SEASONAL AND HIGH-FREQUENCY OCEAN TEMPERATURE DYNAMICS AT SANTA CATALINA ISLAND

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Abstract—An array of underwater thermographs at various depths and sites around Santa Catalina Island has recorded temperatures since 1992. Temperature was sampled at hourly intervals, providing a unique, long-term temperature record suitable for analysis of both annual variation and high frequency internal waves. Seasonal temperature responses varied by depth, with temperatures at 5 m peaking in August and those at 30 m peaking in October. There was often a small increase in temperature during March that was well correlated with the nearest National Oceanic and Atmospheric Administration (NOAA) buoy measurements. The El Niño event of 1997–98 was clearly defined. On shorter time scales, there was evidence for very large internal waves at many sites around the island. Wave amplitude was much larger during the summer when temperature stratification was greatest. In addition, the measurement of high-frequency internal waves provided evidence for non-linear interactions between diurnal and semi-diurnal tidal components. The influence of internal waves on the transport of nutrients and larvae is a key issue in understanding the distribution and abundance of benthic organisms. We computed the spatial and temporal correlations between sites and depths for the semi-diurnal component and briefly review its implications for ocean dynamics and marine biology.

Keywords: El Niño, internal waves, ocean temperature, Santa Catalina, Southern California Bight

INTRODUCTION

Ocean temperature measurements have been recorded along the California coast for many years. List and Koh (1976) analyzed decades of daily samples acquired by bucket drops from piers along the coast, including one at Avalon, Santa Catalina Island. This data set provided excellent seasonal coverage of near-surface water temperature. The California Cooperative Oceanic Fisheries Investigations have recorded temperatures during ship surveys, ongoing since 1949, with some of their sampling sites being near Santa Catalina (CalCOFI 2004). The CalCOFI data have good depth coverage but the time between samples for the most frequently visited stations is on the order of months. For more than 20 years, the National Oceanic and Atmospheric Administration (NOAA) routinely collected ocean surface temperature and other meteorological data from buoys off the California coast. Data from the NOAA archive were analyzed and included in this study.

There also have been many short-duration (i.e., several months) campaigns that addressed specific physical oceanographic issues (Winant 1979, Winant and Bratkovich 1981, Bratkovich 1985, Rosenfeld 1990, Hickey 1992, Lerczak et al. 2003). These studies were located where the depth or bottom topography differed significantly from the shallow but steep slopes of Santa Catalina Island. A review of internal waves indicated the importance of the bottom gradient for ocean dynamics and provided expectations that the Santa Catalina wave environment may be significantly different from that found on a shelf or open ocean (Baines 1986).

Since 1992, Catalina Conservancy Divers (CCD) have maintained an array of underwater thermographs at various depths and sites about Santa Catalina Island. Temperature was sampled at hourly intervals, providing a long-term temperature record suitable for analysis of both annual variation and short-term events. The CCD project complemented the above efforts through its long duration, depth coverage, high-frequency sampling and unique location. For example, the CCD program extended long-term, near-shore collections with additional sampling in depth so that the seasonal changes in the water column may be ascertained. It also sampled frequently enough to permit analysis of tidally-driven internal waves.

Santa Catalina lies in the middle of the Southern California Bight where both seasonal currents and events such as El Niño may differ considerably from those on the Bight's continental shelf. Temperature data have been taken on Santa Catalina in support of specific marine biological studies (Zimmerman and Kremer 1984, Findlay and Allen 2002). However, these experiments were of short duration and therefore not applicable to studies of seasonal effects and were not analyzed for the high-frequency variations we describe below. Hence, the CCD data are a rich resource applicable to analyses of dynamics and seasonal responses with depth for the middle of the Bight.

Our study focused on two specific time scales. Our analysis of long-term variations was designed to answer questions such as, how does temperature vary with season, how does temperature change with depth, and what is the temperature signal of El Niño – Southern Oscillation? The analysis of short-term events emphasized the temperature dynamics associated with internal waves, especially those at diurnal and semi-diurnal frequencies. The influence of internal waves on the transport of nutrients and larvae is a key issue in understanding the distribution and abundance of benthic organisms (Leichter et al. 1996, Leichter and Miller 1999, Pineda 1999, Findlay and Allen 2002). Characteristics of the internal wave environment on Santa Catalina are virtually unknown. The CCD data are valuable for measuring the distribution, amplitude and seasonal variations of these waves.

METHODS

The study was performed at Santa Catalina Island (33°27'N, 118°29'W), one of the southern Channel Islands, which lies approximately 40 km south of the California mainland and within the Southern California Bight. The physical oceanography of the Bight is a complex system consisting of basins, islands and submarine canyons (Hickey 1993). The Santa Catalina slope is much steeper (~6°) than nearby continental shelf regions (~1°) (Smith and Sandwell 1997), where similar type temperature measurements have been performed (Winant and Bratkovich 1981, Bratkovich 1985, Lerczak et al. 2003). The island is surrounded by depths greater than 500 m and is sometimes enveloped by the California Counter Current (Hickey 1993), a small poleward flow adjacent to the coast. At other times the island is within the Southern California Eddy, a cyclonic eddy centered in the middle of the Bight (Lynn and Simpson 1987).

