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TEMPORAL SAMPLING REQUIREMENTS FOR LOW FREQUENCY TEMPERATURE VARIABILITY IN THE EASTERN EQUATORIAL PACIFIC OCEAN

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CONTENTS

Temporal Sampling Requirements for Low Frequency Temperature Variability in the Eastern Equatorial Pacific Ocean

Stanley P. Hayes and Michael J. McPhaden

Abstract. The effects of temporal subsampling of the near equatorial thermal field are examined using Monte-Carlo techniques. Approximately 3 years of continuous data from moored temperature sensors on the equator at 110°W and 140°W in the Pacific Ocean were randomly subsampled at frequencies of 1, 2, and 5 samples per month. Spectra of subsampled and original series demonstrate that the errors caused by subsampling are position, depth, and frequency dependent. In general, for a given number of samples errors are larger at the eastern location and in the thermocline. Adequate (spectral agreement to within a factor of two) resolution for periods longer than 3 months can be obtained at most depths with five samples per month. Fewer measurements are required near the surface.

1. INTRODUCTION

Theoretical (e.g. Moore and Philander, 1977) and observational studies (e.g. Hayes and Powell, 1980) indicate that on time scales of a few days to several months upper ocean temperature variability increases near the equator. This increase is associated with equatorial trapped waves and, particularly in the eastern Pacific, the existence of approximately monthly period oscillations forced by the instability of the meridional shear of the zonal currents (Legeckis, 1977; Philander, 1978). This enhanced variance suggests that special considerations may be required in order to adequately sample the low frequency, near-equatorial temperature variability and to avoid temporal and spatial aliasing. In this note we consider the temporal sampling requirements.

In general, characteristics of the low frequency thermal field variability in the tropical Pacific have been inferred from analyses of ship-of-opportunity XBT data (e.g. White *et al.*, 1982). These data are collected along ship tracks and only a few samples per month are available near any particular location. By combining data into bins with dimensions of a few hundred kilometers on each side and by considering seasonal time steps, it is possible to estimate low frequency space-time autocorrelation functions. However, month-to-month variability and the importance of aliasing cannot be determined. Furthermore, the geographical grid size smooths over the small-scale variability which may be important near the equator.

An exception to these XBT data studies is the analysis of the NORPAX Hawaii-to-Tahiti Shuttle Experiment sampling (Firing and Lukas, 1985). This study considered leakage and aliasing problems in a multiple linear regression determination of the annual and semi-annual signals in the Shuttle data sets. Confidence limits for the regression model coefficients were determined empirically from Monte Carlo subsampling experiments on the moored time series near 0°, 153°W. These measurements extended for about 13 months (May 1979–June 1980).

Firing and Lukas (1985) determined that temperature sampling requirements were a strong function of depth. In the surface mixed layer one sample every 3 weeks was sufficient to determine the annual period; however, weekly sampling was required in the thermocline. Determination of the semiannual component required more frequent sampling.

In this paper we consider further the temporal sampling requirements for temperature measurements in the eastern equatorial Pacific. Data from long-term equatorial moorings near 110°W and 140°W are analyzed using Monte Carlo subsampling and spectral techniques analogous to those discussed by Luther and Harrison (1984). Results indicate sampling requirements vary with location and depth. More measurements per month are required at the eastern location and in the thermocline.

2. DATA

As part of the Equatorial Pacific Ocean Climate Studies (EPOCS) program (Hayes *et al.*, 1986) a moored current and temperature array has been maintained on the equator near 110°W and 140°W (Halpern, 1987; McPhaden and Taft, 1988). The basic averaging and recording interval for these data is 15 min. Instruments were distributed throughout the upper 250 m and their locations relative to the mean thermal structure at each longitude are shown in Fig. 1. At 110°W high stratification extended to the surface and instruments at 25 m, 45 m and 80 m sampled the thermocline. At 140°W near surface stratification was weak and instruments at 80 m and 120 m were in the thermocline.

Time series of daily averaged temperature at each location are shown in Fig. 2. For our analyses we concentrated on the period November 1983 to May 1986 at 0°, 110°W and June 1983 to May 1986 at 0°, 140°W. We use slightly shorter records at 110°W because prior to November 1983 instruments at 110°W were located at different depths than those shown in Fig. 2.

Characteristics of the time series are illustrated by the variance preserving spectra shown in Fig. 3. These spectra were computed from hourly averaged time series and were smoothed by averaging the variance estimates in adjacent frequency bands (3 spectral estimates were averaged for periods between 10 d and 3 years). At 110°W near surface temperature variance was dominated by the lowest frequency estimate. A second variance peak occurred at periods of about 20 d. In the deeper records the sub-monthly variance increased relative to the low frequency fluctuations. Similar features occurred at 140°W; however, at this longitude a variance peak at periods near 100 d is apparent at all levels. The 10–30 d variance is less important in the central Pacific and periods longer than 1 month contain most of the variance in all records. At both 110°W and 140°W the relative importance of the semi-diurnal tide varied with depth; it was most pronounced at the 160 m level at 140°W.

The potential problems of characterizing these data by a few samples per month are illustrated by hourly averaged time series of isotherm depth (Fig. 4) for temperatures in the thermocline. At both longitudes the low frequency variations in these isotherm depths are of the same order as the hourly fluctuations. The high frequency contamination is worse at 110°W than at 140°W. For example, although an annual signal appears in the 14°C, 110°W record, subsampled hourly values can be picked which would seriously distort this low frequency structure. The importance of this distortion will be quantified in the remainder of this paper.

3. SUBSAMPLING

The basic time series used in many studies of tropical ocean variability are monthly averaged data. If these series are constructed from XBT data, then such monthly averages generally contain only a few samples. To study the effects of this subsampling, we constructed analogous series by randomly subsampling the continuous moored temperature records. Twenty realizations of each record were obtained with 1, 2, and 5 samples per month. Monthly average time series constructed from these subsampled data sets were compared to those obtained from the full record. Deviations between the full and subsampled monthly averaged time series were used to estimate the errors associated with subsampling.

In Table 1 results for the two longitudes considered are summarized. The root mean square (rms) deviation between the monthly averaged values obtained from the full (referred to as "true") and subsampled temperature records indicates the noise (N) introduced by subsampling. The signal (S) is taken to be the standard deviation of the time series of true monthly average temperatures. A signal-to-noise ratio of one means that the month-to-month changes in the monthly average values computed from the full series have the same magnitude as the error in the monthly averages associated with subsampling. At 110°W, S/N is largest near the surface and has a minimum in the lower portion of the thermocline. The relatively small error caused by subsampling near the surface is expected because this temperature spectrum (Fig. 3) is dominated by low frequency (periods longer than semi-annual) variance. At 140°W, S/N is also largest near the surface and decreases with depth. The higher S/N observed at most levels at 140°W compared to 110°W is also expected from the shape of the spectra (Fig. 3) since the approximately monthly period variance is relatively more important at the eastern location.

