Pergamon

Continental Shelf Research, Vol. 15, No. 8, pp. 1023–1041, 1995

0278–4343/95 $9.50+0.00

0278–4343(94)00046–8

NOTE

An internal tidal bore regime at nearshore stations along western U.S.A.: Predictable upwelling within the lunar cycle

JESÚS PINEDA*†

(*Received* 8 *September* 1993; *accepted* 15 *April* 1994)

Abstract—Nearshore upwelling due to predictable large internal bores may be a widespread phenomenon along the west coast of North America. Internal tidal bores (breaking internal tidal waves) cause drops in surface water temperature that last for 2–9 days. Negative surface water temperature anomalies (anomaly = daily datum *minus* day-of-the-year average) often reflect large internal tidal bores. These anomalies are predictable within the lunar cycle in spring and summer (but not in winter and fall) at a Southern California shore-station, the Scripps Institution of Oceanography Pier [Pineda (1991) *Science*, **253**, 548–551]. The internal tidal bore hypothesis has been invoked to predict and explain this result: anomalies are predictable (on average) within the lunar cycle because of a lunar or spring-to-neap cycle in internal bore activity. The anomalies are more predictable in spring and summer than in fall and winter because internal waves are most energetic when the water column is well stratified.

Long time series (18–64 years) of surface water temperature from 10 U.S. west coast shore stations from Oceanside in southern California to Neah Bay in Washington, were analyzed to evaluate the generality of the Scripps results. Nine stations showed that temperature anomalies are predictable on average within the lunar cycle in spring or summer, but not in fall and winter. There is high variability in the magnitude and variance of the average anomaly among stations. In general, for spring and summer, the most negative anomalies tend to occur on days 7–12 (-) and 19–24 (-) of the lunar cycle (day one being day after the new moon ●). Few most-negative-anomalies occurred around new moon or full moon. The Farallon Islands station showed a more random distribution of anomalies within the lunar cycle during spring and summer.

INTRODUCTION

Studies have documented water temperature variability in the Southern California Bight; scales from seconds to hours generally have been related to internal waves, while large-scale variability has been associated to meso-scale processes such as Ekman upwelling (Dorman and Palmer, 1981) or other meteorological phenomena (List and Koh, 1976). While there is little direct evidence for Ekman upwelling (Jackson, 1986), many studies have shown that internal waves play a prominent role in generating temperature variability, from diurnal and semidiurnal and higher frequencies to spring-neap tidal frequencies (Morberg and Allen, 1927; Arthur, 1954; Lee, 1961; La Fond, 1962; Cairns, 1966, 1967; Cairns and Nelson, 1970; Winant, 1974; Winant and Bratkovich, 1981; Pineda, 1991, 1994). Variance in temperature, correlated with internal wave activity, peaks in

*Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093-0208, U.S.A.
†Current address: Biology Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, U.S.A.

spring and summer and decreases in fall and winter (Cairns and Nelson, 1970; List and Koh, 1976; Winant and Bratkovich, 1981), paralleling the seasonal cycle in water-column thermal stratification (Cairns and Nelson, 1970; Winant and Bratkovich, 1981).

Daily seasurface temperature has been recorded at shore stations along the west coast of the U.S. for several decades. List and Koh (1976) found that these observations include seasonal cycles (cold water in winter, warm water in summer) and considerable "high-frequency" ($f < 14\ d^{-1}$) variability in spring and summer that decreases in fall and winter. The high-frequency variability described by List and Koh can be observed in the records as drops in surface water temperature that last several days. Drops in surface water temperature at nearshore stations in spring and summer have been explained as the result of Ekman upwelling (Tont, 1976, 1981; Dorman and Palmer, 1981). However, List and Koh (1976) found little correlation in surface temperature between nearshore stations at these frequencies (<14 days; stations were separated from about 40 to more than 2000 km); these findings do not support meso-scale upwelling. It has recently been proposed that these drops can also be explained as fluctuations due to large internal tidal bores: nearshore upwelling is caused by groups of two or more large internal tidal bores of diurnal or semidiurnal periodicity; the onshore transport and shoaling of subsurface masses of water can cause the surface water temperature to drop for two to nine days (Pineda, 1991). Large internal waves generated at diurnal or semidiurnal periodicities can transform into internal bores as they shoal and become non linear (Cairns, 1967; Winant, 1974; Pineda, 1991, 1994).

Balch (1986) has shown that the surface water temperature anomalies observed at the Scripps Institution of Oceanography (SIO) Pier, in the Southern California Bight, tend to occur non-randomly within the lunar cycle. As an hypothesis test, Pineda (1991) further partitioned the water temperature anomalies into day-of-the-lunar cycle and calendar-season, and attributed the peculiar resulting distribution of anomalies to an internal tidal bore regime. In fall and winter, when the water column is weakly stratified, the anomalies are uniformly distributed with respect to the lunar cycle, while in spring and summer, when the water column is well stratified, the anomalies are distributed non-randomly. This supports the idea of an internal tidal bore regime because internal tides are most energetic when the water column is well stratified, and, given that internal tidal bores are generated by the surface tide, one could expect them to have some semi-lunar ($\approx$14.7 days) periodicity. The causes of the particular distribution of the anomalies within the lunar cycle (Fig. 2 of Pineda 1991) are unknown, but on average the most negative anomalies (the coldest water) tended to occur on days 19–25 of the lunar cycle in spring and summer at SIO. Cold water anomalies also occur on days 5 and 6 in summer only.

This paper evaluated whether the seasonal and lunar non-random distributions of temperature anomalies found at the SIO Pier are also found at other localities. Long temperature records from ten stations along the Pacific west coast of North America are used to analyze the distribution of anomalies within the lunar and seasonal cycles. This extends a previous analysis of the SIO Pier historical temperature record (Pineda, 1991) to other localities.

METHODS

While an internal tidal bore regime can be inferred from daily temperature records, individual internal tidal bore events can only be measured with higher frequency

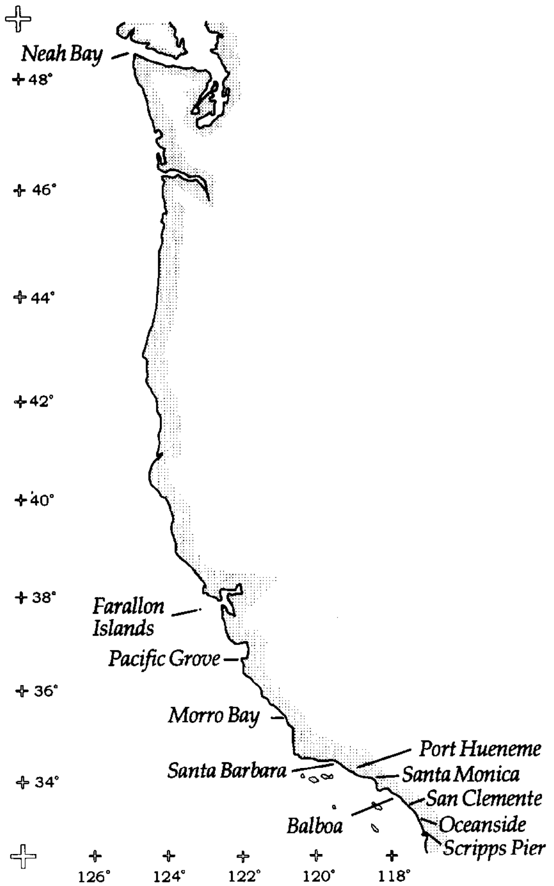

Fig. 1. Nearshore stations.

temperature measurements (see examples in Cairns, 1967; Winant, 1974; Winant and Olson, 1976; Shea and Broenkow, 1982; Pineda, 1991, 1994). To illustrate the relationship between large internal tidal bores and the daily temperature record used for testing lunar and seasonal periodicity, a high frequency record from the SIO Pier is used. High frequency temperature data (observations at 5 min intervals), used to detect internal-tidal-bore events, were obtained at the SIO Pier, in Southern California. The record is part of an automatic weather station. Two sensors located about 300 m from the coastline where the water depth is, on average, about 6 m; one sensor is located about 1.5 m above the bottom (the depth varies due to accretion/erosion of the sandy seafloor), while the sub-surface sensor is located about 3 m above the bottom sensor (about 0.5 m below the lowest tidal water level).

