# Bottom Temperature Fluctuations in the Northeast Pacific Ocean at Depth 920 to 1140 m

HOWARD W. BROEK

*Bell Telephone Laboratories, Whippany, New Jersey*

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## ABSTRACT

Motions of water at medium depths on the continental slopes have seldom been measured. In this experiment, seven thermistors were placed on the ocean bottom at depths from 920 to 1410 m on the continental slope from 32° to 47°N in the northeast Pacific Ocean. Daily readings were taken for up to five years. Maximum-to-minimum fluctuation of the isotherms were as much as 320 m. A temperature decline in March coincides with the spring reversal of surface current. The largest oscillation is semiannual, and its amplitude shows little or no dependence upon latitude. The amplitude of the annual oscillation increases in the poleward direction. The Madden–Julian oscillation is prominent in the temperature spectra and cross spectra at 48 to 50 days periodicity; its amplitude has little dependence upon latitude.

## 1. Introduction

Currents and their fluctuations in the upper few hundred meters off the California coast were summarized by Hickey (1979). Work on these currents has continued, and many reports are available in the recent literature. In contrast, few reports are concerned with observations at greater depth, and fewer still are concerned with the continental slope.

This paper reports on temperature fluctuations on the continental slope, at depths from 920 to 1410 m and from 32° to 47°N. Temperature fluctuations imply vertical motions of the isotherms, motions that may or may not be wavelike. Measurements are made simultaneously at different latitudes in order to determine if the vertical motions of the isotherms are wavelike and to determine the alongshore component of wave propagation velocity.

Vertical motions of water are superimposed upon horizontal motions at the corresponding depths. If fluctuations in the isotherms proceed along the slope faster than the known horizontal water velocity, then the process can be called wavelike.

Surface currents off California have a well-known seasonal reversal in March that ‘‘affects the entire water column’’ (Breaker and Mooers 1986). Another objective of the present study is to see what effects the reversal has at 920-m to 1410-m depth and trace how the reversal progresses with latitude.

Data presented here cover 1961–65, when only the weak El Niño of 1963 occurred (Quinn et al. 1987; Graham and White 1988). Hence no effect of El Niño is expected in the present paper.

The Cape Mendocino data from the present paper were previously reported (Broek 1969a) and showed a very strong semiannual periodicity, a fortnightly tide, three diurnal tidal components, and one semidiurnal. Tides are also found near 3400 m on the continental slope of the northeast Atlantic (Thorpe 1987). The south Cape Mendocino data has a strong periodicity at 49 days (Broek 1969a), and this peak can be identified with the Madden–Julian oscillation (MJO) (Madden and Julian 1971, 1972, 1994). On the other hand, temperature fluctuations from 2000 m on the northwest Atlantic slope show no spectral peaks at all (except for a possible broad peak near 50 days periodicity), but increases in temperature are consistently more sudden than decreases (Broek 1969b).

Previous studies are extended by analyzing five years of data taken over an extent of 15° lat and depths from 920 to 1410 m. This paper is unique in that the wide range of latitudes studied permits observation of possible wavelike motion along the continental slope.

## 2. Method

### a. Experiment

Thermistors were placed along the northeast Pacific continental slopes at seven locations, listed in Table 1. The thermistors were enclosed in telephone cables. Measurements were performed once each day, usually but

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*Corresponding author address:* Howard W. Broek, 57 White Oak Circle, St. Charles, IL 60174-4164.

TABLE 1. Location of thermistors on sea bottom.

| Station | Location | Latitude (°N) | Depth (m) | Record length (yr) |
|---|---|---|---|---|
| 1 | Off Pacific Beach, Washington | 47 | 920 | 5.25 |
| 2 | Off Cape Mendocino, California | 41 | 1160 | 5 |
| 3 | 90 km south of Sta 2 | 40 | 1410 | 5 |
| 4 | Off Pt. Sur, California | 37 | 1360 | 5.25 |
| 5 | 90 km south of Sta 4 | 36 | 1380 | 5.25 |
| 6 | Off San Nicolas I., California | 33 | 1080 | 3.2 |
| 7 | 70 km south of Sta 6 | 32 | 1050 | 3.2 |

not always at the same time of day. Stations 6 and 7 produced only 3.2 years of data 1 January 1961 to 15 March 1964, before the galvanometer failed.