The rms difference between true and subsampled monthly averaged temperatures in Table 3 is approximately inversely proportional to $\sqrt{n}$ as would be expected for normally distributed random noise. Thus, even though the spectra in Fig. 3 indicate frequency-dependent structure in the variance at periods less than 1 month, assuming a normal distribution provides a reasonable way to estimate S/N for a given randomly subsampled record.

The frequency distribution of the errors introduced by subsampling the true temperature series are obtained by computing spectra of the 20 random realizations with 1, 2 and 5 samples per month. Figure 5 shows the results at 110°W for $n = 1$. The heavy line is the "true" spectrum obtained from the full record; light lines indicate spectra of the 20 realizations. Two points are apparent in the figure; (a) individual realizations can deviate substantially from the true

Table 1. Temperature signal (S) and signal-to-noise ratios (S/N) at 0°, 110°W and 0°, 140°W for selected depths in the upper 250 m. Signal is defined as the standard deviation of monthly means based on the complete time series. Noise (N) is defined as the root-mean-square difference between monthly means based on the complete time series and those based on n = 1, 2 or 5 samples per month.

Depth	S (°C)	S/N n = 1	S/N n = 2	S/N n = 5
		0°, 110°W		
10 m	1.50	1.64	2.32	3.61
45 m	1.14	0.83	1.18	1.95
120 m	0.24	0.62	0.91	1.46
250 m	0.22	1.06	1.40	2.10
		0°, 140°W		
10 m	1.32	2.64	3.64	5.64
80 m	2.13	1.94	2.88	4.48
160 m	0.86	1.17	1.71	2.70
250 m	0.21	0.96	1.39	1.95

spectrum and (b) there is a frequency-dependent bias in the ensemble average spectra of the random realizations. Deviations between the true and subsampled spectra were smallest at 10 m and largest at 120 m in agreement with the signal-to-noise ratios in Table 1. At 120 m, spectra of individual realizations deviate from the true spectrum by an order of magnitude at periods near 3 months and by a factor of 5 at the longest periods resolved (20 months).

The frequency dependent bias in the subsampled spectra is seen by the ensemble-averaged spectra (Fig. 6) for n = 1, 2 and 5. The bias is caused by aliasing of the high frequency (shorter than monthly period) variance. This aliasing decreases as the monthly sample size increases; hence the ensemble averaged subsampled spectra converge on the true spectrum. Again, this bias is least important near the surface where the spectrum is dominated by low frequency variance. With n = 1, true and ensemble mean subsampled spectra agree to within a factor of two for periods longer than 4 months at 10 m and about 1 year at the deeper levels. With n = 5, agreement to within a factor of two holds for nearly all periods at all the depths examined.

Spectral results for 0°, 140°W are shown in Figs. 7 and 8. As expected from Table 1, contamination by subsampling is not as severe at this longitude. Nevertheless, deviations of individual realizations from the ensemble mean can be substantial. Again 160 m appears to be a worst case with order of magnitude differences between true and subsampled spectra over a broad range of frequencies. Ensemble averaged spectra of the subsampled realizations show the great improvement associated with increasing the sample size to 5 per month. At depths other than 160 m the main effect of the small samples per month is to fill in the dip at periods near 4 months. At 160 m n = 1 leads to a nearly uniform overestimate of the variance density at all frequencies. Aliasing of the relatively strong semidiurnal tide is an important factor at this depth.

4. DISCUSSION

Monte Carlo subsampling of the moored temperature time series on the equator at 110°W and 140°W indicate that resolution of month-to-month variations require several samples per month. Seasonal and longer period variations can be adequately resolved with 5 samples per month. The subsampling requirements are more severe at 110°W because of the spectral variance peak associated with approximately monthly fluctuations. Contamination by subsampling is less important near the surface where low frequency fluctuations dominate.

The importance of these results depends upon the processes being studied and the data available. Real time assessment of monthly changes at a given location will be difficult unless the signal-to-noise ratio is at least 2 (i.e., expected month-to-month fluctuations twice as large as the rms error caused by subsampling). Table 1 suggests that in the thermocline this ratio requires five samples per month. On the other hand, the sub-monthly ocean variability may have small spatial scales and be reduced by spatial averaging. In this case, a smaller number of XBT sections may be adequate. Examination of the frequency-two dimensional wave number spectrum of the temperature variance is required to address this question.

This study points out the problems inherent in studying ocean variability with a sparsely sampled data set. The spectra of the individual realizations in Figs. 5 and 7 demonstrate that errors in spectral estimates can be quite large (factors of 5–10) even at annual and longer periods. Therefore infrequently sampled data at a given location must be treated cautiously and the expected error limits which are location and depth dependent must be established.