The temperature records for the ten nearshore stations (Fig. 1; Table 1) consist of daily temperature observations taken at piers, jetties, or beaches. Measurements are taken from surface waters in the morning. (Data in Fig. 2, upper panel, was sampled in a similar manner.) Some records have gaps of a period of one to several days. One record has two one-year-long gaps. The data have been archived by the Marine Life Research Group at SIO.

Table 1. Stations and span of the time series used in the analyses and for the SIO Pier (Pineda, 1991). *For descriptions of sites see* Scripps Institution of Oceanography (1989)

	Latitude	Longitude	Number of data years
Neah Bay	48°22′N	124°37′W	≈30
Farallon	37°42′N	122°60′W	≈48
Pacific Grove	36°37′N	121°54′W	≈64
Morro Bay	35°22′N	120°52′W	≈28
Santa Barbara	34°24′N	119°42′W	≈30
Port Hueneme	34°07′N	119°13′W	≈38
Santa Monica	34°01′N	118°30′W	≈30
Balboa	33°36′N	117°54′W	≈64
San Clemente	33°25′N	117°37′W	≈23
Oceanside	33°12′N	117°20′W	≈18
SIO Pier	32°53′N	117°15′W	≈68

The records were analyzed as follows (see also Balch, 1986). For each station, the day-of-the-year average was calculated (e.g. the average of all temperatures from 2 January is the day-of-the-year average for day 2). Anomalies were then obtained by subtracting the day-of-the-year average from each daily observation. Each anomaly was fitted to a day of the lunar cycle and to a calendar season. Day-of-lunar cycle was obtained by dividing the lunar cycle (from new moon to following new moon; about 29.5 days) into 29 units (days of lunar cycle; day 1 the day after the new moon). For each day of the lunar cycle and for each season, the average and standard error of the anomaly were obtained.

RESULTS

Figure 2 presents once-a-day temperature observations at the end of the Scripps Pier and two corresponding higher-frequency records. The arrows point to four dates when drops in the daily surface and bottom water temperature record correspond to groups of several large internal tidal bores in the higher frequency record (Pineda, 1991).

Figures 3–12 show average temperature anomalies per day-of-lunar-cycle per season for the ten nearshore stations. Non-random distribution of anomalies occurs in spring and/or summer at Neah Bay (Fig. 3), Pacific Grove (Fig. 5), Morro Bay (Fig. 6), Santa Barbara (Fig. 7), Port Hueneme (Fig. 8), Santa Monica (Fig. 9), Balboa (Fig. 10), San Clemente (Fig. 11) and Oceanside (Fig. 12). The magnitude of the average anomaly and variance varies considerably among stations. The stations with highest average anomalies were Morro Bay (Fig. 6; spring and summer) and Neah Bay (Fig. 3; summer). At Neah Bay (Fig. 3) and Santa Barbara (Fig. 7), the distribution of anomalies appears random in spring. For Farallon Island (Fig. 4), patterns in temperature anomalies within the lunar cycle in spring and summer appear more random, relative to other stations and relative to winter and fall.

Table 2 presents the standard deviation of the average temperature anomalies within the lunar cycle for data analyzed in this paper and in Pineda (1991). Higher standard deviations would reflect higher deviations from a random record. (Stations with smaller time series might produce higher standard deviations because small time series might produce less smooth averages.) The ranks of the maximum standard deviation per station

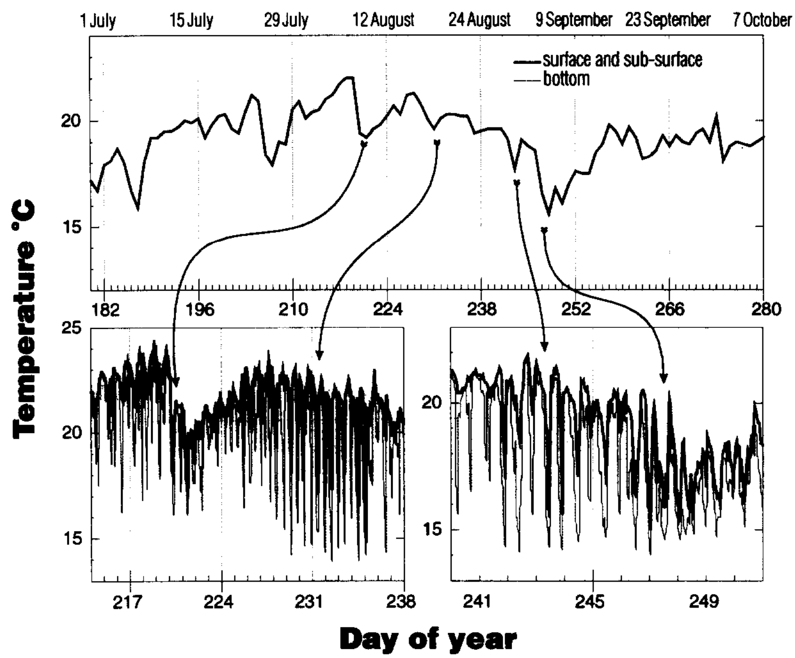

Fig. 2. Daily and higher-frequency temperature records at the Scripps Pier (*ca* 300 m from the shore) by day-of-the-year (day 1 = January 1) in 1989. Arrows cross-reference cold-water events. Upper panel: temperature sampled daily at the surface. Lower panel: temperature sampled every 5 min, but for this trace the record was subsampled each hour. Continuous line (——) near-surface water temperature; dotted line (.......) near-bottom temperature. Bottom and subsurface sensors were about 1.5 m and 4.5 m above the bottom.

