Steric Sea Level Trends in the Northeast Pacific Ocean: Possible Evidence of Global Sea Level Rise

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ABSTRACT

Thirty-year time series of hydrographic observations from Ocean Station PAPA and Line 'P' are used to estimate secular trends in monthly mean steric sea level heights relative to depths of 100 and 1000 decibars in the northeast Pacific Ocean. Linear trends at station 'P' (50°N, 145°W) indicate that steric heights relative to the 1000 db (approx. 1000 m) level are rising at a rate of 1.1 mm yr^{-1}, comparable with the order 1 mm yr^{-1} global trends suggested by analysis of selected long-term coastal tide gauge records. Approximately 67% of the increase in steric levels is due to thermosteric changes at depths below 100 m; the smaller 33% contribution from the halosteric component appears to be confined to the upper 100 m. Steric height trends at line 'P' locations are also of order 1 mm yr^{-1} but, in contrast to station 'P' trends, arise mainly through the halosteric component.

Confidence levels for the linear trends are calculated in two ways: (i) using the Student-t test assuming that each monthly observation is a statistically independent sample; and (ii) using the Student-t test in conjunction with the effective number of degrees of freedom derived from integral time scales. For station 'P', trends based on (i) are reliable to the 99% confidence level while for line 'P' only stations on the eastern portion of the line have significant trends relative to the 1000 db level. Confidence levels obtained from (i) fail to take into consideration the long-term fluctuations in steric level records. To obtain more reliable estimates of the confidence intervals, we use integral time scales to determine the effective number of degrees of freedom for each monthly time series. Subsequent recalculation of trend-line confidence intervals indicates that the total steric height trends at Station 'P' remain significant at the 90% confidence level. The halosteric trend relative to 100 db is significant at 90% while the thermosteric trend relative to 1000 db is marginally significant at 70 to 80%. With the exception of stations 5 and 6, trends for line 'P' stations are no longer significant above the 70% level. The lower statistical reliability in the line 'P' trends is due, in part, to the sparse sampling rate relative to station 'P'. We conclude that steric sea levels in the northeast Pacific are rising at approximately 1 mm yr^{-1} and that this increase may be associated with a combined regional warming of the deeper waters and dilution of the surface waters. Although the observed trends appear to be linked to climate-induced eustatic changes in global sea level, the records are not of adequate length or spatial coverage to rule out effects of shifting regional circulation patterns.

1. Introduction

The concentration of "greenhouse" (infrared absorbing) gases in the atmosphere is increasing. If present rates continue, the combined effect of all such gases would be equivalent to a doubling of present-day atmospheric carbon dioxide levels by the year 2050. The increased solar heat trapped by these gases is expected to cause an accelerated atmospheric warming, with some climate models predicting an average increase in the surface temperature of the earth of 1.5 to 4.5°C depending on the type of feedback mechanisms included in the analysis. The increased warming will subsequently lead to higher global sea levels through thermal expansion of the ocean and melting of land-based glaciers (e.g., Gornitz et al. 1982).

Melting of the Antarctic Ice Cap is considered to be of particular importance in estimates of world sea level change (Mercer 1978; Thomas 1987). Revelle (1983) predicts that global sea level will rise 0.7 m over the next century and that 0.3 m of this rise will be due to thermal expansion and 0.4 m to ice melt. Hansen et al. (1981) estimate a 0.2 to 0.3 m eustatic rise in water level in the next 70 yr. Graphs of predicted total sea level rise by Thomas (1987) indicate that global water levels will increase by 0.9 to 1.7 m by the year 2100 with the most probable increase in the range of 1.1 ± 0.1 m. A global warming of 6°C by the year 2100 would lead to a rise of about 2.3 m but this is considered extreme. A delayed oceanic response associated with diffusion of heat into the deep ocean (Hansen et al. 1984; Siegenthaler and Oeschger 1984) would significantly reduce the initial sea level trend and lead to a net sea level rise of 0.6 m by 2100. Sustained sea level increases of the magnitudes suggested by the various predictions will have a profound effect on human set-

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tlement and are therefore of considerable scientific, economic and political concern. There is a clear need to give serious consideration to the problems of coastal management and public awareness in light of possible climatic warming (cf. Devoy 1987).

With few exceptions, estimates of global sea level rise associated with changes in ocean volume (eustatic changes) are based on coastal tide gauge records with their attendent inaccuracies, skewed worldwide coverage and intermittancy. The estimates are further contaminated by noneustatic components linked to tectonic, glacio-isostatic, atmospheric and oceanographic responses (e.g., Thomson and Tabata 1982; Barnett 1984; Aubrey and Emery 1986). Gornitz et al. (1982) compared the global sea level trend of approximately 1 mm yr^{-1} derived from selected tide gauge records with the global surface temperature curve from Hansen et al. (1981) and concluded that roughly half of the sea level rise over the past century has been caused by thermal expansion of the upper ocean. Barnett (1983), on the other hand, concludes that thermal expansion of the upper ocean accounts for less than 5 cm over the past century. None of the oceanographic time series Barnett considered revealed statistically significant trends in steric height. Aubrey and Emery (1986) attempted to separate eustatic, oceanographic and tectonic components in 50 yr of tide gauge observations from Japan and concluded that such separation is not possible using present information. An extensive trend analysis by Pirazzoli (1986) using 229 world sea level records also indicates that eustatic sea level changes are overshadowed by tectonic and oceanographic factors. A number of Pirazzoli's conclusions serve to emphasize the problems with using sea level records to detect climate-related sea level change. For example, he suggests that the relatively uniform, high rates of sea level rise along the east coast of the United States may be linked to oceanic rather than to geological factors. Stewart (1989), on the other hand, argues that coastal subsidence is the dominant factor determining sea level rise along this geologically "passive" continental margin.