Sixteen thermographs were deployed among seven sites and five depths (Fig. 1). Four sites had thermographs fixed about 0.5 m above the bottom at depths of 4.6, 9.1 and 18.3 m (15, 30, and 60 ft). These sites were Cactus Bay, Little Harbor, East End and one located near the Wrigley Institute of Environmental Studies (WIES). The WIES site had an additional thermograph deployed at 30.5 m (100 ft). Data from these four standard sites were collected beginning in 1992. Three additional sites, Casino Point, Italian Gardens and Pumpernickel, had one thermograph each, located at 12.2 m (40 ft), and each logged data between 1998 and 2000. All thermographs were programmed to sample hourly.

The original thermographs were manufactured by Ryan Instruments (Redmond, WA); later, TidBits^{TM} (Onset Computer, Pocasset, MA) were

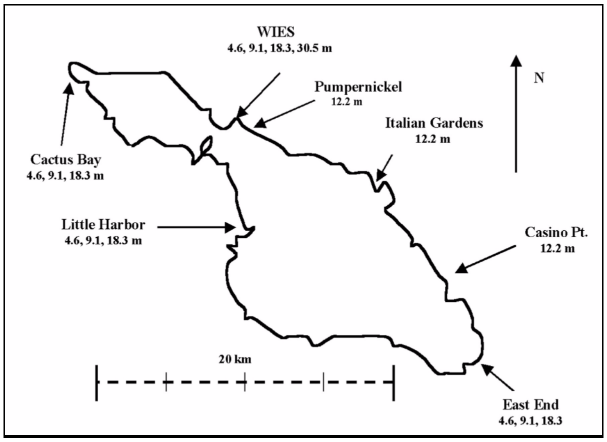

Figure 1. Thermograph sites and depths around Santa Catalina Island.

deployed. Both types typically have an accuracy of 0.3°C and an advertised response time of less than five minutes. The internal clock was stated to be accurate to within a minute a week. Examining calibration data, we found that individual sensors may be as much as 0.5°C biased. However, for the large, relative temperature variations and sampling examined in this study this level of accuracy and response was adequate.

Additional hourly temperature samples measured at NOAA buoys in and around the Southern California Bight were retrieved from the electronic archive of the National Data Buoy Center (2004). Ancillary tidal data were obtained from the Center for Operational Oceanography Products and Services (CO-OPS 2004) sponsored by NOAA. We retrieved hourly samples corresponding to the closest station from which archived data are available, namely, Los Angeles Harbor.

The CCD data were evaluated by examining temperature consistency between depths at a site and comparing the dynamic range and absolute values with measurements from the nearest NOAA buoy (#46025, 33°44’42”N, 119°05’02”W). Outliers produced when the thermographs were at the surface just prior to deployment or after retrieval were deleted. Also deleted were anomalous features and other questionable data determined by long sequences of constant values or physically unrealizable temperatures.

For the analysis of long-term variations, data for each depth were averaged among all the standard sites for the period 1992–2001. Because there was considerable, short-term natural variability in the temperature record, fluctuations were reduced for the study of long-term trends by smoothing the data with a 31-day moving average filter. Measurements from the nearest NOAA buoy were similarly filtered. The temperature anomaly record was constructed by subtracting the mean temperature for each day and depth as determined over the length of the study.

We defined short-term variations as those occurring within one day or less. We characterized the frequency and amplitude of these temperature variations at each depth and correlated variations among the depths and, to a more limited extent, around the island. The WIES-site data were emphasized due to the better depth coverage and quality of data obtained there. For these data the frequency and amplitude characteristics also were examined in relation to season.

Table 1. Study intervals for short-term temperature variations around Santa Catalina Island.

ID	Start date	End date
W98	19 December 1998	29 January 1999
W99	19 December 1999	29 January 2000
W00	18 December 2000	29 January 2001
S98	10 July 1998	20 August 1998
S99	1 August 1999	11 September 1999
S00	10 July 2000	20 August 2000

Six periods from 1998–2000 were chosen for analysis of short-term variations: three during the summer and three during the winter, when stratification was expected to be the greatest and least, respectively. Each period consisted of a contiguous set of 1,000 hours of data sampled hourly (Table 1). WIES-site thermograph data were available for each depth and for each interval. Data also were available for at least one depth for every site about the island for the summer 1999 (S99) interval. Temperature stratification at the WIES site was computed from the average temperature for each 1,000-hour interval for each depth.