5. ACKNOWLEDGMENTS

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FIGURES

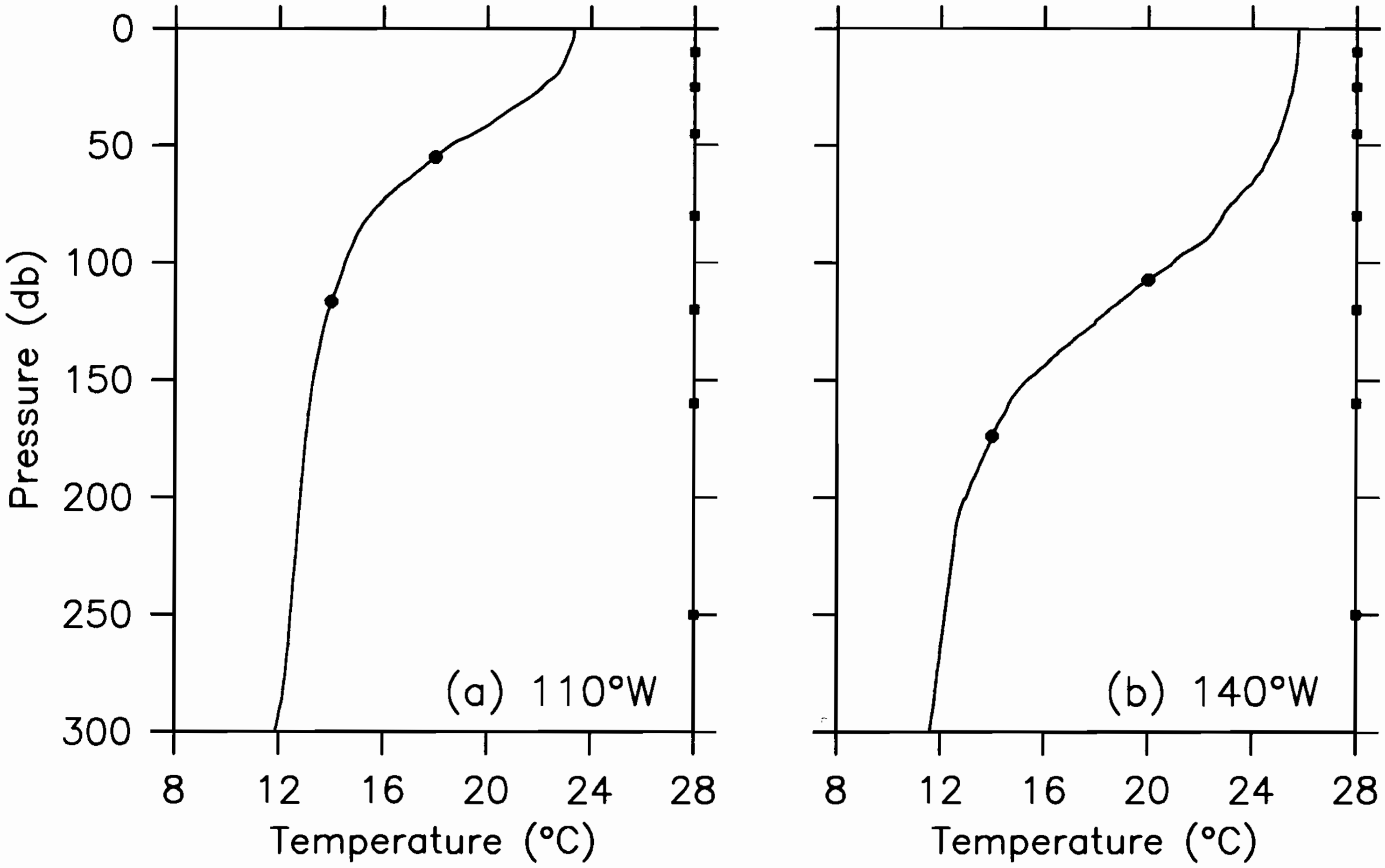

Fig. 1. Mean equatorial temperature profiles for June 1983 to June 1986 at (a) 110°W and (b) 140°W. Profiles are based on 39 CTD casts between 1°N and 1°S at 110°W and 22 CTD casts between 1°N to 1°S at 140°W. Depths of temperature time series shown in Fig. 2 are indicated by squares on right axes. Circles indicate the mean depths of the 14°C and 18°C isotherms at 110°W, and the 14°C and 20°C isotherms at 140°W.

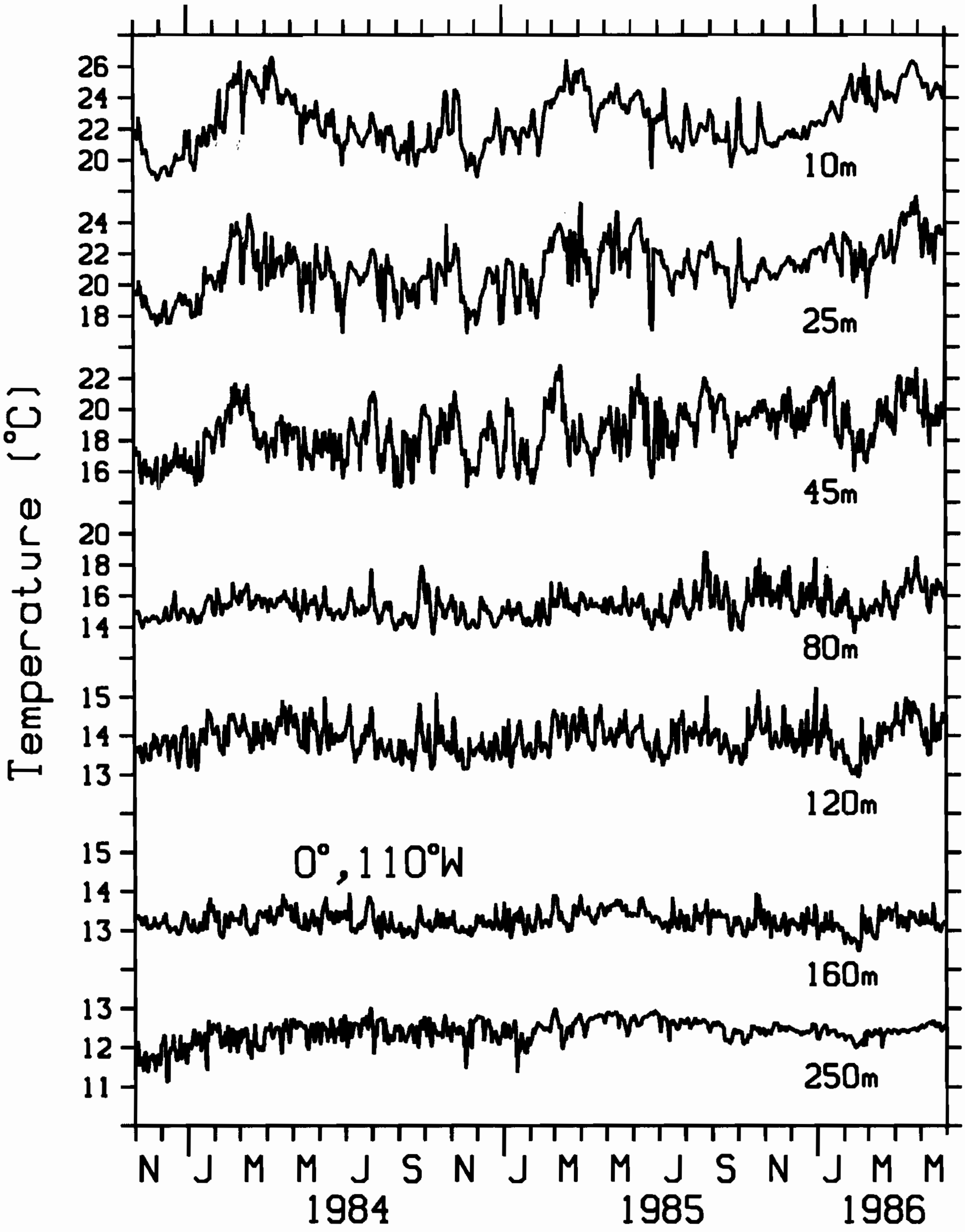

Fig. 2a. Time series of daily averaged temperature at 0°, 110°W.