Table 2. Standard deviation of average temperature anomalies within the lunar cycle for data analyzed in this paper (Figs 3–12) and from Pineda (1991) *for the SIO Pier*; n = 29 *in each case*. RMSD *are ranks of the maximum standard deviation per station (for each station, the maximum standard deviation within the four seasons was picked and ranked in a list containing similar values for all stations)*; RMMSD *are the ranks of the ratio of maximum standard deviation to minimum standard deviation (for each station, the maximum and minimum standard deviations were picked; the ratio is then obtained and ranked as in* RMSD

	Winter	Spring	Summer	Fall	Rank of max s.d. (RMSD)	Rank of max s.d./min s.d. (RMMSD)
Neah Bay	0.073	0.057	0.249	0.125	2	2
Farallon Islands	0.059	0.057	0.070	0.051	11	11
Pacific Grove	0.043	0.093	0.086	0.060	9	7
Morro Bay	0.079	0.454	0.521	0.111	1	1
Port Hueneme	0.062	0.111	0.105	0.103	7	8
Santa Barbara	0.077	0.085	0.123	0.073	6	9
Santa Monica	0.059	0.144	0.183	0.064	3	4
Balboa	0.043	0.102	0.095	0.072	8	5
San Clemente	0.074	0.166	0.159	0.105	4	6
Oceanside	0.092	0.152	0.154	0.109	5	10
SIO Pier	0.026	0.081	0.091	0.044	10	3

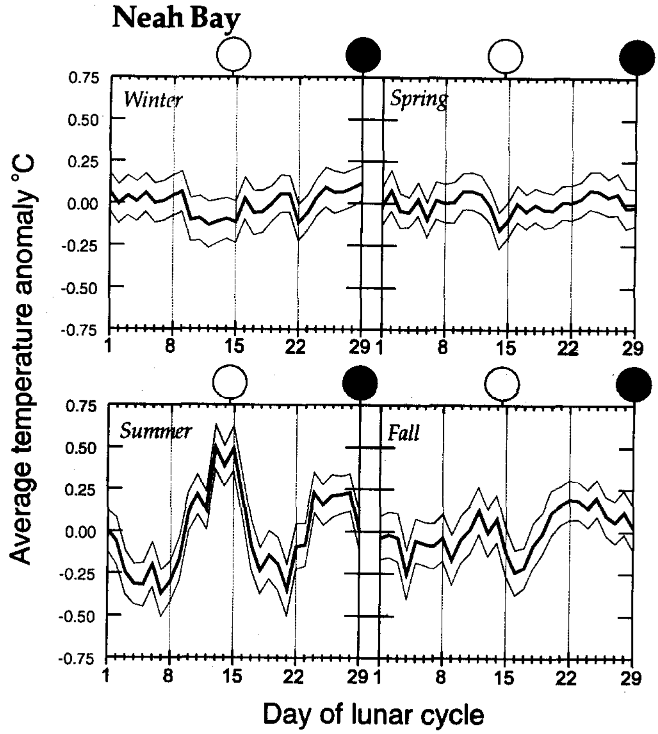

Fig. 3. Neah Bay: average temperature anomalies (daily datum *minus* day-of-the-year average) partitioned by day of the lunar cycle and by season. Fine lines are two standard errors. See Table 1 for exact geographic position and length of the time series used in the analysis.

(RMSD) and the ranks of the ratio of maximum to minimum standard deviation per station (RMMSD) are presented to highlight differences among stations. While RMSD could yield some information on the differences of the "strength" or predictability of the process among stations, RMMSD is a criteria for comparing the strength of the process in spring or summer vs winter or fall among different stations. Table 2 shows that in seven cases standard deviations were highest in summer, with four cases in spring and none in winter or fall. Nine smallest standard deviations occurred in winter and two in fall. Morro Bay and Neah Bay had the highest values and were ranked 1 and 2 in both RMSD and RMMSD. Farallon Islands and Scripps Pier had the smallest RMSD; Farallon had the lowest RMMSD. The Scripps RMMSD, however, was 3, constituting the station with the strongest discrepancy between RMSD and RMMSD. Therefore, while Scripps showed a relatively weaker signal in summer, its relative difference between summer and winter was amongst the highest.

Figure 13 tabulates the days of the lunar cycle with most negative anomalies (e.g. the coldest water) from those stations that showed a non-random distribution of anomalies in spring and/or summer. Farallon Islands results were omitted. The most negative anomalies in spring tended to occur on the same day of the lunar cycle as in summer. (From 1 to 2 occurrences at all stations, except for Scripps, where there were no coincidences between spring and summer.) Figure 14 presents a histogram of the frequency of occurrence of the

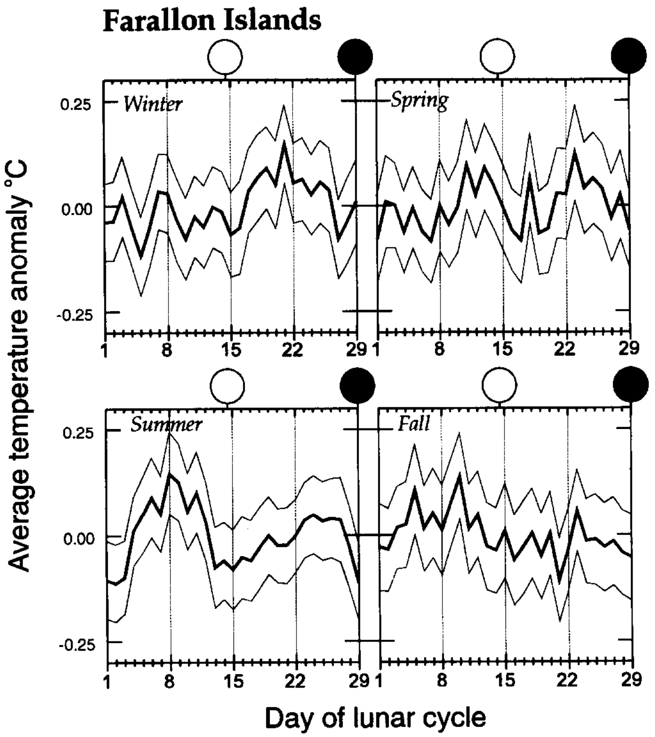

Fig. 4. Farallon Islands: explanation as in Fig. 3 legend.

three most negative anomalies per category of day-of-lunar cycle. Each station tabulated in Fig. 13 contributed three numbers to the histogram if it was tabulated only in summer or six if it was also included in spring. The anomalies tended to concentrate on days 7–12 and 19–24 in spring and in summer. Few most-negative anomalies occurred around new moon or full moon (days 29 and 14.5).

In all stations that showed non-random distribution of anomalies there were two water temperature anomaly cycles per lunar cycle in summer. At Balboa (Fig. 10) one cycle appears particularly weak. In several stations the number of water temperature anomaly cycles per lunar cycle appears to vary from spring to summer. In Santa Barbara (Fig. 7), Santa Monica (Fig. 9), Balboa (Fig. 10), San Clemente (Fig. 11) and Scripps (Fig. 2 in Pineda, 1991) there are two cycles in summer and one cycle in spring. (The Santa Barbara cycle in spring appears very weak.)

DISCUSSION

Pineda (1991) tested the hypothesis that internal tidal bores could be responsible for the non-random distribution of water temperature anomalies in the lunar cycle by partitioning data from the SIO Pier into the four calendar seasons. In this paper, analysis of temperature records from 10 other nearshore stations has shown similar results at nine of the 10, with one station (Farallon) showing a weaker signal. This section considers the following issues: (1) the rationale of the analysis performed in this paper and why the

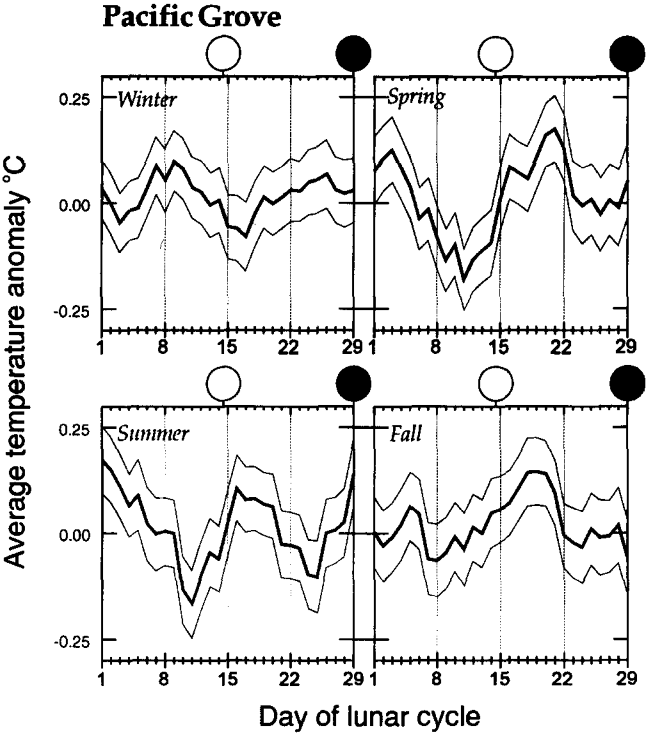

Fig. 5. Pacific Grove: explanation as in Fig. 3 legend.

results support large internal tidal bores as the cause of the patterns found in Figs 3–12; (2) the distribution of most negative anomalies within the lunar cycle; (3) other phenomena that might influence the results found here; (4) factors that might generate and reduce noise in detecting large internal tidal bores and how this could influence the results; and (5) some general implications.