### *b. Data*

The period starting 1 January 1961 was chosen for analysis. Occasional missing data were supplied by interpolation. A few badly inconsistent measurements were replaced with interpolated values. Plots of data reveal a dominant semiannual oscillation in temperature (Figs. 1 and 2) and sometimes semimonthly oscillations.

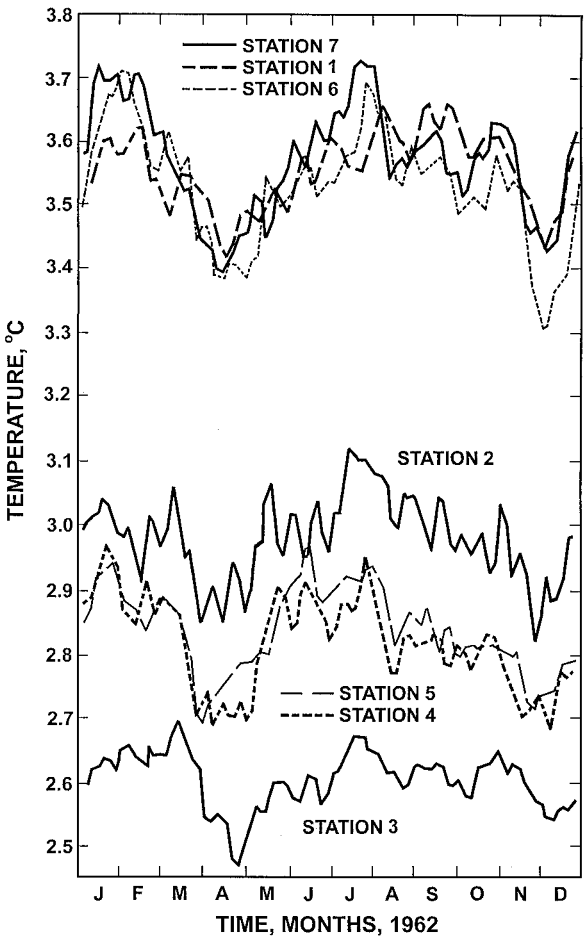

FIG. 1. Temperature data from the seven thermistors for 1962. Locations are given in Table 1.

### *c. Spectral analysis*

Linear fits were made and subtracted from the data. This zero-average data was then filtered by taking a running average of four sucessive data points, then taking a running average of five data from the resulting series, and then likewise with six. Spurious peaks introduced by this triple filter are at least 45 dB below the corresponding real peak, and hence are too small to contaminate the spectra. Numerical filters were discussed by Blackman and Tukey (1959). The data were decimated to every fourth datum of the filtered data. Covariance and spectral analyses were performed on the decimated data. The Parzen cubic lag window was used because its very low sidelobes (26.9 dB down: Parzen 1961) preclude introduction of spurious peaks.

Spectral estimates from analysis of the filtered data have a 90% chance of being within a factor of 2.23 of the true value, according to the tables in Blackman and Tukey (1959).

### *d. Tides and tidal aliasing*

Motion along the continental slopes is known to be affected by tides, and sampling once per day introduces the possibility of aliases of the diurnal and semidiurnal tides.

The periodicities and potentials of the tides were computed exhaustively by Doodson (1922) and by Wunsch (1967). The semiannual tide has a potential 6.3 times as great as that of the annual tide. The strongest monthly tide is at the anomalistic month, 27.554 days or 0.0363 cpd. The strongest semimonthly tides are at 13.660 and 13.633 days or 0.0732 and 0.0734 cycles per day.

The diurnal and semidiurnal tides are expected to produce their strongest alias peaks at 14.765 and 14.191 days periodicity (0.0677 and 0.0705 cpd). Aliasing to one or two cycles per year is not a great problem since seasonal effects and long-period tides are expected to be prominent at one and two cycles per year.