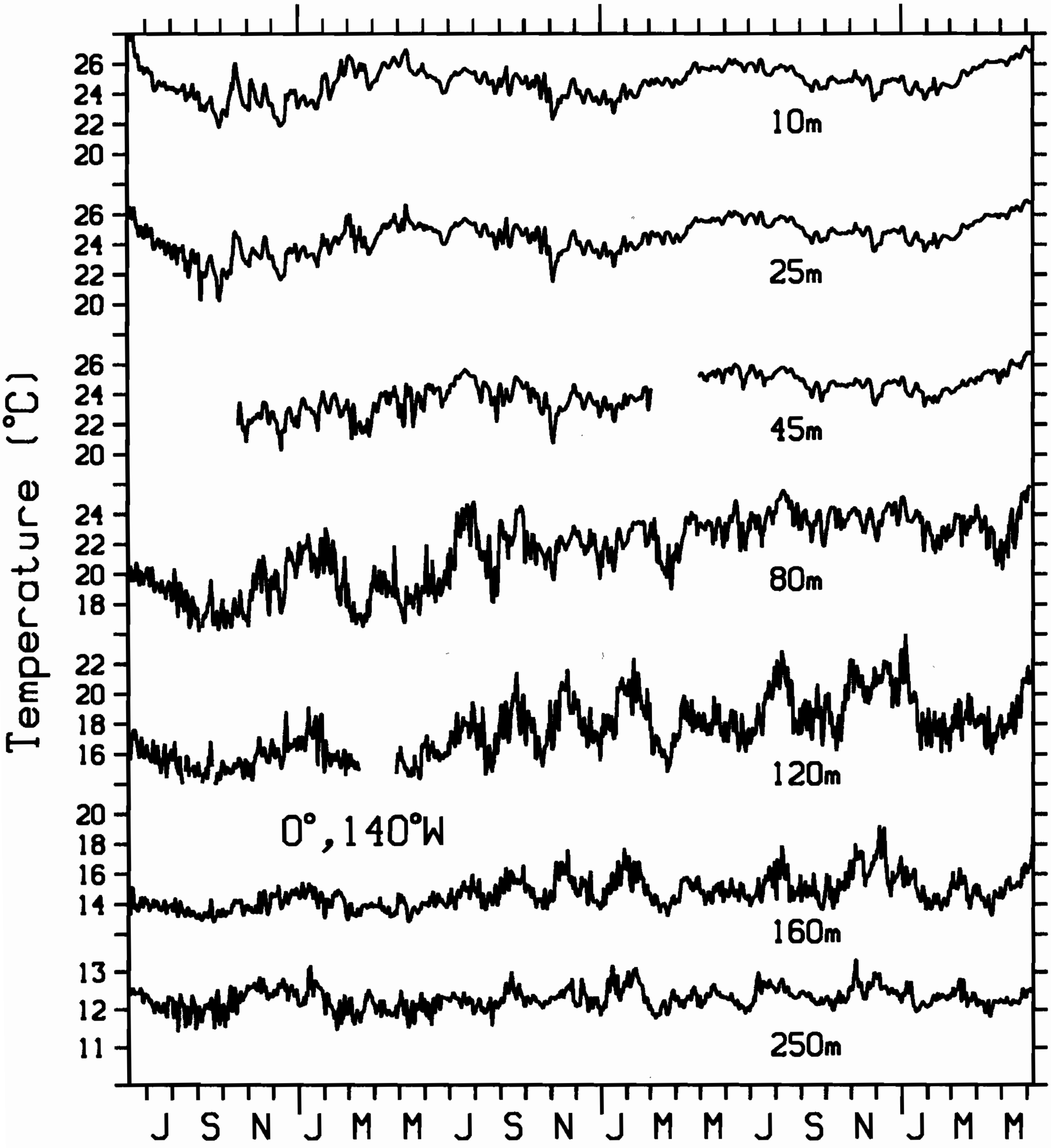

Fig. 2b. Time series of daily averaged temperature at 0°, 140°W.

