated (pers. comm.) that a possible explanation for the low-frequency temperature fluctuations is that they are due to the sequence of spring and neap tides. With spring tides, greater turbulence and mixing would produce lower surface temperatures, and vice versa with neap tides. However, in the series from point B, it is interesting to notice that greater diurnal temperature ranges, corresponding to spring tides, were presented with both valleys and crests of the temperature low-frequency fluctuations. This can be seen in the other time series also, but it is particularly clear in this one.

From January 8 through 13, another case of very low diurnal variability was evident. This was also shown in the series from point C (Figures 7 and 8), and it was possibly due to a horizontal temperature gradient near zero in the estero. The difference from the May-June case, mentioned above, was that in January there was a gradual temperature increase throughout the estero. This was possibly due to more intense solar radiation, with a sequence of clear days, and with relatively high water residence time. During several days after January 13, spring tides increased the diurnal temperature ranges, but the general warming tendency continued until January 16 at both points, B and C (Figures 7 and 8).

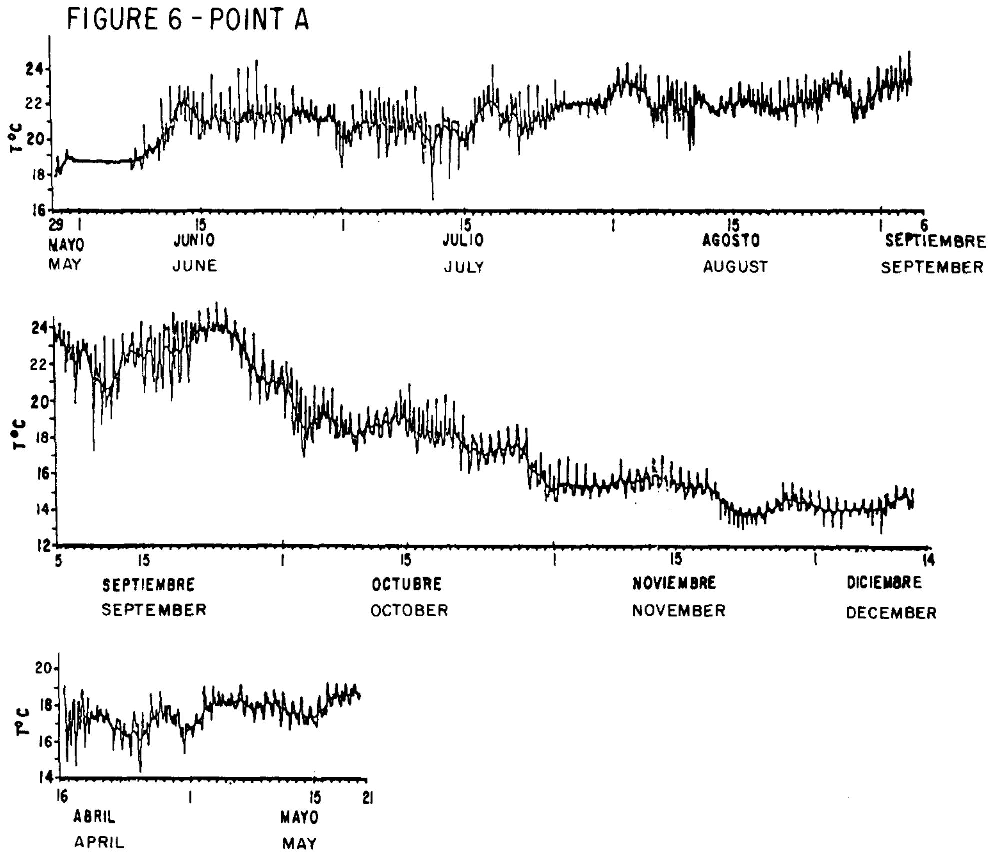
In general, the temperature behavior at point C was very similar to that at point B (Figures 7 and 8), except during the second half of winter, when there was a greater variability. At both sampling points there was a clear low-frequency fluctuation (with a period of about two weeks) towards the end of fall and during winter. This was possibly due to the incidence of atmospheric events. Air temperature and solar radiation changes have a strong effect on the estero's shallow waters. Again, it is interesting to notice that at point C spring tides coincided sometimes with higher water temperatures.