Spectral content, coherence and phase values were computed via Fourier transforms of the time series. The power spectral density (PSD) was computed from the entire 1,000-hour time series after subtraction of the average for each depth. The power spectral estimates were averaged over five frequency bins, providing a frequency resolution of 0.005/hr and a Nyquist frequency of 0.5/hr. Random toggling of the least significant bit at the reported temperature resolution produced a noise of –22 dB relative to a power of 1°C^2-hr. The spectral coherence and phase differences were computed with 30 degrees of freedom, which for random noise yielded an average coherence of 0.1.

RESULTS

Seasonal, Annual and Long-Term Variations

Long-term variations were examined using the five time series (Fig. 2) representing the standard-site averaged and temporally smoothed data (i.e., the four depths and the surface data from the

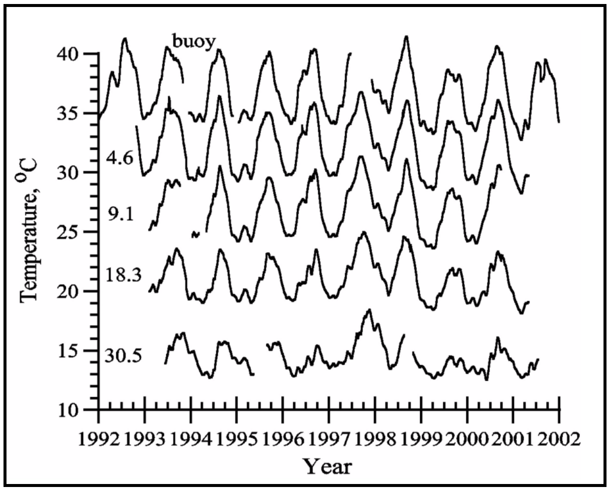

Figure 2. Averaged temperatures by depth measured by both the thermograph array off Santa Catalina Island and the Santa Monica Basin buoy, 1992-2001. All traces except the 30.5 m depth are offset from adjacent ones by 5^{0} C.

nearest NOAA buoy). The 30.5-m depth time series represented data only from the deep thermograph at WIES. There was no overall trend through the decade, however there was considerable variation year to year (Fig. 2). The seasonal and yearly modulations at shallow depths were consistent with those found at the nearest NOAA buoy. The maximum temperature was 22°C at the 4.6-m depth, measured in the summer of 1998. The coldest temperature was slightly less than 13°C at 30.5-m depth, measured during the winters of 1999 and 2000.

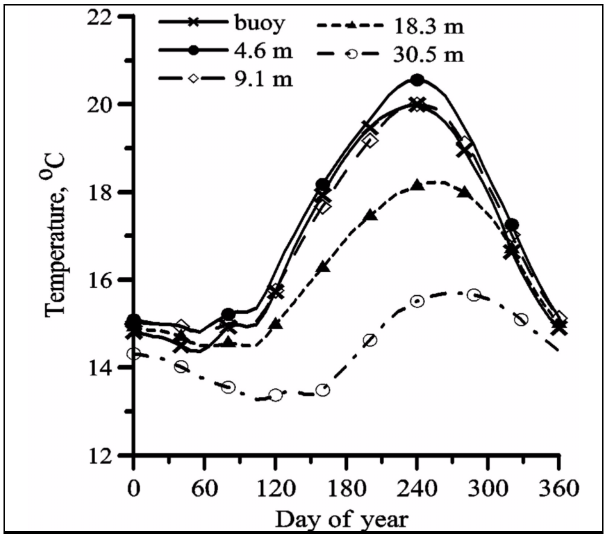

Figure 3. Average daily temperature from 1992–2001, Santa Catalina Island array and Santa Monica Basin buoy.

The average yearly variation was 6°C at 4.6 m but only 2.5°C at 30.5-m depth (Fig. 3). The temperature at 4.6 m reached its maximum in August, but at 30.5 m, the maximum was in October. Similarly, the minimum temperature at shallower depths occurred at the end of February while at the deepest depth (30.5 m) the lowest temperature was in April. There was a rise in temperature with varying amplitude observed repeatedly in March that we termed the “March Hump”. In the yearly averages shown, this rise had amplitude of 0.25°C (Fig. 3).

El Niño - Southern Oscillation (ENSO) events were responsible for the high-temperature years of 1994 and 1997/1998. The 1997/1998 El Niño was followed by some of the coldest temperatures (La Niña) measured by the CCD array as shown by the yearly anomaly (Fig. 4). The El Niño event of 1997/1998 was the most prominent anomaly, with temperature changes of almost 3°C at the deepest depth. The large signal of the 1997/1998 El Niño commenced in June of 1997 and reached its maximum at all depths in February 1998. The anomaly was largest, 3°C, at the 30-m depth and slightly smaller, 2.5°C, at the other depths. The temperature then decreased until March 1998 when it increased again, reaching a local maximum in August/September 1998. The largest temperature anomalies for this second signal peaked at the deeper depths first. The El Niño event was followed by La Niña when the coldest temperatures of the array were recorded. The La Niña anomaly was –2°C at 30.5 m, in September 1999.