Drops in surface water temperature and predictable upwelling

Figure 2 shows that some drops in surface water temperature are correlated with large internal tidal bores. The signature of the large internal tidal bores at SIO is the high diurnal or semidiurnal variability in surface and bottom water temperature (Fig. 15). If diurnal or semidiurnal fluctuations in water temperature were caused by the surface tide associated ascending and descending of a stratified water column over fixed temperature sensors, maximum cross-correlation between temperature and sea level would occur at 0 time lag. However, this idea is not supported by the finding that maximum cross-correlation was 3–5 h in a location close to SIO (Cairns and LaFond, 1966) and 5 h at the Scripps Pier (temperature close to the bottom; own unpublished data). Nor does the diurnal breeze explain semidiurnal variability in temperature because of the difference in frequency of the two phenomena. Bottom and surface water temperature falls and rises suddenly, and then falls and rises again one or several more times (Fig. 15; see also Fig. 2, lower panels). These groups of large internal bores appear to be responsible for drops in surface water

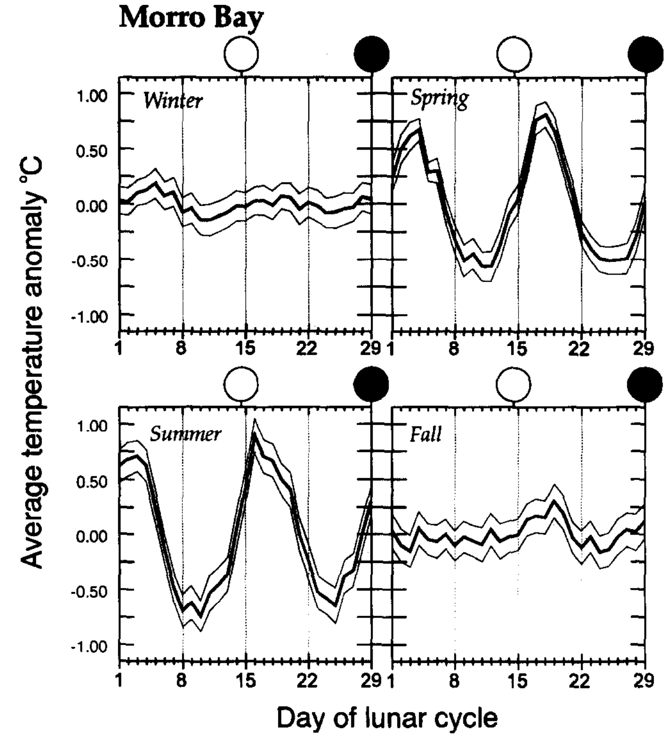

Fig. 6. Morro Bay: explanation as in Fig. 3 legend.

temperature lasting from two to nine days [Fig. 2; Fig. 2 in Pineda (1991); Figs 8 and 9 in Pineda (1994)]. This inference that drops in surface water temperature in other nearshore stations could also be correlated with large internal tidal bores is supported by several types of evidence: the fact that drops observed at the SIO Pier appear to be caused by large internal bores, that large internal tidal bores might have semi-lunar cycle, as Cairns (1966) has claimed for the internal tide, and that the necessary conditions for the occurrence of the internal tidal bores (e.g. topographic loci of internal tide generation and a thermally stratified water column) are widespread.

The hypothesis that large internal tidal bores can cause the non-random patterns like those shown in Figs 3–12 is supported by the data in Fig. 2. The inference is that if large internal-tidal bores cause drops in surface water temperature, and if internal tides have a lunar periodicity, then the drops in surface water temperature might occur on certain days of the lunar cycle. If this phenomenon is of sufficient regularity and magnitude the drops should be detected in analyses such as those presented in Figs 3–12. Another issue that gives credibility to the hypothesis includes many observations of large internal waves (amplitude up to 120 m) advancing onshore in the Southern California Bight (Lee, 1961; La Fond, 1962; Summers and Emery, 1963; Cairns, 1967; Emery and Gunnerson, 1973; Shea and Broenkow, 1982). Furthermore, strong cross-shore currents are associated with large internal tidal bores (Winant and Olson, 1976; Pineda, 1994). In sum, if large internal tidal bores measured at high frequency (e.g. Figs 2 and 15) produce the strong signature found in Fig. 2 of Pineda (1991) (predictability within the lunar cycle in summer and spring

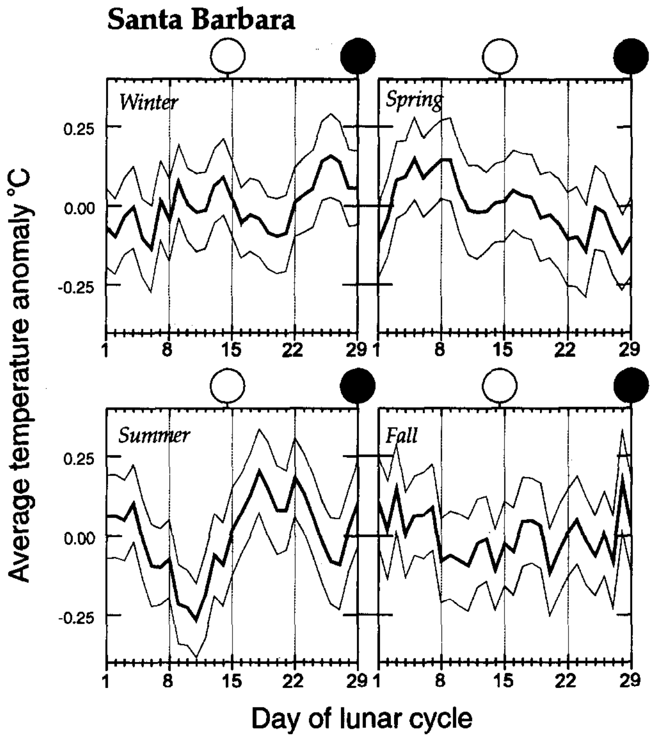

Fig. 7. Santa Barbara: explanation as in Fig. 3 legend.

only, with most negative anomalies in days 5–6 and 19–25 of the lunar cycle), then the results in Figs 3–12, which also show the same characteristic signature, might also be caused by the large internal tidal bores.