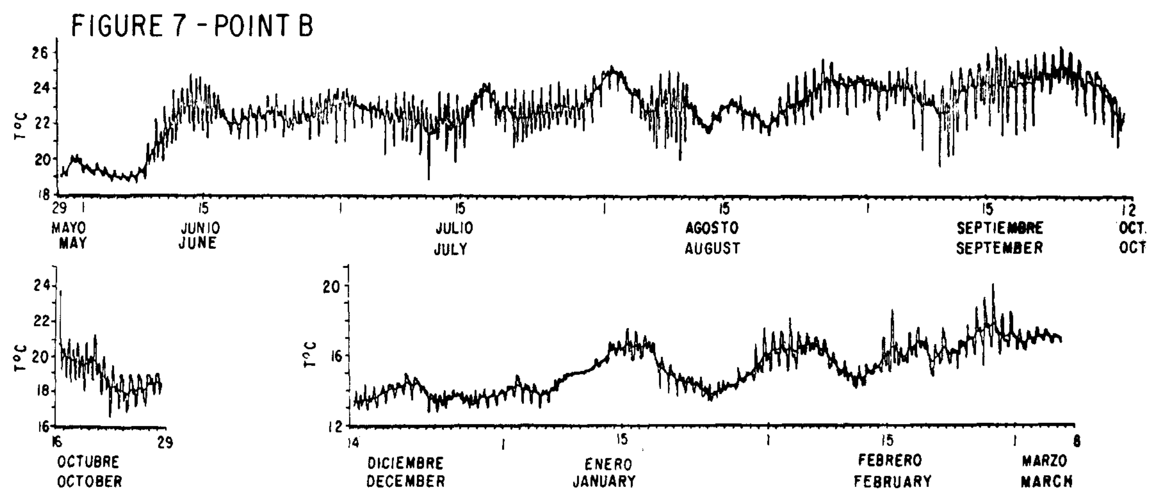
During summer, temperature was significantly greater at the estero's entrance than at the mouth of San Quintin Bay. During winter these two places had similar temperatures (Figures 2 and 6).

During spring and summer, low-frequency temperature fluctuations in Estero de Punta Banda are similar to those of San Quintin Bay, especially with regard to low temperatures between July 11 and 15, between September 7 and 12, and around April 25 (Figures 2 and 6). The strongest upwelling event registered at the mouth of San Quintin Bay had a minimum temperature on July 12. On that same date, the summer's minimum temperature at the estero's entrance was registered. This indicates that upwelled water from outside Todos Santos Bay was being carried to the lagoon by coastal currents.

Cross correlation and spectral analysis of time series

Table 1 shows the maximum cross-correlation coefficients and the lags in hours. These are for the different temperature time series, and between them and the tide series. Summer and winter data are separated to deal with the upwelling season separately. The highest cross-correlation coefficients were those for thermograms from points C and D of San Quintin Bay (0.91 for summer and 9.95 for winter, with zero lag). This indicates the similarity of physical phenomena acting on both extremes of the bay. Cross-correlation coefficients for the San Quintin mouth series with those from points C and D were lower for summer than for winter, because of upwelling events during summer. Cross-correlations between the mouth's and the interior's temperature series of Estero de Punta Banda were higher than those for San Quintin Bay. This was due to the smaller influence of oceanic events on the entrance to the estero, because it is inside Todos Santos Bay. The negative lag of the cross-correlation between points A and D of San Quintin Bay in summer (−12 hr) may be due to the occurrence of spring tides before an upwelling event, which happened on several occasions (cross-correlation coefficients were significantly lower for lags between −11 and +12, at the 95% confidence limit). For example, at the beginning of July, temperature started to decrease in point D (Figure 5) because of the effect of spring tides currents that were carrying colder water from the area near the bay's entrance to point D. At point A, the temperature started to decrease on July 5 because of an upwelling event (Figure 2).





Figures 6 and 7. Thermograms from points A and B of Estero de Punta Banda. Marks on the horizontal axis are midnights. Numbers are dates.

Cross-correlation coefficients were low for temperature and tide series, both for San Quintin Bay and Estero de Punta Banda. Oceanic and atmospheric events, such as upwelling, and seasonal changes of air temperature and solar irradiance were responsible for most of the water temperature variance. This is indicated by the high low-frequency component of the variance spectrum (Figure 9).