Short-Term Variations

A representative example of the short-term variations is found in the 200 hours of data from S99 for the four thermographs at WIES (Fig. 5). Temperatures measured simultaneously showed a trend of decreasing temperature with depth, with exceptions falling within the published error (0.3°C). Strong cyclic fluctuations increased in amplitude with depth. Changes as large as 6°C were found in the data from the deepest thermograph (Fig. 5). The modulations at the 4.6-m thermograph were smaller and the discreteness produced by the digitization can be seen in its trace. The major fluctuations had a period of about 12 hours, with considerable variation in amplitude.

The three intervals per season exhibited similar stratification values. We found that the water was highly stratified during the summer with an average temperature gradient of 0.2°C/m, but there was little stratification in the upper 20 m during the winter and a gradient of 0.05°C/m at the deepest depth. These were the same stratification values derived from the yearly averages (Fig. 3).

PSDs corresponding to the data from S99 for each of the four depths at WIES (Fig. 6) showed well-defined spectral peaks at every depth. The largest peak was at a frequency of 0.081/hr (i.e., a 12.3-hour period) and corresponded to the M_2 semidiurnal tide. The next largest peak besides the DC level was at 0.041/hr, i.e., at the diurnal period. These peaks were also found in the PSDs computed from water-height records of Los Angles Harbor for the same period (Fig. 7). In addition to these tidal peaks, there existed temperature oscillations at four other frequencies not found in the water-height records: 0.121/hr (8.3 hr), 0.163/hr (6.1 hr), 0.201/hr (5.0 hr), and 0.243/hr (4.1 hr). The power values were greatest at the deepest depth. Coherence between the depths (Fig. 8) was high, averaging 0.8 at the semidiurnal frequency and 0.4 at the ultrasemidiurnal frequencies.

The PSDs generated from S99 (Fig. 6) were typical of those computed for the six time intervals studied. The summer fluctuations were more energetic than the winter ones (not shown) by approximately 10 dB. The ultrasemidiurnal peaks also were much weaker during the winter.

We examined phase differences among the depths at the WIES site, an example of which is the phase relative to the variations at 30.5 m for the semidiurnal frequency (Fig. 9). There was a pronounced seasonal difference in the phases. During the summer, variations at all depths were in phase, defined here as being within 45°. However, during the winter, the 4.6-m data were opposite in phase from the deeper depths. This was usually the case for the peaks at the diurnal frequency, too. The phase relationship at other frequencies was markedly more complicated and not systematic between seasons.

Large semidiurnal variations were found around the island. Valid data existed for the middle depths at seven sites about Santa Catalina for the three summer intervals with the exception of Pumpernickel (missing S00 data) and Italian Gardens (missing S98 data). PSDs were generated from S99 data from six of these sites (Fig. 10). Multiple, large ultrasemidiurnal peaks were found at each site with the exception of East End, where only the diurnal and semidiurnal peaks were seen. There was a large similarity between the adjacent sites, Pumpernickel and WIES, which were separated by approximately one kilometer. Although the single thermograph at Pumpernickel had a high noise level (~-6 dB) its spectra looked

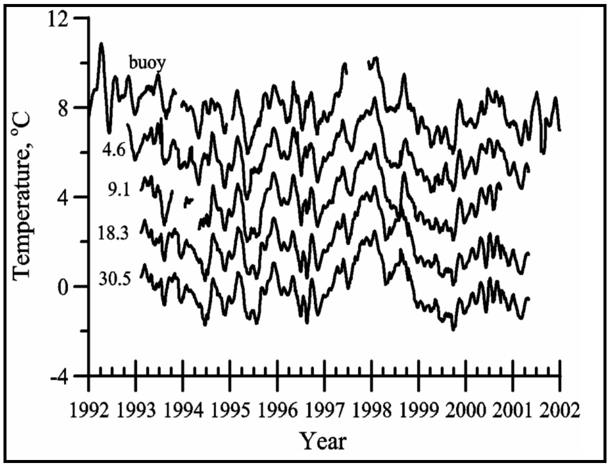

Figure 4. Temperature anomaly for Santa Catalina Island and Santa Monica Basin buoy, 1992–2001. All traces except the 30.5 m depth are offset from adjacent ones by 2^{o} C.