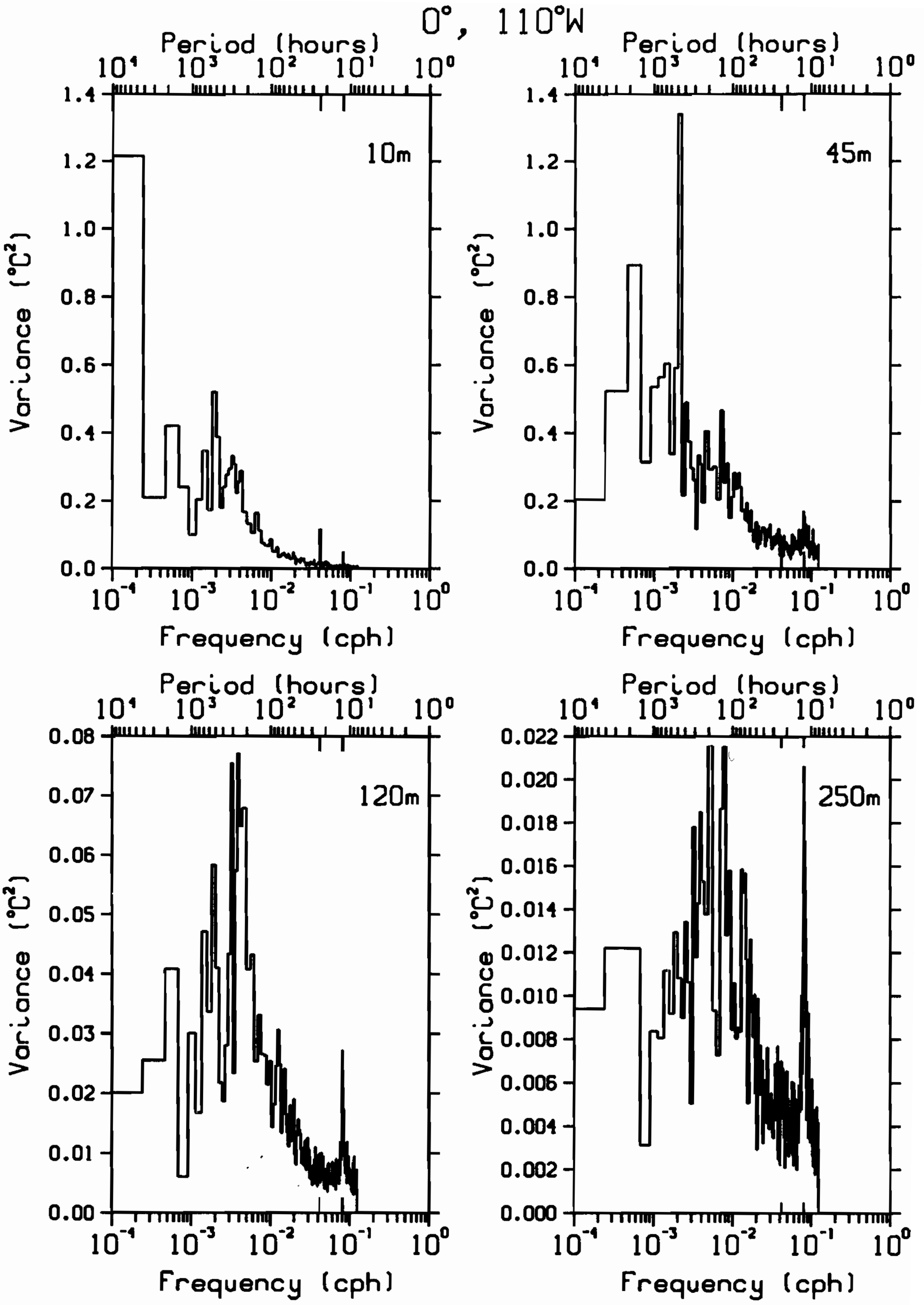

Fig. 3a. Variance preserving temperature spectra at several depths at 0°, 110°W.

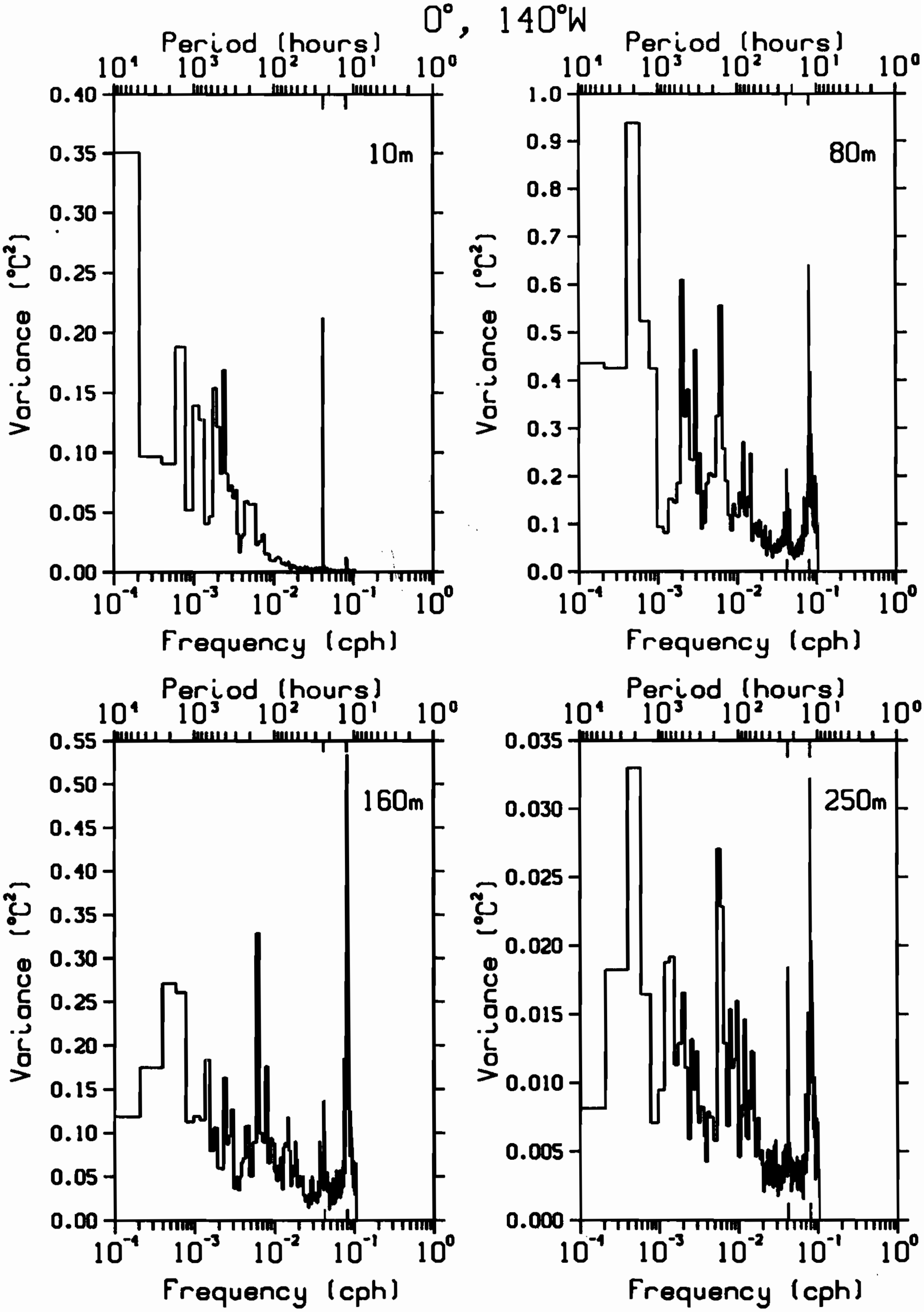

Fig. 3b. Variance preserving temperature spectra at several depths at 0°, 140°W.