Distribution of most negative anomalies within the lunar cycle

The factors responsible for the peculiar distribution of the most negative anomalies across stations in Fig. 14 are not known. Since most coldest-days tend to cluster on days 7–12 and 19–24, there is presumably some general underlying mechanism. Cairns (1966) claimed that internal tides behaved as the surface tide, with larger amplitudes in spring than in neap tides. And that the thermocline weakened, and showed "a greater tendency to break up and diffuse" in spring tides. A conceivable explanation for the results in Fig. 14, then, is that large internal tidal waves generated during spring tides would break on average offshore, at or close to their site of generation, and that only those generated in days 7–12 and 19–24 would propagate all the way into the coastline. Another conceivable explanation, not independent from the one put above, is that mixing by the surface- and internal-tide around spring tides could result in weak baroclinic currents around spring tides and strongest baroclinic motions on days 7–12 and 19–24. A similar argument, increased mixing by the surface tide in spring tides, was put by Geyer and Cannon (1982) to explain increased stratification and baroclinic exchange during neap-tides in a fjord.

Because internal motions are strongly influenced by topography and stratification

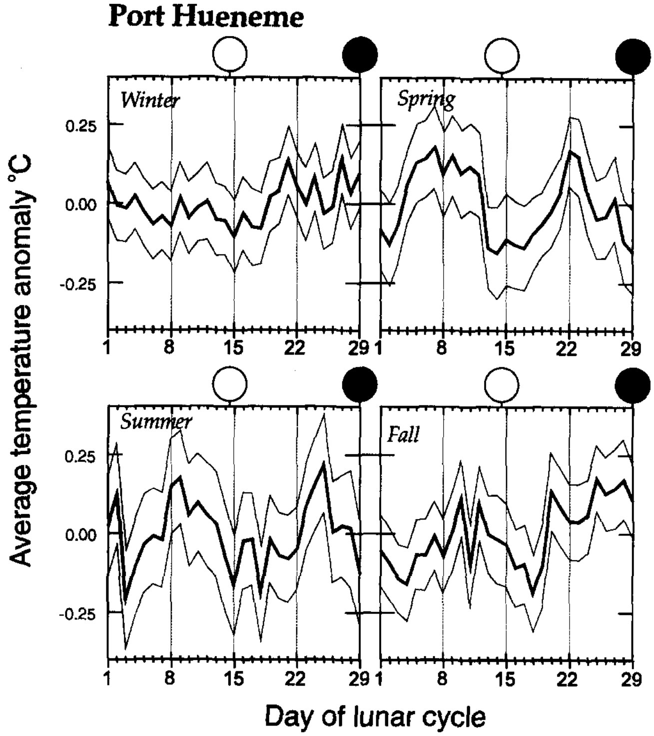

Fig. 8. Port Hueneme: explanation as in Fig. 3 legend.

conditions, and because these vary alongshore, one can expect exceptions to the results in Fig. 14.

Alternative explanations

Other phenomena that could account for the results in Figs 3–12 should also have lunar or spring–neap periodicity. The surface tide could produce cooling of surface waters through mixing enhancement. Mixing enhancement should be greatest in spring tides, as on the European continental shelf, where the spring to neap surface tidal cycle defines the position of a front dividing stratified and unstratified waters (Simpson and Pingree, 1978; Pingree *et al.*, 1977). However, these results show that in general, most negative anomalies do not occur on spring tides (see also Balch, 1986). At most locations where data were analyzed (Fig. 1), the surface tides are much less energetic than on the European continental shelf, where abut 10% of the total world dissipation of the M_2 tide in coastal oceans occurs (Simpson and Pingree, 1978). Surface-tide mixing does not explain the result obtained here, that at several stations there were two cycles of water temperature anomaly per lunar cycle in summer but only one in spring. Strong mixing by the surface tide has not been documented in the Southern California Bight (but see Leipper, 1955). Thus, the hypothesis that the surface tide might be producing the patterns observed in Figs 3–12 seems unlikely.

Results presented here show that the temperature anomalies are predictable in spring

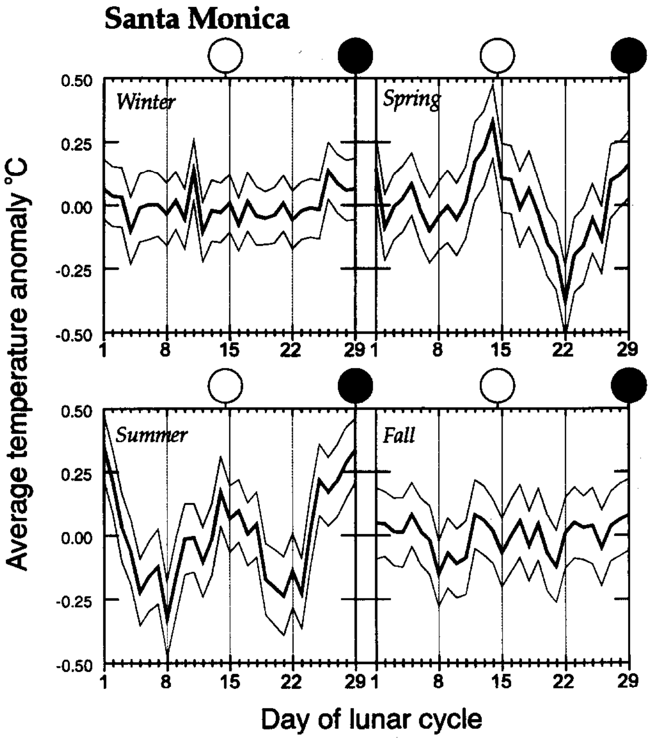

Fig. 9. Santa Monica: explanation as in Fig. 3 legend.

and summer, but less in winter and fall. This has been interpreted as a result of the seasonal variation in internal motions. An alternative hypothesis is that random patterns in fall and winter might not reflect lack of internal tidal bores, but only a well mixed water column. That is, the pattern in fall and winter could result from internal bore currents acting over a well mixed water column. This alternative is not supported by Winant and Bratkovich (1981) who found a well defined seasonal cycle in the baroclinicity of currents in the nearshore; the energy of the internal motion is highest in spring and summer, with little energy in winter and fall. The seasonal variation in the energy of internal motions parallels the nearshore stratification cycle.

Factors that might generate or reduce noise in detecting large internal tidal bores

While results show that, on average, the internal tidal bores tend to occur on some days of the lunar cycle (summary in Fig. 14) my unpublished observations suggest that they also occur on other days and that drops do not always occur on the "most probable" days of the lunar cycle (i.e. the days of the most negative anomalies). The fact that List and Koh (1976) found little correlation between nearshore stations in temperature variability at frequencies smaller than 14 days might be a reflection of this issue. Internal tides are highly variable (Baines, 1986; Winant and Bratkovich, 1981; Rosenfeld, 1990) and are not locked consistently in phase with the surface tide (Morberg and Allen, 1927; Arthur, 1954; Lee, 1961; La Fond, 1962; Winant and Bratkovich, 1981). While the surface tide contains a few