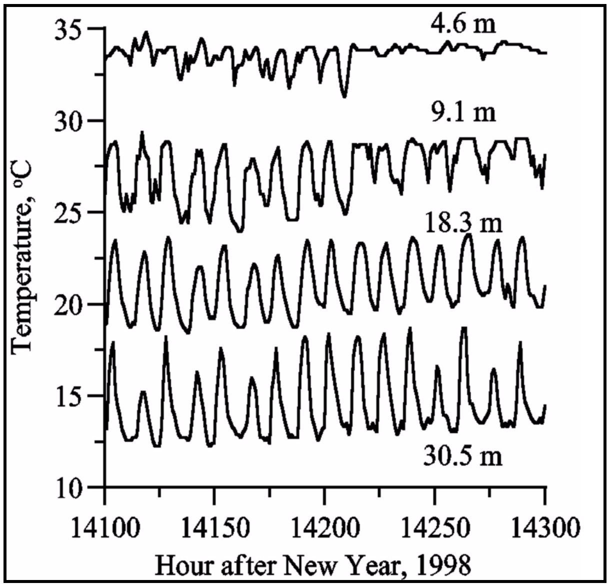

Figure 5. Original temperature records for four depths at WIES, Santa Catalina Island, 11–19 August 1999. All traces except the 30.5-m depth are offset from adjacent ones by 5^{o}C.

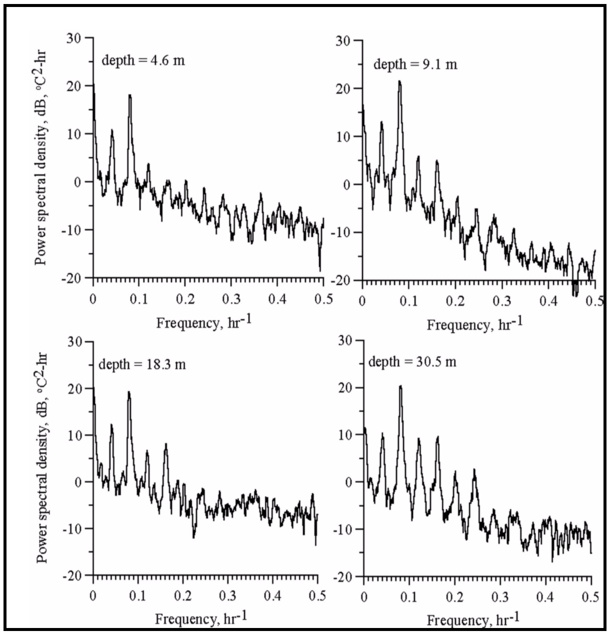

Figure 6. Power spectral densities for each depth at WIES, Santa Catalina Island, for 1 August 1999 to 11 September 1999.

very similar to those from WIES for power densities above this value.

We measured phase differences at the semidiurnal frequency among the various sites on the leeward side of the island for all summer intervals. These conditions yielded the strongest signal and therefore the least phase error. Phase differences relative to the WIES 18.3-m data were computed with respect to distance east of WIES (Fig. 11). This distance coordinate was chosen to align East End closer to Casino Point by compensating for the curvature of the island on its eastern side. The Pumpernickel and WIES data were in phase, i.e., differed by less than 45°; however, between WIES and Italian Gardens there were pronounced phase differences of about 150°. The measured differences between WIES and the other sites varied significantly. The positive shift in phase between WIES and Italian Gardens, as well as between Casino Point and East End suggests that phase values may have been aliased between Italian Gardens and Casino Point (i.e., they changed by more than 180° relative to WIES). Accordingly, we unwrapped the values (Fig. 11). The result implied a smooth progression in phase across the leeward side of the island. Positive values indicated a phase lead relative to WIES, i.e., the apparent phase velocity was east to west.

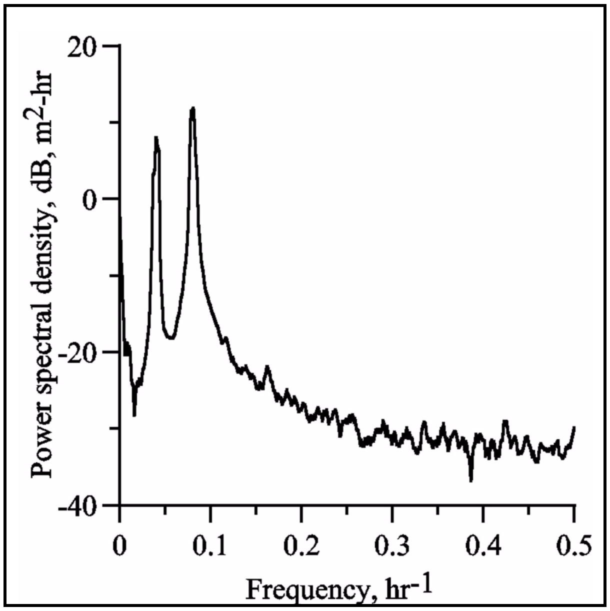

Figure 7. Power spectral density for the water level in the Los Angeles Harbor for 1 August 1999 to 11 September 1999.

DISCUSSION

Analysis of the CCD temperature data produced several unexpected results. In the yearly and seasonal trends, the most surprising feature was a small rise in temperature that occurred around March in most years. The effect was most noticeable in the shallower sensor records but it was also found in the Santa Monica Basin buoy data. However, it did not appear in the data from any other NOAA buoys located north or south of the Santa Monica Basin (not shown). The only independent record that we have of this “March Hump” is from List and Koh (1976); compiling data from bucket drops from piers over several decades, they noted an anomalous winter warming of similar magnitude measured at all of the southern California stations, but not at central and northern California locations. Curiously, the warming did not appear in ancillary studies by Souza and Pineda (2001) using some of the same southern California data taken from the Scripps’s pier in La Jolla, CA.