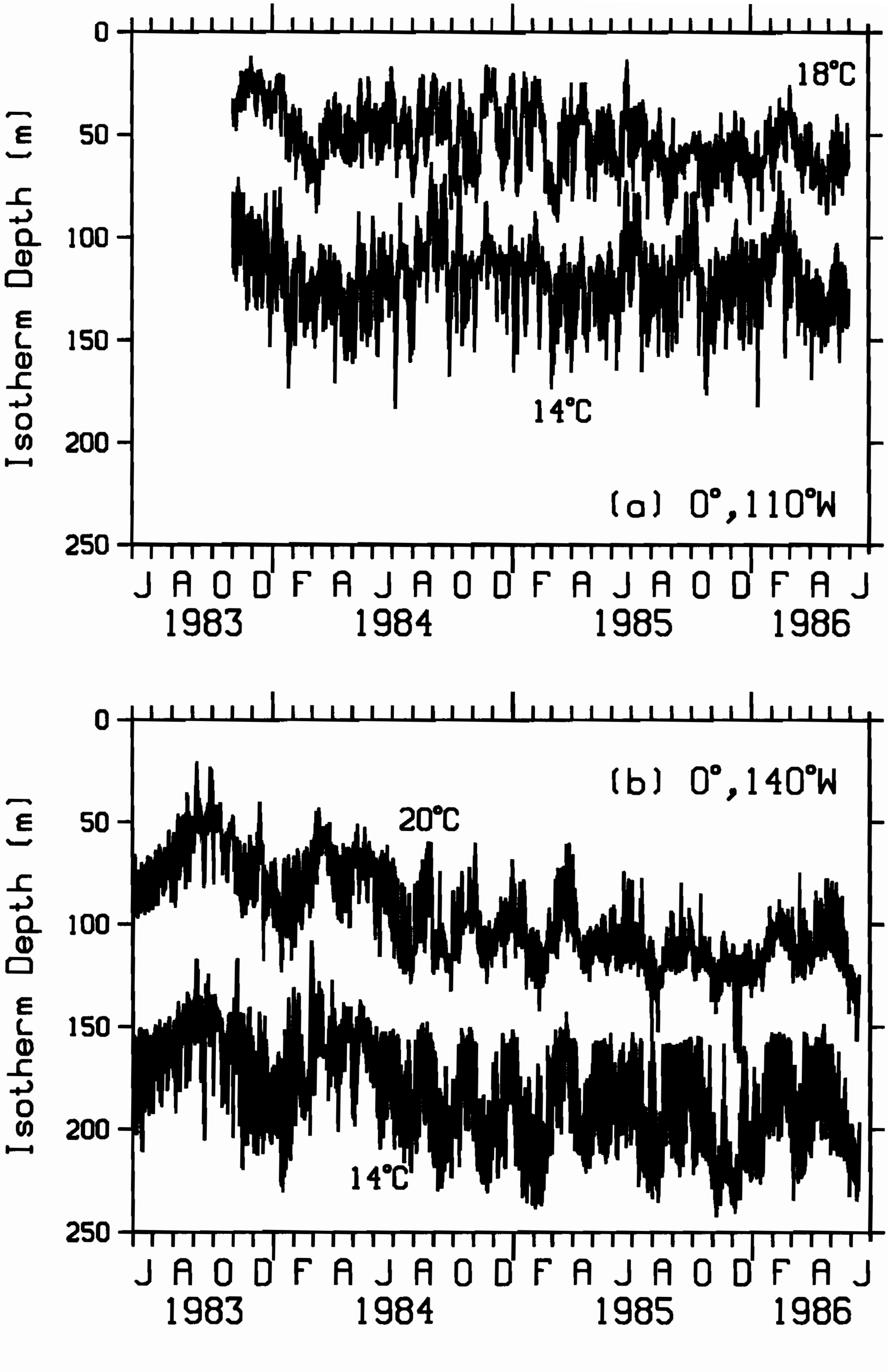

Fig. 4. Hourly time series of the depth of (a) the 18°C and 14°C isotherms at 0°, 110°W and (b) the 20°C and 14°C isotherms at 0°, 140°W.

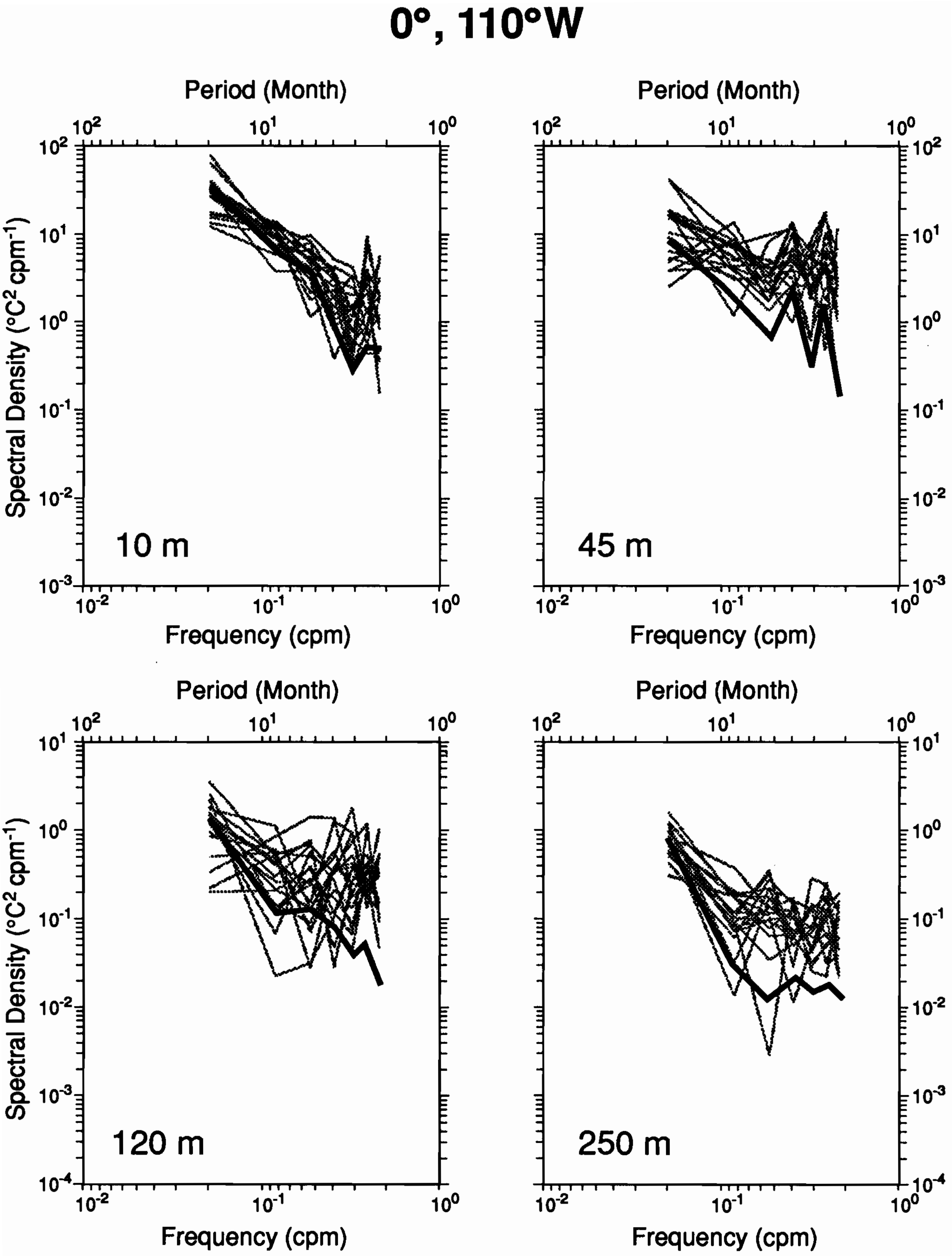

Fig. 5. Spectral density for monthly mean temperature at several depths at 0°, 110°W estimated from the complete time series (heavy line) and from 20 realizations of the subsampled series with one sample per month (light gray lines).