We illustrate only one variance spectrum because differences between spectra from the seven sampling points are not statistically significant (Figure 9). Spectral analysis shows that temperature variance generally decreased with frequency. Seasonal temperature changes caused a greater variance than that due to processes of intermediate frequency (~0.0025 cph), such as the sequence of spring and neap tides,

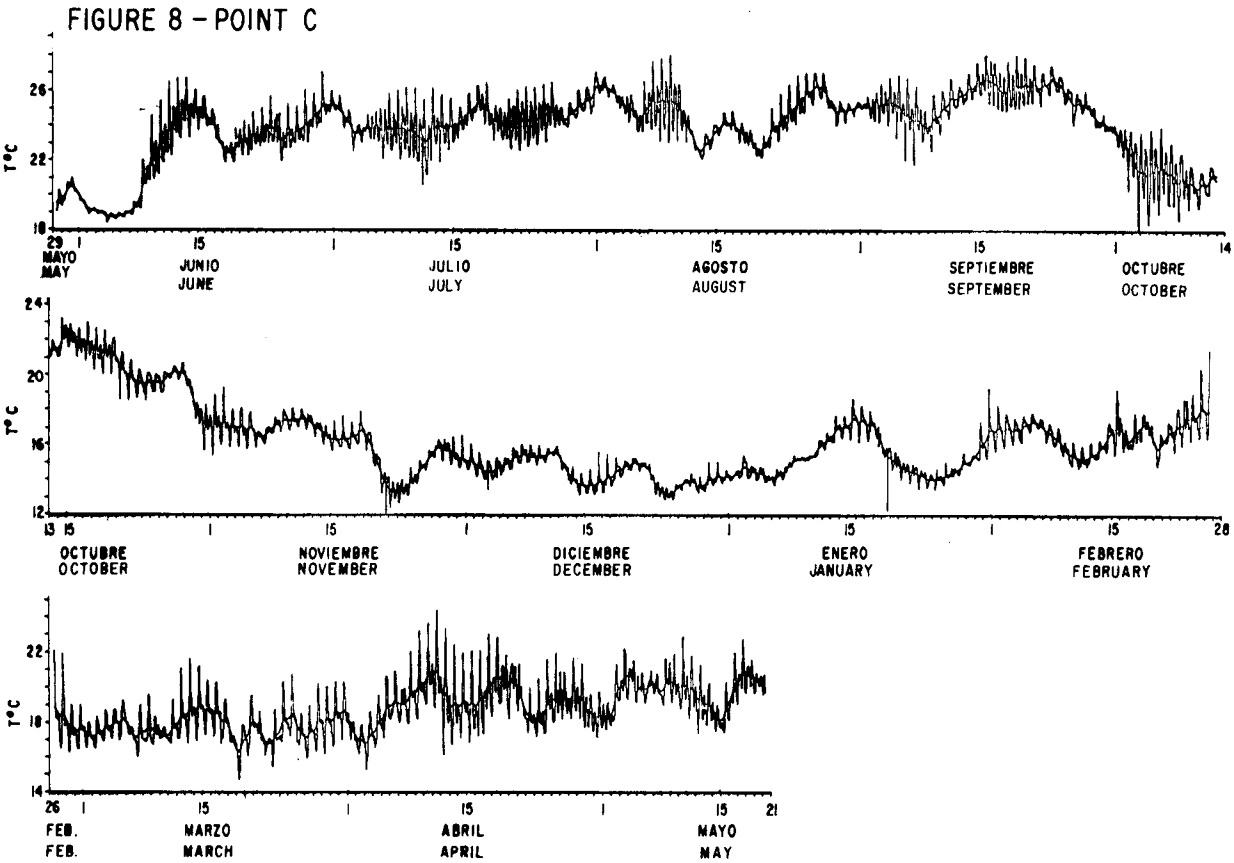


Figure 8. Thermogram from point C of Estero de Punta Banda. Marks on the horizontal axis are midnights. Numbers are dates.