The seasonal changes at Santa Catalina were different from those reported on the nearby continental shelf (Winant and Bratkovich 1981). There, the bottom water (i.e., at depths greater than

20 m) was warmest during the winter and cooled during the summer. In the CCD data we found that changes in the deeper depth temperature lagged those in the shallower depths by approximately one month and that the deep-depth maximum temperature was in the early fall.

The measurements recorded during the 1997/1998 El Niño were consistent with the values reported for the 10-m depth by Lynn and Bogard (2002). Their results are derived from the CalCOFI data base, specifically, station line 90, which extends from Dana Point, CA, along 240°T, and passes between Santa Catalina and San Clemente Islands. Although their anomaly calculation was based on annual biharmonic means from 1950–1998 and ours was based on the CCD data interval (Fig. 2) there was good agreement between the two data sets. From their published maps, they also measured two temperature peaks, between 2° and 3°C, occurring at the same time and place (within the coarse resolution of the ship surveys) as those found in the CCD data.

In the short-term trends, we were surprised by the size of the temperature fluctuations, their high frequency and that they increased in amplitude with depth. A 2-m amplitude tidal cycle during the summer stratification with a gradient of 0.2°C/m will produce a temperature signal with amplitude of 0.4°C; however we found fluctuations of up to 6°C at the 30.5-m sensor. These corresponded to a vertical water displacement of 30 m at a depth of 30 m. Temperature changes of this magnitude also were found near WIES by Zimmerman and Kremer (1984). Essentially, surface water was being transported to depth. This phenomenon appeared at all the thermograph sites. The large amplitudes of the WIES-site fluctuations produced large PSD peaks of up to 20 dB. For comparison, a 1.0°C amplitude modulation produces a power spectral density peak of 16 dB when smoothed and processed as the CCD data were. The importance of these large fluctuations is that deep depths experienced a daily range in temperature that was equivalent to its yearly variation. The approximately 10 dB difference in power values found between summer and winter measurements corresponded well to the difference in average stratification, i.e., the temperature gradient was almost four times larger (i.e., 12 dB) during the summer relative to the winter.

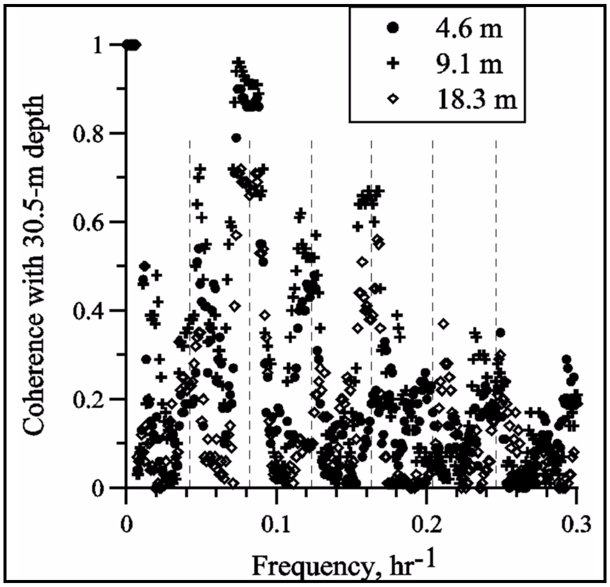

Figure 8. Coherence at WIES between the temperature at 30.5 m and those at the designated depths from 1 August 1999 to 11 September 1999. Dashed lines indicate frequencies of prominent peaks in the power spectra.

Rosenfeld (1990) measured much smaller temperature variations at similar depths to those studied here. However, that study was conducted in the open ocean where the seabed was much deeper. With an experimental setup off the Florida Keys similar to the CCD arrays, Leichter et al. (1996)

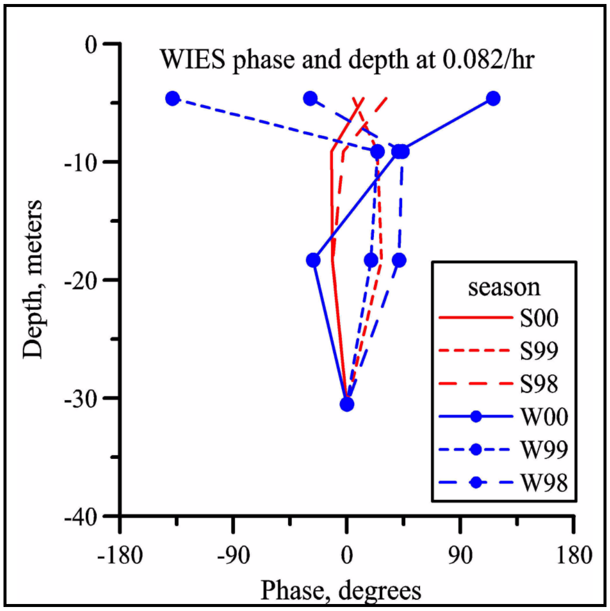

Figure 9. Phase of the M2 tidal frequency relative to that at 30.5 m, measured at the Wrigley Institute of Environmental Studies, Santa Catalina Island, summers and winters from 1998–2000.