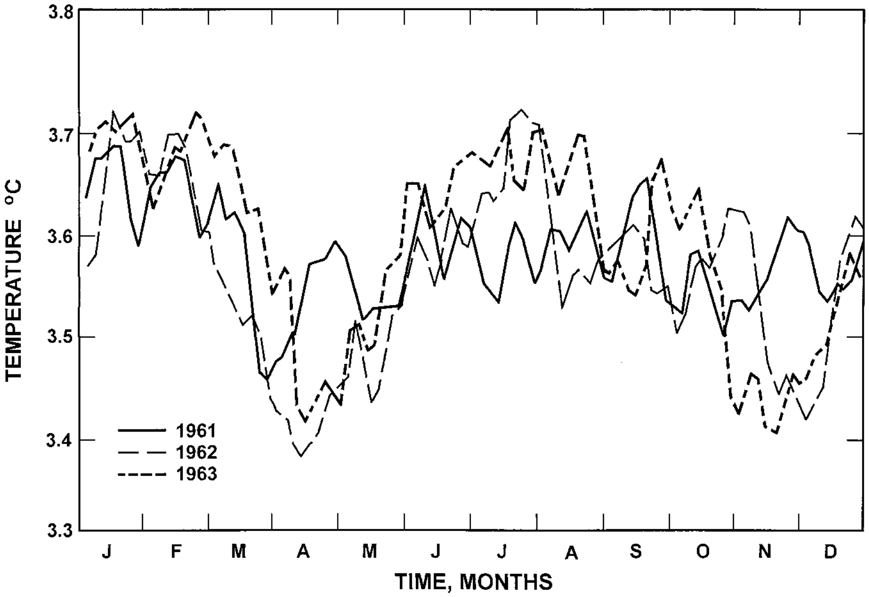

FIG. 2. Temperature data from station 7 for 1961–63.

## 3. Results

### a. Temperature data

The semiannual oscillation (Figs. 1 and 2) has temperature maxima near 1 February and 15 July and minima near 15 April and 15 November. The semiannual effect is seen in all years.

In the last half of 1962 and early 1963, surface waters had ‘‘extensive and persistent warmth’’ (Namias 1963). Weather was abnormally warm. Typhoon Freda hit northern California in October 1962. Neither of these effects appear at depths studied, 920 to 1410 m (Figs. 1 and 2).

### b. Temperature densities

Temperature densities (at intervals of 0.01°C) were plotted for each of the seven stations. Five of the densities are symmetric, but a low-temperature tail was seen at stations 1 and 7. A low-temperature tail is also seen in temperature densities at 2000 m in the northwest Atlantic (Broek 1969b).

The average temperatures (Table 2) are compared to values interpolated from linear interpolation of data of Emery and Dewar (1982). Data in this study is 0.23°C lower at station 1, 0.11° lower at stations 2 and 3, 0.05 lower at stations 4 and 5, but 0.10° higher at stations 6 and 7. Differences can be attributed to measuring temperature over the continental slope instead of in the water away from the slope, and averaging five years of daily data.

Rate of change of temperature with depth (i.e., vertical temperature gradient) was between 0.00155 and 0.0026°C $\mathrm{m}^{-1}$ for all thermistors, according to Emery and Dewar (1982) data. These rates of change gave the approximate extents of displacement of an isotherm (Table 2). Over a 5-yr period, the highest and lowest inferred positions are up to 320 m apart in depth.