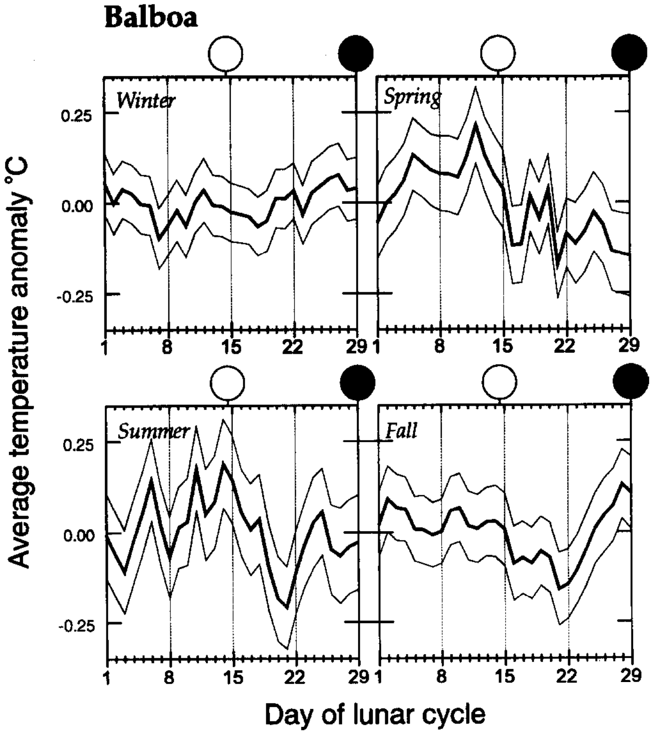

Fig. 10. Balboa: explanation as in Fig. 3 legend.

discrete frequencies and is highly predictable, several processes could increase the variability of the internal tide: variability in internal tide generation, stratification conditions, and currents. This in turn would produce variability in the internal tidal bores. In addition, internal tides generated at different sites could occur simultaneously in a single locality. Phenomena such as Ekman upwelling might destroy stratification and influence the internal tide (e.g. Rosenfeld, 1990). These factors might produce substantial alongshore and inter-annual variability.

An issue that might influence how large internal tidal bores are recorded in daily records is the timing of the arrival of the bore and the temperature measurement. Because internal tidal bores can have diurnal or semidiurnal periodicities, a single daily measurement could record either very cold or warmer water. For example, in Fig. 15, consider the difference of sampling the subsurface water at 3 a.m. (21.2°C), 11 a.m. (15.5°C), 1 p.m. (21.1°C), 10 p.m. (15.6°C) and 11 p.m. (20.4°C). This could produce systematic biases in Figs 3–12 if the cold water due to the large internal bores occurs non-randomly within a day.

The magnitude of the temperature anomaly and its small variance in spring and/or summer in the Morro Bay and Neah Bay data are conspicuous. While these results might be due to stronger and/or more predictable internal tidal bores, other phenomena might play a role. The temperature record in Morro Bay is influenced by physical processes associated with a small coastal lagoon, while the Neah Bay station is at the entrance of the Straits of Juan de Fuca and a bay with a constricted mouth (Scripps Institution of Oceanography, 1989). In both cases, surface-tidal currents might be important. Tidal

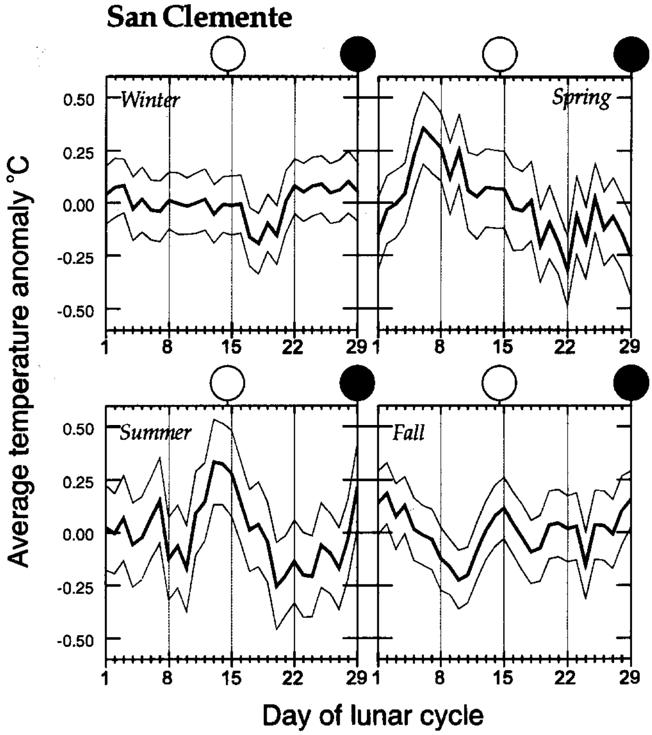

Fig. 11. San Clemente: explanation as in Fig. 3 legend.

flushing and tidal currents acting over a weakened thermocline might enhance mixing in these stations. Enhanced surface-tide mixing acting over waters also being influenced by large internal bores might "smooth" the diurnal or semidiurnal variability. Mixing would reduce the error due to sampling time because, presumably, surface water would cool due to the mixing, and water thus cooled would be more likely to be sampled than a single large bore. Another issue to consider is that at times large internal bores do not bring cold water to the surface, but only very close (personal observation). A surface temperature measurement, such as those taken at the nearshore stations, would not reveal the large internal bore unless mixing, such as that produced by tidal flushing of a coastal lagoon, had cooled the surface water. Surface tidal mixing might also reduce the noise in detecting large internal bores with temperature data. While the noise reduction by tidal mixing could apply to Morro Bay and Neah Bay, there is substantial variability in the other nearshore stations, and it is not known what might cause the differences in internal tidal bore regime. Topography might be important, because topography plays a role in the generation (e.g. Baines, 1986) and in the focusing of the internal tide (Shepard *et al.*, 1974).

These results support the hypothesis that upwelling related to large internal tidal bores is widespread along California and a station in Washington. The hypothesis that large internal bores produce nearshore upwelling has been tested for sites in the vicinity of heads of submarine canyons (Shea and Broenkow, 1982; Pineda, 1991). Submarine canyons are known to intensify and direct internal waves (Shepard *et al.*, 1974), and the results from Monterey and SIO could be related to the presence of submarine canyons. While canyons

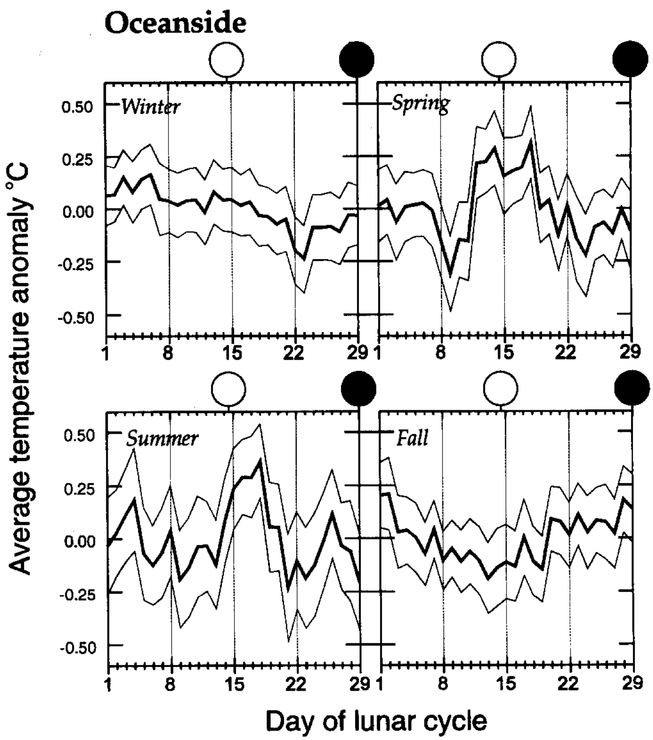

Fig. 12. Oceanside: explanation as in Fig. 3 legend.

might have an effect, the results obtained in this paper suggest that nearshore upwelling by large internal tidal bores is not restricted to locations close to submarine canyons.