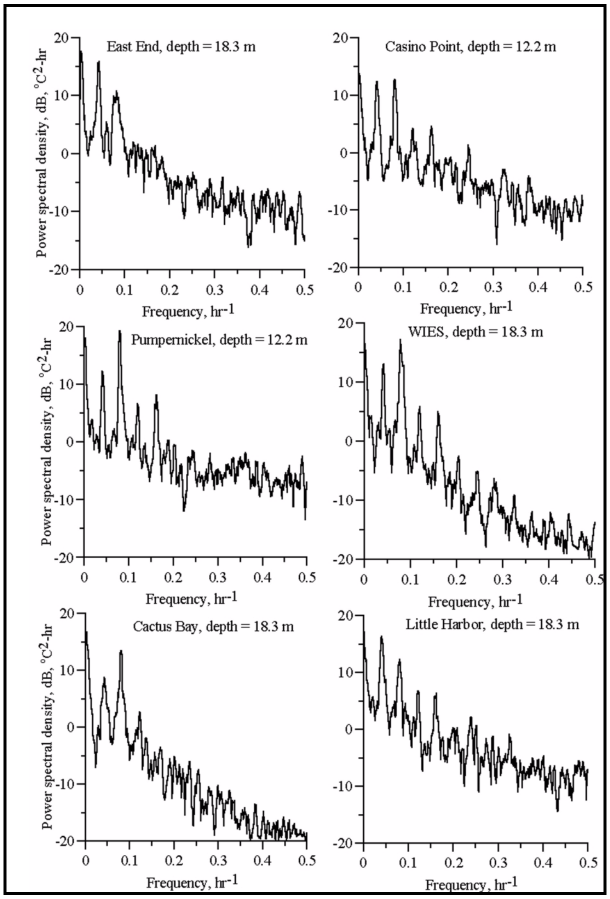

Figure 10. Power spectral densities computed from data measured simultaneously at six sites around Santa Catalina from 1 August to 11 September 1999.

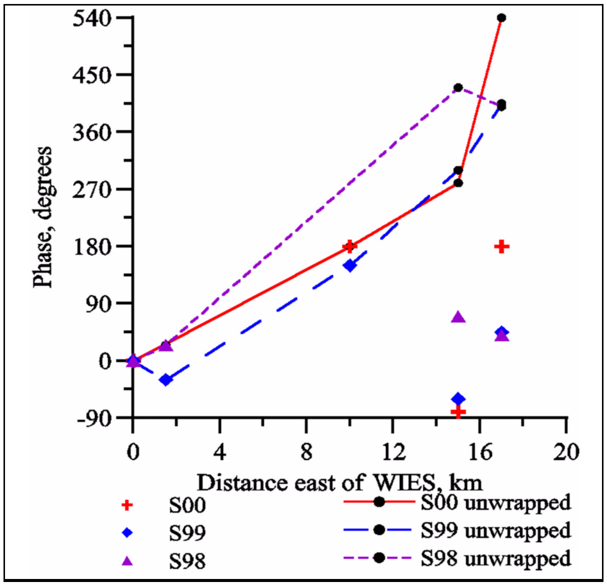

Figure 11. Phase differences at the semidiurnal period, between WIES and other leeward sites of Santa Catalina Island for the three summer seasons listed in Table 1.

found that deeper sensors measured larger temperature fluctuations. Those variations were comparable in size to the CCD results. Leichter et al. (1996) also found that the temperature variations with the diurnal tide were more complex than just the shifting of water level and thermocline.

Perhaps the most similar experiments to the CCD program were those conducted by the Scripps Institute of Oceanography (Winant 1979, Winant and Bratkovich 1981, and Bratkovich 1985) on the continental shelf off Del Mar, California, about 150 km to the southeast of Santa Catalina Island. Using both temperature loggers and current meters situated with comparable bottom and instrument depths they reported temperature variations similar to those observed at Santa Catalina, with the corresponding currents directed cross-shore. From graphs provided in their report, we found that their bottom sensors in 30-m depth water occasionally measured temperatures similar to those measured at the surface, again suggesting that surface water was brought to depth.