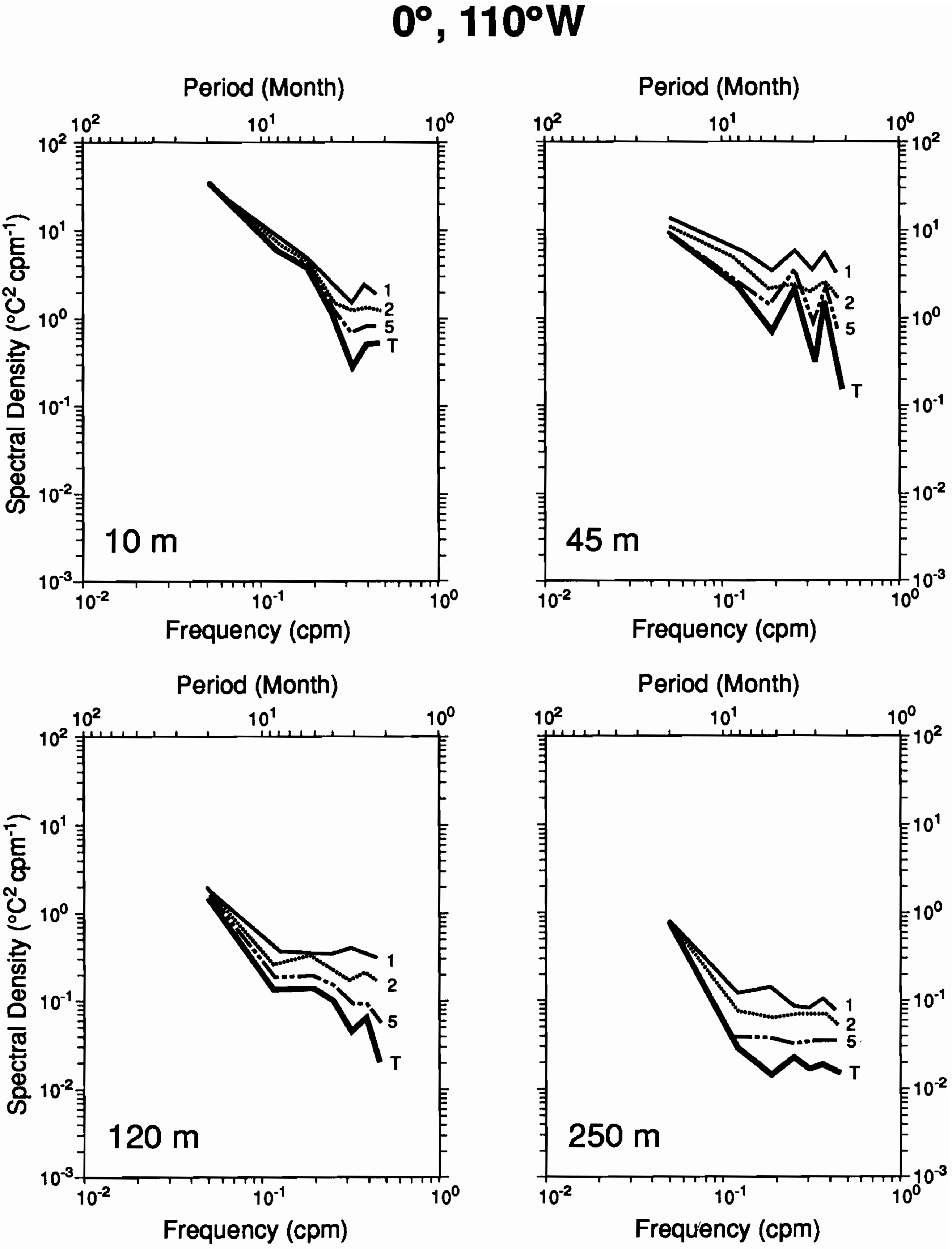

Fig. 6. Spectral density for monthly mean temperature at several depths at 0°, 110°W. Heavy line labeled "T" is the "true" spectrum based on the full time series. The other lines denote spectra with n = 1, 2, and 5 samples per month.