The hypothesis that temperature anomalies illustrated in Figs 3–12 are due to tidally generated internal tidal bores predict two peaks at about 14.7 day intervals. However, some stations in southern California (Figs 9–11 and Fig. 2 in Pineda, 1991) showed a single peak in spring. I am unable to account for this discrepancy by the internal tidal bore hypothesis. In all four cases listed above, most negative anomalies in spring occur between days 20 and 29 of the lunar cycle. And this could be a clue for explaining this result if conditions around new-moon tides would differ from conditions around full-moon tides (e.g. differences in the strength of the surface-tide currents) in generating or inhibiting the internal tide in those sites, and if those conditions would change from spring to summer (e.g. differences in the strength of the stratification).

General implications

Internal tidal bores play a role in cross-shore exchange of material and heat; onshore transport of water column and neustonic larvae are important ecological examples (Pineda, 1991, 1994). Internal tidal bores might be important in understanding other aspects of nearshore ecology. Drops in surface water temperature in the nearshore lasting a few days, such as those depicted in Fig. 2, have had a role in explaining the nearshore ecological regime in the Southern California Bight. For example, they have been

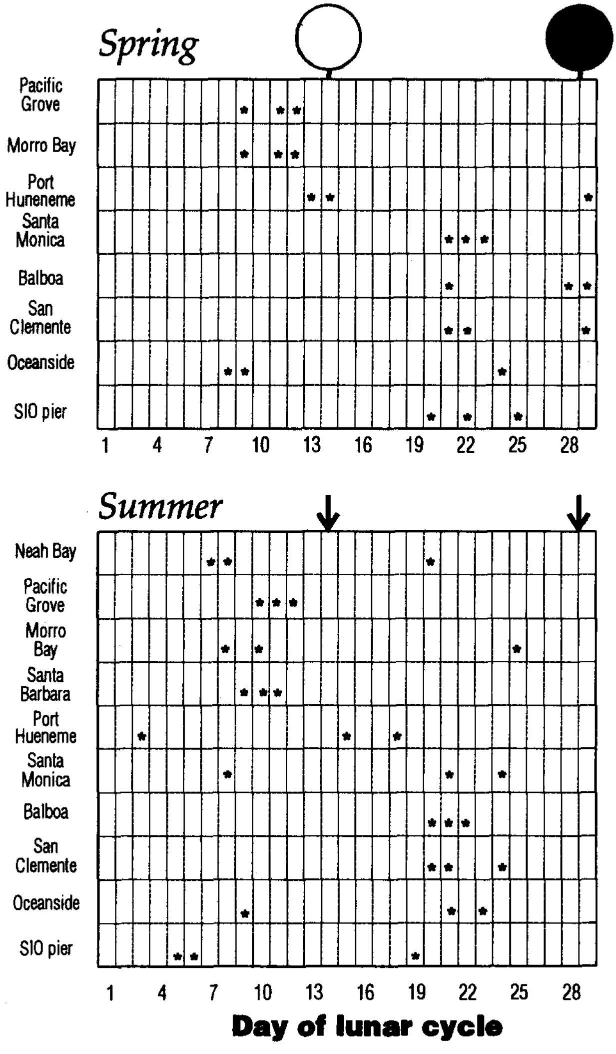

Fig. 13. Days of the lunar cycle for the three most negative daily anomalies for spring and summer; data depicted only for those stations and for those seasons that showed a pattern in the distribution of anomalies within the lunar cycle. SIO data from Pineda (1991).

correlated with increases in phytoplankton biomass and number (e.g. Tont, 1976, 1981; Smith and Eppley, 1982). These drops have been explained as the result of cooling of the water column by Ekman upwelling (Strickland *et al.*, 1970; Tont, 1976, 1981; Dorman and Palmer, 1981). While Ekman upwelling in the Southern California Bight certainly occurs (e.g. Kamykowski, 1974), it is not the only explanation for a drop in temperature. Often Ekman upwelling is invoked without corroborative evidence (e.g. wind data) or without considering alternative hypotheses. The hypothesis of Ekman upwelling within the Southern California Bight is based on very few measurements (Jackson, 1986). In addition, wind forcing in the Bight is weak (Winant, 1983). List and Koh (1976) found little correlation among nearshore stations of temperature variability in their "high frequency"

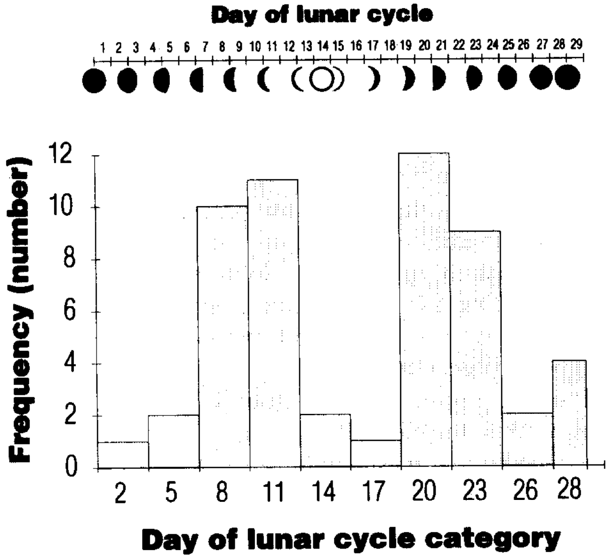

Fig. 14. Distribution of the three most negative anomalies within the lunar cycle in spring and summer for all stations in Fig. 13 according to day-of-lunar cycle (with phases of the moon). Each category includes three days of the lunar cycle (e.g. category 2 includes days 1, 2 and 3) except for category 28 which includes only days 28 and 29. Smaller bar width in category 28 is for smaller number of days included. For spring or summer each station contributed three numbers. Data from Fig. 13.

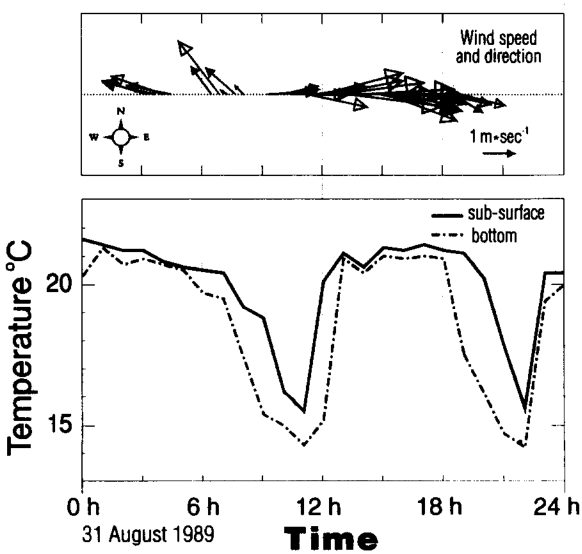

Fig. 15. Wind speed and direction (upper panel) and high-frequency temperature records from the SIO Pier, 31 August 1989. For the explanation of temperature data, see Fig. 2.

band ($f < 14\ \mathrm{d}^{-1}$), suggesting that the phenomena that would cause the drops were local (such as large internal bores) rather than mesoscale (such as Ekman upwelling). (Little correlation between nearshore stations is not explicitly predicted by the internal tidal bore hypothesis, but this result is not inconsistent with the high variability of the internal tide phenomenon.)