### c. Temperature correlations

The temperature autocorrelation at station 1 (Fig. 3) crossed zero at about 90 days lag and had broad peaks near one and two years lag. The temperature autocorrelations at stations 2 and 3 show broad peaks at semiannual intervals (Fig. 4) rather than the annual intervals

TABLE 2. Temperature fluctuations.

| Station | Average temperature (°C) | Standard deviation (°C) | Extent of variation (°C) | Isotherm motion (m) | Rms 2-cpy amplitude (°C) |
|---|---|---|---|---|---|
| 1 | 3.551 | 0.085 | 0.45 | 86 | 0.035 |
| 2 | 2.971 | 0.092 | 0.50 | 160 | 0.037 |
| 3 | 2.580 | 0.067 | 0.35 | 113 | 0.034 |
| 4 | 2.825 | 0.076 | 0.45 | 125 | 0.036 |
| 5 | 2.836 | 0.060 | 0.45 | 125 | 0.030 |
| 6 | 3.508 | 0.093 | 0.50 | 132 | 0.047 |
| 7 | 3.580 | 0.097 | 0.50 | 132 | 0.048 |

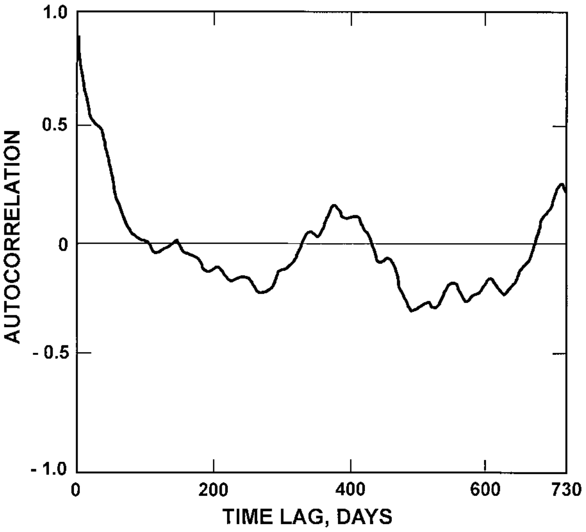

Fig. 3. Autocorrelation of temperature from station 1.

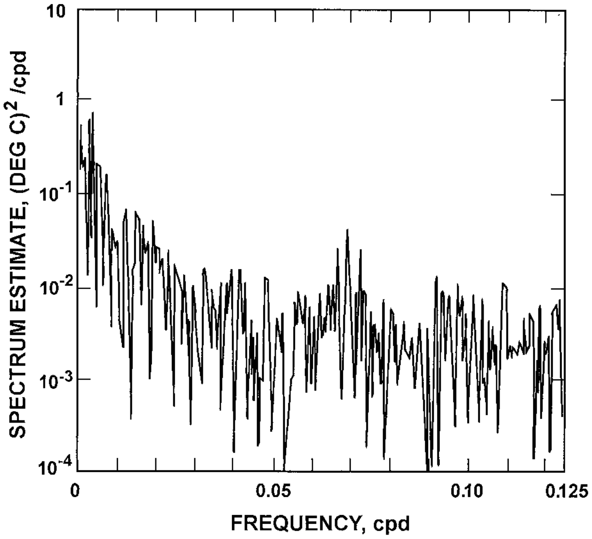

Fig. 5. Spectral estimate from station 3 from the Fourier transform.

observed at station 1. The autocorrelation at station 2 has a semimonthly wiggle of tidal origin.

Crosscorrelations of temperatures at adjacent stations show dominant annual or semiannual oscillations.

### *d. Temperature spectra*

The spectrum from station 1 has its greatest peak at 1 cycle per year (cpy) or 0.00274 cycles per day (cpd), and a second peak at 2 cpy. A peak at 0.020 cpd lies at the frequency of the Madden–Julian oscillation (MJO) (Madden and Julian, 1971, 1972, 1994).

Spectra from stations 2 and 3 have greatest peaks near 1 and 2 cpy (Broek 1969a). The spectrum from station 3 has a wide peak near 0.07 cpd. The analysis was repeated via the fast Fourier transform (Fig. 5). Peaks are seen at 0.0674, 0.0703, and 0.0733 cpd, in agreement with the tidal predictions of 0.0677, 0.0705, 0.0732 cpd. The peaks are interpreted, respectively, as an alias of a semidiurnal tide, an alias of a diurnal tide, and a semimonthly tide.

These three peaks also appear in the spectrum from station 4, and two of them appear in the spectrum from station 5 (Fig. 6). The Madden–Julian oscillation was seen at 0.02 cpd at stations 4 and 5.