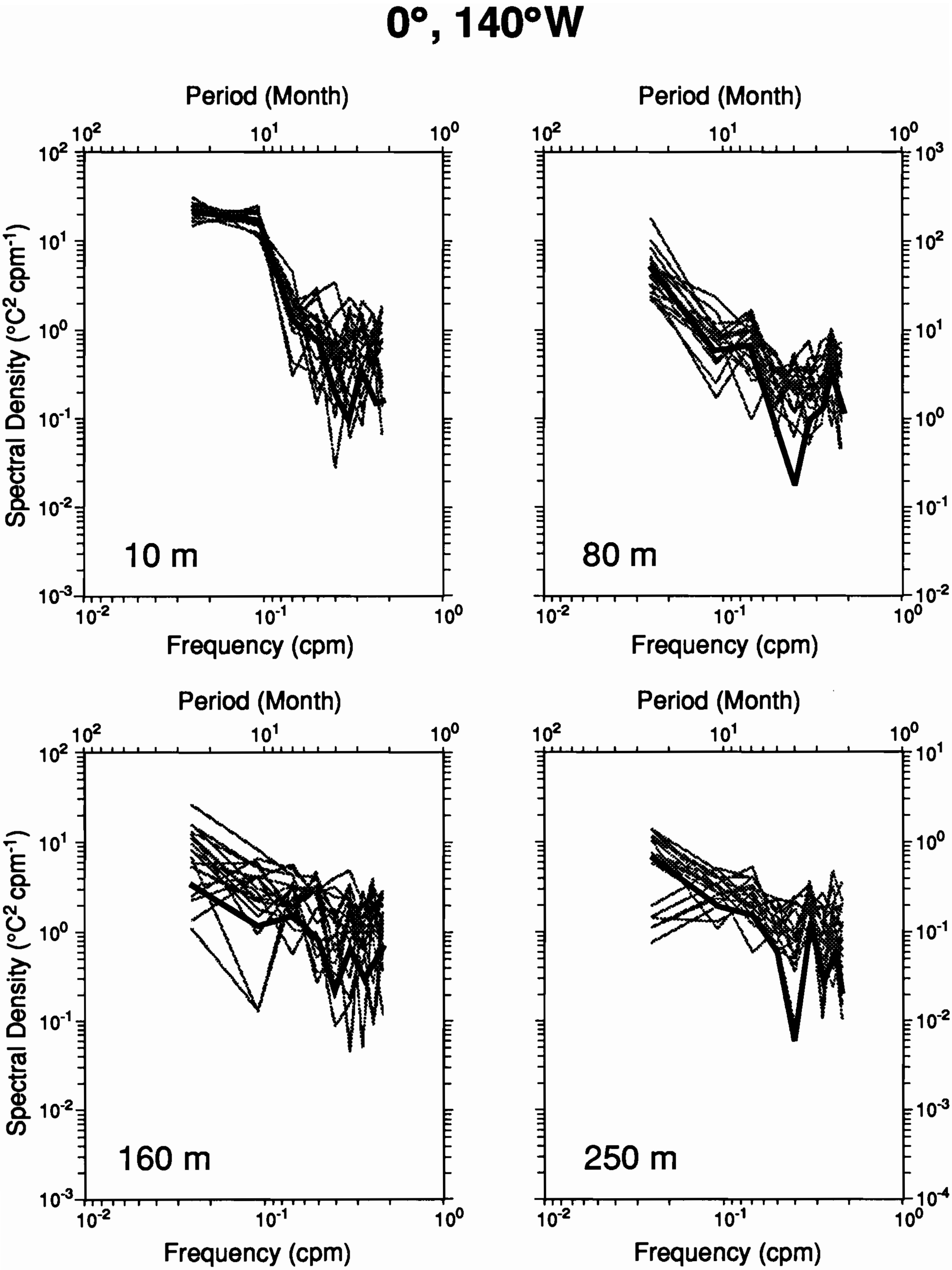

Fig. 7. Spectral density for monthly mean temperature at several depths at 0°, 140°W estimated from the complete time series (heavy line) and from 20 realizations of the subsampled series with one sample per month (light gray lines).

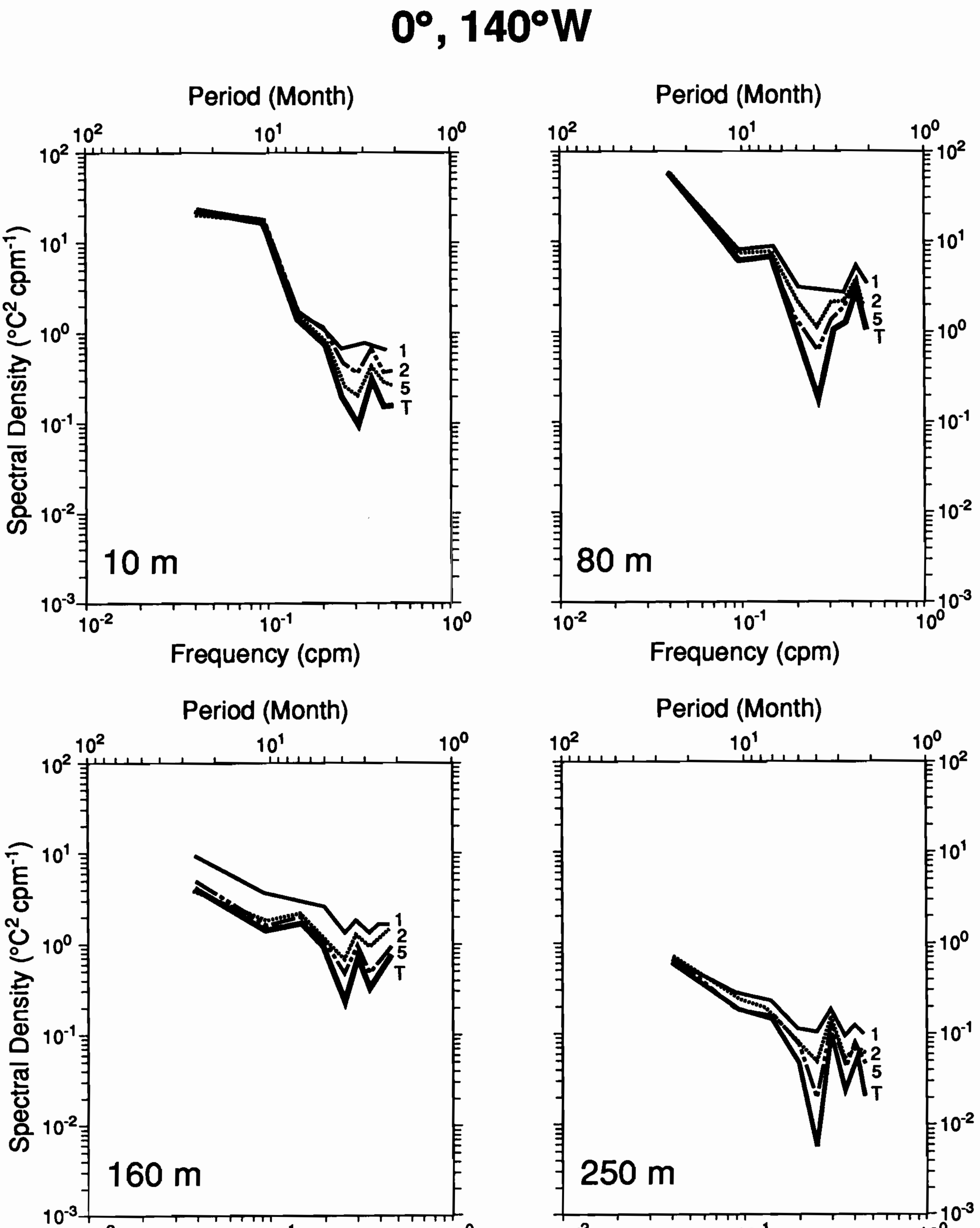

Fig. 8. Spectral density for monthly mean temperature at several depths at 0°, 140°W. Heavy line labeled "T" is the "true" spectrum based on the full time series. The other lines denote spectra with n = 1, 2, and 5 samples per month.

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