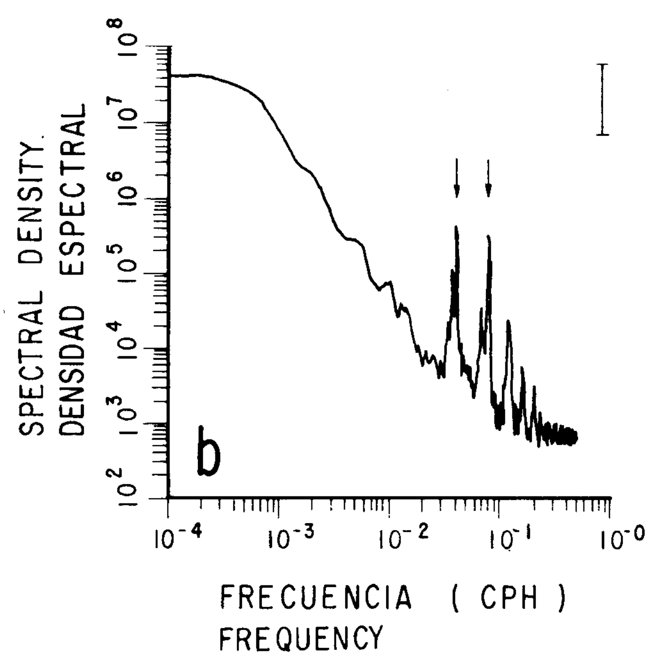


Figure 9. Spectral density of thermograms from San Quintin Bay and Estero de Punta Banda. Differences between spectra of the different time series were not significant, at the 95% confidence level. The bar at right shows the 95% confidence interval, with 36 degrees of freedom. CPH means cycles per hour. Arrows mark the diurnal and semidiurnal frequencies.

the sequence of upwelling events, or the incidence of winter storms. The spectrum shows distinct peaks at the diurnal and semidiurnal periods (0.04 and 0.08 cph frequencies, respectively), indicating the effect of tidal currents on temperature. As is to be expected from this, coherence between temperature and tide was high for the diurnal and semidiurnal periods (not illustrated).

DISCUSSION

When sampling seawater temperature at a fixed point, one finds that the short period variations (smaller than diurnal) are mainly caused by tidal currents and horizontal temperature gradients. In general, temperature increases from the mouths of San Quintin Bay and the Estero de Punta Banda to the extremes, with some exceptions during winter, when low air temperatures invert the surface seawater temperature gradients. Therefore, temperature generally increases with ebb flow, at a fixed point, and vice versa. Very short period temperature variations (on the order of a few hours) are mainly due to the irregular bathymetry of these coastal lagoons. This bathymetry causes an irregular warming of the water by solar radiation, or

TABLE 1
Maximum Cross-Correlation Coefficients (R) between the Thermograms (Represented by Letters) from the Different Sampling Points, and between the Thermograms and Tides in San Quintin Bay and Estero de Punta Banda.

	DATES	SERIES	R	LAG
BAHIA DE SAN QUINTIN	MAY 17 TO AUGUST 5	A - C	0.70 ± 0.03	+ 1
		A - D	0.64 ± 0.03	-12
		C - D	0.91 ± 0.01	0
		A - TIDE	-0.47 ± 0.03	- 2
		D - TIDE	-0.21 ± 0.04	- 1
	DECEMBER 22 TO FEBRUARY 29	A - B	0.62 ± 0.03	+ 2
		A - C	0.80 ± 0.02	+ 2
		A - D	0.76 ± 0.02	+ 2
		B - C	0.80 ± 0.02	0
		B - D	0.84 ± 0.01	0
		C - D	0.95 ± 0.01	0
		A - TIDE	-0.32 ± 0.04	- 1
		D - TIDE	-0.18 ± 0.05	- 1
ESTERO DE PUNTA BANDA	MAY 29 TO AUGUST 5	A - B	0.86 ± 0.02	+ 2
		A - C	0.80 ± 0.02	+ 1
		B - C	0.93 ± 0.01	0
		A - TIDE	0.29 ± 0.05	+ 7
		C - TIDE	0.30 ± 0.05	+ 4
	NOVEMBER 12 TO DECEMBER 12	A - C	0.85 ± 0.01	0
		A - TIDE	0.17 ± 0.06	+13
		C - TIDE	-0.14 ± 0.06	- 1

Lag is the number of hours that the series represented by the letter at the left has to move to the right to obtain the maximum R. Intervals are at the 95% confidence level.

cooling by evaporation and low air temperature. It also causes irregular mixing processes by tidal currents and winds. During summer, water is generally warmer in shallow areas than in channels. Atmospheric temperature, solar input, and winds affect the interiors of these lagoons more than the areas near the entrances, because of shallow depths and greater residence times in the interiors. Long period temperature variations (one week or more) are caused by phenomena that change the temperature throughout the whole lagoon and adjacent oceanic area in a similar fashion. Examples of these phenomena are the sequence of upwelling events during spring and summer; a sequence of clear, warm days; the incidence of winter storms; the seasonal change of atmospheric temperature and solar irradiance; or a combination.