Spectra from stations 6 and 7 have a strong semiannual peak, but no annual peak at all. The spectrum from station 6 has a semidiurnal tidal alias at 0.0677 cpd, while the spectrum from station 7 has a diurnal

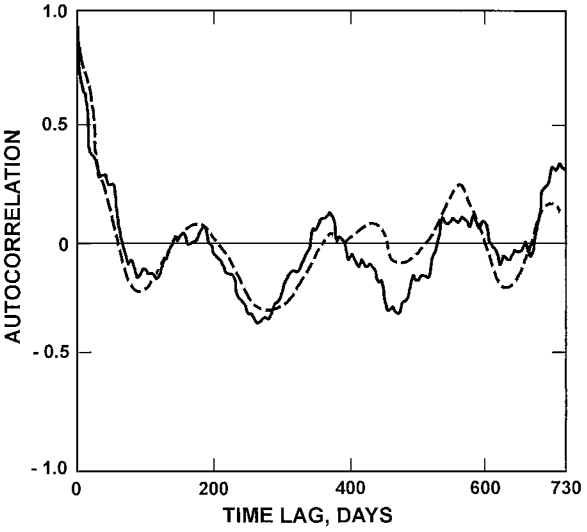

Fig. 4. Autocorrelation of temperature from the station 2 (solid line) and station 3 (dashes).

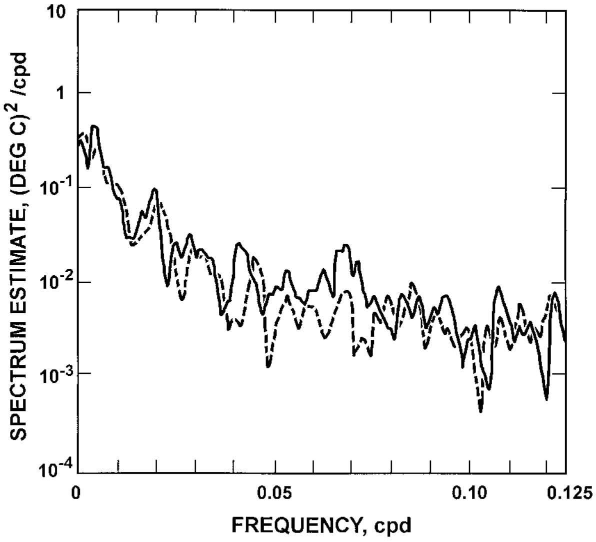

Fig. 6. Spectral estimates from station 4 (solid line) and station 5 (dashes).

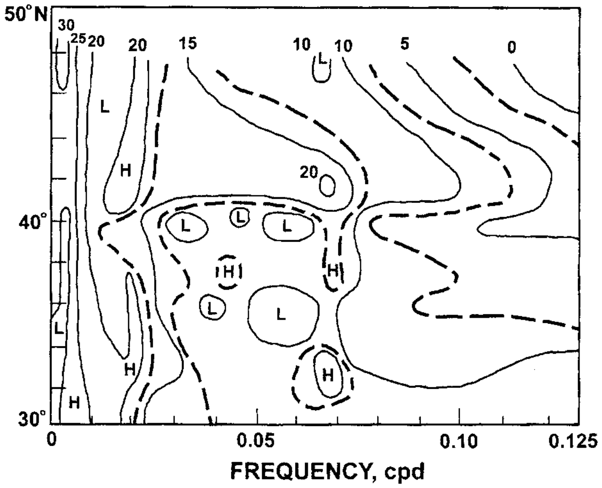

FIG. 7. Contours of spectral estimates from stations 1 to 7 vs latitude and frequency. Labels on the curves represent decibels (dB) above 0.001 $(°C)^2$ $\text{cpd}^{-1}$. Local maxima and minima are marked "H" and "L" (high and low). Dashed curves represent intervals of 2.5 dB.

tidal alias at 0.0705 cpd. The MJO was seen at 0.021 cpd at station 6, but not at station 7.