The observations that power peaks are found at frequencies greater than the semidiurnal tidal frequency was likewise unexpected. These higher frequency components were widespread in the CCD data, occurring across the island with the exception of East End. Reports of higher-frequency (greater than 0.081/hr) modulations appear to be rare. Baines (1986), in a discussion of internal tides on continental slopes, reported a single observation of higher-frequency waves out of 18 studies. Winant and Bratkovich (1981) and Bratkovich (1985) found these ultrasemidiurnal frequencies in their Southern California shelf experiment for summer data; however, the powers at these higher frequencies were much larger in the Santa Catalina data.

These ultrasemidiurnal features were not observed with any significance in the nearest available corresponding tidal record. The Scripps' experiments also did not find water-level variations corresponding to these higher frequencies. The frequencies at which the features appeared are consistent with a nonlinear interaction of the two principal tidal components (diurnal and semidiurnal), plus interactions between the primary and the secondary components. For example, the sum of frequencies of the primary components, the diurnal (0.041 hr^{-1}) and the semidiurnal (0.081 hr^{-1}), yield the quadratic component at 0.122 hr^{-1}. Similarly the sum of the frequencies of the diurnal and the first quadratic component equals the frequency of the first cubic at 0.163 hr^{-1} while the sum of the semidiurnal and first quadratic yield the frequency of the second cubic at 0.203 hr^{-1}, etc. The summation of the various frequency components produced large temperature changes when they occurred in phase. Interaction of the basic tidal frequencies is expected to produce complicated vertically-structured currents, i.e., higher baroclinic modes, and the phase data (Fig. 9) provided evidence for the existence of these modes during the winter. However, interpretation of the phase data was complicated by the displacement of the thermographs in cross-shore distance as well as depth because they were bottom rather than water-column sensors.

Phase differences between sensors may be due to an error in the time stamps. Because some thermographs were left in the field for well over a year and the timing was not calibrated and reported upon retrieval, there may be significant, unknown timing errors among the instruments due to timing drift within the advertised specifications. The error could be as large as 30° in phase for the semidiurnal period. However, consistency among phase measurements made over three summer seasons (Fig. 9) and with different instruments suggests that the timing errors were small.

The currents implied by the short-term temperature variations have implications for marine biology. For example, the intra-day temperature variation at 30 m in some cases may be as large as the average yearly variation. To the extent that nutrient supply is non-linearly correlated with temperature (Zimmerman and Kremer 1984), these short-term variations indicated that more nutrients may be available than an analysis of yearly variations would indicate. Nonlinear internal waves (internal bores) are conjectured to be a physical mechanism for larval transport in the near-shore region (Pineda 1999). In an analysis of internal wave bores off La Jolla, California, Pineda (1999) found that surface waters were directed toward shore, while water at depth flowed offshore. Pineda (1999) measured enhanced densities of larvae in the shoreward flow. Findlay and Allen (2002), in work performed on Santa Catalina, suspected internal bores of enhancing the settlement of kelp bass, *Paralabrax clathratus*, and of shortening larval duration.

Finally, we note that the CCD array permitted measurements of the along-shore scale length of the semidiurnal variations. The relative-phase measurements suggested that the along-shore scale length of the temperature variations was on the order of tens of kilometers. The along-shore distance between WIES and Casino Point or East End is greater than 20 km (Fig. 1) and the phase difference was approximately one cycle (unwrapped) or less (measured). This derived scale length did not imply the existence of a propagating signal as it was only an apparent velocity that was measured.

CONCLUSIONS

Findings of the analysis of seasonal and yearly temperature fluctuations in the ocean adjacent to Santa Catalina Island are that the average yearly temperature variation was 6°C at 4.6 m and 2.5°C at 30.5 m and that the temperature variations at deeper depths lagged changes found in the shallower depths by approximately one month. There was also an average 0.25°C increase in temperature observed in many years during March. The 1997/98 El Niño temperature anomaly exhibited two maxima followed by cold La Niña temperatures. The El Niño signal was largest (3°C) at 30.5 m.

Results from the study of high-frequency variations suggest statistically significant changes in temperature occurred at all study depths and at all locations around Santa Catalina Island at diurnal and semidiurnal frequencies. The modulation amplitudes were greater in summer relative to winter and quantitatively consistent with the seasonal change in stratification. The amplitude of the temperature variations increased with depth and were much larger than expected from tidal shifting of the thermocline alone. Temperature variations were found at frequencies higher than those of the primary tidal components were. These higher frequency components were frequency combinations of the principal tidal components and components derived from the principal components.

Phase analysis among the different depths at WIES indicated that the shallow (4.6-m depth) variations at the diurnal and semi-diurnal frequencies during the summer were in phase with the variations at deeper depths; however, they were of opposite phase during the winter. Phase analysis among the different sites found that the alongshore scale length of the semidiurnal modulation was tens of kilometers.

The original purpose of the CCD project was to establish a temperature baseline for Santa Catalina. By accomplishing this goal, a unique dataset was recorded that provided the opportunity to address the physical oceanography of the Southern California Bight and oceanic islands, and its effects on local marine biology. Future work will be directed toward understanding these measurements and their consequences.

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