During summer, temperature variations at a given location in these coastal lagoons are related to changes of the water residence time for that location. With low residence times causing high water renewal, temperatures tend to be lower, and vice versa. Residence times in these coastal lagoons do not depend only on their geometry and the spring-neap tide sequence. They also depend strongly on the adjacent ocean dynamics. During summer, at the mouth of San Quintin Bay upwelling causes surface water temperatures sometimes lower than 12°C, with dissolved oxygen saturation of about 60%. This low oxygen saturation shows that the low-temperature water is the result of upwelling and not, for example, the result of mesoscale structure of advection off the bay. During summer, low water temperatures generally correspond with high salinities, low dissolved oxygen, high nutrient concentrations, relatively low chlorophyll concentrations, and low phytoplankton productivity, and vice versa (Lara-Lara et al. 1980). In general, all year round, there are horizontal salinity and temperature gradients, with values increasing from the mouth to the extremes of the lagoon (Chavez de Nishikawa and Alvarez-Borrego 1974; Alvarez-Borrego et al. 1975). The entrance to Estero de Punta Banda is some 14 km from the upwelling area outside Todos Santos Bay. In general, all year round there are horizontal salinity and temperature gradients, with values increasing from the mouth to the extreme of the estero (Acosta-Ruiz and Alvarez-Borrego 1974; Celis-Ceseña and Alvarez-Borrego 1975).

During periods with weak coastal currents in the adjacent oceanic area, water leaving the lagoon during ebb flow returns in high proportion with flood flow, causing a high residence time in the lagoon. With strong currents parallel to the coast, water leaving the lagoon during ebb flow is carried away from the area near the entrance, and during flood flow "new" water enters the lagoon, causing a low residence time. The thermograms show that if spring tides occur simultaneously with the attenuation of coastal currents, high temperatures are produced, indicating high residence times. On the other hand, if neap tides occur simultaneously with strong coastal currents, water temperatures are relatively low, indicating low residence times. This happened in June 1979 in the Estero de Punta Banda (Figure 6). Around June 15, with spring tides, greater temperatures were registered than during the first days of that month, with neap tides. Contreras-Rivas (1973) detected a northward current parallel to the coast, off the estero's entrance, on July 30, 1972. Alvarez-Sanchez (pers. comm.) has measured these currents using drifting buoys. Maximum measured surface velocity is 30 cm sec^{-1}. Velocity changes of these currents are not adequately known yet, but there is evidence they are associated strongly with the wind regime. Alvarez-Borrego, Acosta-Ruiz, and Lara-Lara (1977) indicated that abrupt temperature and salinity decreases, detected sometimes at the estero's entrance at the beginning of flood flow, were caused by currents parallel to the coast. Lowest residence times in these lagoons occur with spring tides coinciding with strong coastal currents.

Lara-Lara, Alvarez-Borrego, and Small (1980) showed that with an upwelling event off San Quintin Bay's mouth, water residence time in the bay decreased greatly, whereas during relaxation periods residence time increased.

Some researchers (pers. comm.) have indicated that low-frequency temperature changes in San Quintin Bay's mouth (periods of 10 to 15 days) during spring and summer could be due to the sequence of spring and neap tides and not to upwelling events. However, minimum winter temperature was 13.5°C and occurred during spring tides (Figure 2); it was 2.5°C greater than minimum summer temperature. Besides, the maximum temperature of the year occurred during spring tides in September. This indicates that the sequence of upwelling events causes most of the low-frequency temperature changes during spring and summer. Also, as indicated above, in the estero spring tides coincided indistinctly with crests and valleys of low-frequency temperature variations.

Both at San Quintin Bay and Estero de Punta Banda temperature maxima for the year were registered at the end of September. This may be due to the attenuation of upwelling events at a time when solar radiation is still high. According to Bakun (1973), in September the upwelling index is about half of the year's maximum, although its value may vary from year to year.

Low temperatures registered in Estero de Punta Banda in June, July, September, and April (Figures 6 and 7) possibly correspond to upwelling waters carried from the oceanic area adjacent to Punta Banda and Todos Santos Island, by coastal currents like those mentioned above. These waters are warmed in the trajectory to the estero's entrance. The temperature time series from San Quintin Bay's mouth (Figure 2) shows an upwelling intensification event occurring from August 31 through September 8, 1979. Millan-Nuñez, Ortiz-Cortez, and Alvarez-Borrego (1981) generated nutrients, chlorophyll and phytoplankton abundance time series from September 1-11, 1979, at the estero's mouth. Their results show high chlorophyll-a concentrations and phytoplankton abundances during the last four sampling days, up to 12 mg m^{-3} and 10^6 cells per liter, respectively. These high values indicate the presence of upwelled waters that after a few days have been "conditioned" in the sense of Barber and Ryther (1969); that is, certain unavailable micronutrients in the freshly upwelled water became available through chelation as the water aged, and phytoplankton populations responded by growing rapidly.

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