Contours of energy density versus latitude and frequency are plotted in Fig. 7. Peaks in the semiannual, MJO, and semimonthly regions appear to extend over most of the latitudes studied.

### *e. Coherences and cross spectra*

The median coherence for zero true coherence is 0.085 for the case of $N/M = 5/2$ (data length divided by maximum lag) and is 0.068 for the case of $N/M = 3.2$, and these values are relevant to the averaged data, which has been used to obtain coherence from zero to 0.08 cpd. Coherence from 0.08 to 0.5 cpd has been derived from the daily data, and median coherence for zero true coherence is 0.021 for 5 years of data and 0.017 for 3.2 years of data.

Coherence between stations 1 and 2 was high at the semiannual frequency and at the MJO frequency of 0.019 cpd. A peak in coherence was seen at 0.068 cpd, which is an alias of the most prominent semidiurnal tide.

Cross spectra between stations is as follows.

- Cross spectra between stations 2 and 3 have a large semiannual peak, a broad MJO peak about 0.020 cpd, tidal aliases at 0.068 and 0.070 cpd, and a tide at 0.073 cpd.
- Cross spectra between stations 3 and 4 have annual and semiannual peaks, a broad peak around 0.020 cpd, and two semimonthly peaks.
- Cross spectra between stations 4 and 5 have a semiannual peak and a peak at 0.020 cpd.
- Cross spectra between stations 5 and 6 show considerable breadth for the semiannual peak. The MJO peak is near 0.020 cpd. The tidal alias at 0.068 cpd is huge.
- Cross spectra between stations 6 and 7 show a broad semiannual peak, and peaks at the tidal alias frequencies of 0.68 and 0.70 cpd.

Coherence at the MJO frequency was 70% between stations 2 and 3; 45% between stations 3 and 4; and 89%, 45%, and 68% for the succeeding pairs of adjacent stations. Thus coherence falls in the interval 68% to 89% for separation of one degree of latitude on the continental slope and about 45% for three degrees separation.

## 4. Discussion

### *a. Time domain*

Linear fits were made to 5-year stretches of data. At station 1 temperature appears to be rising 0.0024°C per year. At stations 2 and 3 the temperature appears to be falling 0.0096 and 0.0014°C per year, respectively. At stations 4 and 5 the temperature appears to be rising 0.0101 and 0.0016°C per year, respectively.

The March drop in temperature is the most dramatic event of the year (Figs. 1 and 2). Likewise at the surface: "The spring transitions typically occur in March and last for about a week; the associated coastal SST drop is $\sim$3°C," according to Breaker and Mooers (1986). The transition in sea level and currents take place in about a week and proceeded poleward in 3 to 10 days (Strub et al. 1987).

In the present data, the March drop in temperature has a magnitude of 0.15° to 0.3°C. Declines take place over an interval of 12 to 56 days (Fig. 1). The timing of the decline may vary somewhat from year to year (Fig. 2). The transition appears to move poleward. Data are consistent with the Breaker and Mooers (1986) observation of poleward motion of the transition at $\sim$64 km per day.

### *b. Frequency domain*

The semiannual peak (0.0055 cpd) is the highest peak at four of the spectra (Figs. 5–7) and is seen in all the spectra. The semiannual peak has rms amplitude in the range from 0.030° to 0.048°C, which is 40% to 50% of the standard deviations of the temperature fluctuations. The motion is about 100 times as great as the semiannual motion of sea level (Patullo 1963). The semiannual oscillation is obvious in the raw data (Figs. 1 and 2). Its March decline coincides with the spring transition at the sea surface (Breaker and Mooers 1986). The power of the semiannual oscillation is within a factor of 2 at all stations, and is not an apparent function of latitude.

The semiannual oscillation for 1962 (Fig. 1) is also seen in the sea level height (SLH) anomalies plotted by Chelton and Davis (1982).

The upper-ocean poleward flow off Pt. Conception "is predominantly semiannual . . . with maxima in December and June" (Chelton 1984). The temperature near

1000 m is also predominantly semiannual and is rising sharply during December and June (Fig. 1).