While 2–9 day drops in surface water temperature might be related to internal tidal bores, observed longer drops in surface water temperature (List and Koh, 1976) require other explanations. For "intermediate frequencies" ($14 < f < 113\ \mathrm{d}^{-1}$) List and Koh (1976) found that temperatures at nearshore stations in Southern California were well correlated (with no time lag), suggesting that such correlation was likely to be caused by a "meteorological" phenomenon with long (> 150 km) spatial scales. Long drops in surface water temperature might be related to local and/or remote Ekman upwelling.

Using spectral analysis, List and Koh (1976) found strong water temperature periodicites for Morro Bay as well as for Neah Bay, Pacific Grove, Santa Barbara, and Santa Monica. While acknowledging that these might be related to a spring-to-neap tidal cycle, they preferred to explain the result as a phenomenon with diurnal periodicity. Results presented here show that periodicity at these and other stations can be better explained as being due to an internal tidal bore regime.

Acknowledgements—Dave Checkley, Paul Dayton, Jim Enright, Loren Haury, Mia Tegner and Clint Winant read critically this manuscript and provided valuable suggestions. Pat Walker generously provided the data for the nearshore stations, and the Scripps Institution of Oceanography provided the high frequency temperature data. J. Enright and C. Winant discussed the data and provided help on its analysis. Erika Del Castillo provided support and encouragement during this study. This research was supported by the people of Mexico through a CONACyT scholarship.

REFERENCES

Arthur R. S. (1954) Oscillations in sea temperature at Scripps and Oceanside piers. *Deep-Sea Research*, **2**, 129–148.

Baines P. G. (1986) Internal tides, internal waves, and near-inertial motions. In: *Baroclinic processes on continental shelves*, Vol. 3, C. N. K. Mooers, editor, American Geophysical Union, Washington D.C., pp. 19–31.

Balch W. M. (1986) Are red tides correlated to spring–neap tidal mixing?: use of a historical record to test mechanisms responsible for dinoflagellate blooms. In: *Tidal mixing and plankton dynamics*, M. J. Bowman, C. M. Yentsch and W. T. Peterson, editors, Springer-Verlag, Berlin, pp. 193–223.

Cairns J. L. (1966) Depth and strength of the seasonal thermocline in shallow water off Southern California. In: *Proceedings, 3rd. U.S. Navy Symposium on Military Oceanography*, **2**, pp. 27–38.

Cairns J. L. (1967) Asymmetry of internal tidal waves in shallow coastal waters. *Journal of Geophysical Research*, **72**, 3563–3565.

Cairns J. L. and E. E. Lafond (1966) Periodic motions of the seasonal thermocline along the southern California coast. *Journal of Geophysical Research*, **71**, 3903–3915.

Cairns J. L. and K. W. Nelson (1970) A description of the seasonal thermocline cycle in shallow water coastal water. *Journal of Geophysical Research*, **74**, 1127–1131.

Dorman C. E. and D. P. Palmer (1981) Southern California summer coastal upwelling. In: *Coastal upwelling*, Vol. 1, F. A. Richards, editor, American Geophysical Union, Washington D.C., pp. 44–56.

Emery K. O. and C. G. Gunnerson (1973) Internal swash and surf. *Proceedings of the National Academy of Sciences of United States of America*, **70**, 2379–2380.

Geyer W. R. and G. A. Cannon (1982) Sill processes related to deep water renewal in a fjord. *Journal of Geophysical Research*, **87**, 7985–7996.

Jackson G. A. (1986) Physical oceanography of the southern California bight. In: *Plankton dynamics of the Southern California Bight*, E. R. W. Eppley, editor, Springer-Verlag, Berlin.

Kamykowski D. (1974) Physical and biological characteristics of an upwelling at a station off La Jolla, California during 1971. *Estuarine and Coastal Marine Science*, **2**, 425–432.

LaFond E. C. (1962) Internal waves. In: *The sea*, Vol. 1, M. N. Hill, editor, John Wiley and Sons, New York, pp. 731–751.

Lee O. S. (1961) Observations on internal waves in shallow water. *Limnology and Oceanography*, **6**, 312–321.

Leipper D. F. (1955) Sea temperature variations associated with tidal currents in stratified shallow water over an irregular bottom. *Journal of Marine Research*, **14**, 234–252.

List E. J. and R. C. Y. Koh (1976) Variation in coastal temperatures on the southern and central California coast. *Journal of Geophysical Research*, **81**, 1971–1979.

Morberg E. and W. E. Allen (1927) I. Observations on the effect of tidal changes on physical and chemical conditions of the sea water in the San Diego region. II. Half-hourly collections of marine microplankton taken at the Scripps Institution Pier in 1923. *Bulletin of the Scripps Institution of Oceanography*, **1**, 1–17.

Pineda J. (1991) Predictable upwelling and the shoreward transport of planktonic larvae by internal tidal bores. *Science*, **253**, 548–551.

Pineda J. (1994) Internal tidal bores in the nearshore: warm-water fronts, seaward gravity currents and the onshore transport of neustonic larvae. *Journal of Marine Research*, **52**, 427–458.

Pingree R. D., P. M. Holligan and R. N. Head (1977) Survival of dinoflagellate blooms in the western English channel. *Nature*, **265**, 266–269.

Rosenfeld L. J. (1990) Baroclinic semidiurnal tidal currents over the continental shelf off northern California. *Journal of Geophysical Research*, **95**, 22,153–22,172.

Scripps Institution of Oceanography (1989) *Surface water temperatures, salinities and densities at shore stations. United States West Coast*, 1988. SIO reference series No. SIO 89-9. Scripps Institution of Oceanography, University of California.

Shea R. E. and W. W. Broenkow (1982) The role of internal tides in the nutrient enrichment of Monterey Bay, California. *Estuarine, Coastal and Shelf Science*, **15**, 57–66.

Shepard F. P., N. F. Marshall and P. A. McLoughlin (1974) "Internal waves" advancing along submarine canyons. *Science*, **183**, 195–198.

Simpson J. H. and R. D. Pingree (1978) Shallow sea fronts produced by tidal stirring. In: *Oceanic fronts in coastal processes*, M. J. Bowman and W. E. Esaias, editors, Springer-Verlag, Berlin, pp. 29–42.

Smith P. E. and R. W. Eppley (1982) Primary production and the anchovy population in the Southern California Bight: comparison of time series. *Limnology and Oceanography*, **27**, 1–17.

Strickland J. D. H., L. Solórzano and R. W. Eppley (1970) The ecology of the plankton off La Jolla, California, in the period of April through September, 1967. Part I. General introduction, hydrography and chemistry. *Bulletin of the Scripps Institution of Oceanography*, **17**, 1–22.

Summers H. J. and K. O. Emery (1963) Internal waves of tidal period off Southern California. *Journal of Geophysical Research*, **68**, 827–839.

Tont S. (1976) Short climatic fluctuations: effects on diatom biomass. *Science*, **194**, 942–944.

Tont S. (1981) Temporal variations in diatom abundance off Southern California in relation to surface temperature, air temperature and sea level. *Journal of Marine Research*, **39**, 191–201.

Winant C. D. (1974) Internal surges in coastal waters. *Journal of Geophysical Research*, **79**, 4523–4526.

Winant C. D. (1983) Longshore coherence of currents on the Southern California shelf during the summer. *Journal of Physical Oceanography*, **13**, 54–64.

Winant C. D. and A. Bratkovich (1981) Temperature and currents in the southern California shelf: a description of the variability. *Journal of Physical Oceanography*, **11**, 71–86.

Winant C. D. and J. R. Olson (1976) The vertical structure of coastal currents. *Deep-Sea Research*, **23**, 925–936.