The annual peak (0.00274 cpd) is the highest peak at station 1, but it is not visible at stations 6 and 7. Its strength increases steadily in the poleward direction.

''Annual and semiannual frequencies dominate'' in sea surface height (SSH) in the North Pacific, according to Jacobs et al. (1996), and in the present data.

The Madden–Julian oscillation was originally discovered in the equatorial atmosphere from sea level up to 80 mb (Madden and Julian 1971, 1972, 1994). They described it as ''an eastward-moving wave whose characteristics change with time.'' A poleward 40–60 day oscillation in sea level was reported by Spillane et al. (1987). These oscillations were attributed to winds in the western equatorial Pacific that produce an oscillation in sea level, which propagates on the coast from Peru to Canada at a phase speed of 150–200 km per day (Enfield 1987). The MJO was found in coastal sea surface temperatures (Breaker and Lewis 1988) and on the continental slope at depth 1160 and 1420 m (Broek 1969a). In the present data, the MJO is seen in spectra from stations 1–6, and in all six cross spectra. Its frequency was close to 0.020 cpd in all cases.

Numerous semimonthly tides and tidal aliases have been mentioned above. Most remarkable was the alias of the semidiurnal tide at station 2; the effect was so strong that the 0.068 cpd peak (14.8 days periodicity) can be seen in the raw data (Fig. 1). Moreover this peak was only a factor of 3 less than the semiannual peak at this location.

### *c. Relative delays*

Coherence between adjacent stations is high from zero frequency up to the MJO peak near 0.020 cpd. From station 6 to 7, phase is directly proportional to frequency from zero frequency up to 0.020 cpd. This proportionality implies that low-frequency temperature changes reach station 6 about 8 days after they reach station 7. However, other adjacent pairs of stations do not show this effect, although phase is always less than 60 deg at frequency peaks below 0.020 cpd. Hence the phase differences at the semiannual frequency and at the MJO frequency were analyzed separately.

Analysis of the phase differences between adjacent stations gives relative delays of 0, 13, 5, 17, 22, and 10 days for stations 2 to 7, respectively, at the semiannual frequency. At the MJO frequency of 0.02 cpd the relative delays are 2, 4, 0, 2, 16, and 7 days for stations 2 to 7, respectively.

Delays for stations 6 and 7 tend to be greater than those for stations 2 to 5. A possible reason is that the data for stations 6 and 7 are only 3.2 years in length, while the other stations accumulated 5 or 5.25 years of data. Another possible explanation is the complicated topography of the California Bight, which lies above stations 6 and 7, whereas the other stations are not near any comparable body of water.

The process, whatever its nature, passes through the region in 22 days or less, and hence must be regarded as wavelike. Its speed must be at least 50 km day$^{-1}$. Speeds of 60 to 100 km day$^{-1}$ in the poleward direction have been reported for oscillations in sea level (Enfield and Allen 1980).

## 5. Summary

Data are dominated by the semiannual oscillation, which has a strong temperature decline in March when the spring reversal occurs near the surface. The decline in temperature proceeds poleward.

The amplitude of the semiannual oscillation has little or no dependence upon latitude. The amplitude of the annual oscillation increases in the poleward direction, possibly due to wind forcing.

No consistent secular warming or cooling at 920 to 1410 m is found.

The Madden–Julian oscillation is seen at stations 1–6 and in all six cross spectra.

Various tides and tidal aliases are found. The most remarkable is the 0.068 cpd alias of the semidiurnal tide at station 2. This alias is visible in the raw data and is only a factor of 3 below the semiannual peak.

High coherence between adjacent stations occurs from zero to 0.020 cpd. Phase difference is proportional to frequency only from station 6 to station 7 and implies a delay of about 9 days at station 6 relative to station 7. Delays between stations at the semiannual frequency and at the MJO frequency were never greater than 22 days. Hence the process is wavelike, with a speed of at least 50 km day$^{-1}$. The speed and direction can not be determined, but the speeds are greater than the motions of the waters (at 920 to 1410 m) and hence indicate wavelike propagation.

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