Improved satellite altimetry observations and networks of tide gauge stations surveyed with highly accurate geodetic positioning techniques based on Very Long Baseline Interferometry (VLBI) and the Global Positioning System (GPS) may eventually enable us to extract the climate-induced signal from the background noise. At present, however, records are too short and the techniques too inaccurate to detect secular trends in sea level. The analysis of long-term hydrographic observations provides the only alternative to the use of coastal tide gauge records. Roemmich (1985) used the 27-yr Panuliris series of deep hydrographic stations off Bermuda (32°10′N, 64°30′W) to investigate secular changes in steric height and their relation to coastal sea level variations. Results indicate that seasonal and short-term interannual fluctuations in temperature-modulated steric height are concentrated in the upper ocean while decade-scale thermosteric fluctuations penetrate well into the deep ocean and are not coupled to variations in the thermocline. Similar results have been reported by Tabata et al. (1986) using a 25-yr hydrographic time series for Ocean Station PAPA (Station 'P') in the northeast Pacific (Fig. 1). A separate investigation of steric height trends at Ocean Station PAPA has been presented by Thomson and Tabata (1987). Based on the 27-yr hydrographic record available to 1983, the latter study revealed that steric heights relative to 1000 db (approximately 1000 m depth) are increasing at a rate of 0.93 mm yr^{-1} and that 67% of the increase is due to thermosteric changes at depths greater than 100 m. The smaller halosteric contribution to the steric trend appears to be confined to the upper 100 m. A critical examination of the results using different segments of the time series and revised estimates of the number of degrees of freedom for each record indicated that long-term sea level changes of this magnitude are probably not statistically reliable and are readily masked by the large (1–10 cm) interannual variations.

The present paper has a three-fold purpose: (i) to revise the trend analysis of the station 'P' time series using the additional data collected from 1983 to 1986; (ii) to recalculate confidence level estimates using integral time scales to determine the effective number of degrees of freedom of each time series; and (iii) to present a more complete analysis of steric height trends derived from fixed stations occupied along line 'P' during transit to and from station 'P'. The relative contributions of temperature and salinity variations are

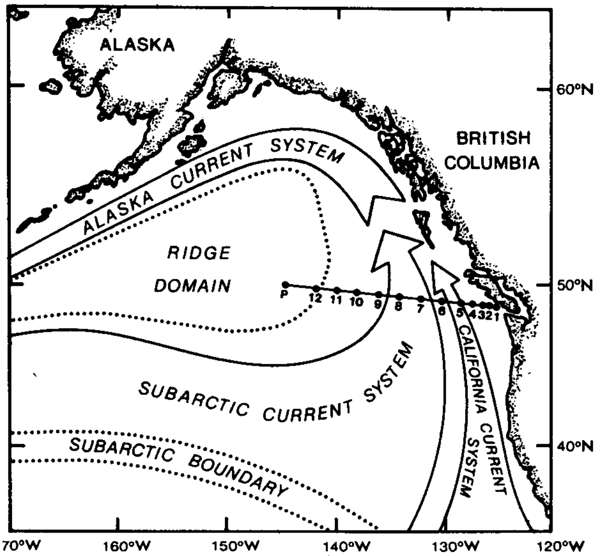

FIG. 1. Locations of station 'P' and the 12 line 'P' stations in the northeast Pacific Ocean. Figure also shows distributions of water-mass types beneath the depth of direct surface influence (adapted from Thomson and Kuwahara 1981).

obtained from separate calculations of the thermosteric and halosteric components of total steric height.

2. Data and analysis

Station 'P' is located at 50°N, 145°W in 4200 m of water approximately 1500 km west of the coast of British Columbia (Fig. 1). The station was initially occupied in 1950 using two weatherships on a rotating 6-week basis. A program of twice-daily bathythermograph (BT) observations was introduced in 1952; in August 1956 weekly bottle casts were added to the schedule. By April 1959, a series of line 'P' oceanographic stations was occupied during transit to and from PAPA. The oceanographic program was further extended in 1969 to include expendable BT (XBT) and salinity–temperature–depth (STD) or conductivity–temperature–depth (CTD) observations at 13 fixed station/line 'P' locations. Termination of the weathership program in early 1981 has resulted in a more intermittent sampling of the stations using Canadian oceanographic research vessels.

Results presented in this paper are based on monthly steric height anomalies calculated for reference levels of 100 and 1000 db for: (i) The 31-yr station 'P' hydrographic time series spanning the period January 1956–December 1986; and (ii) The 28-yr line 'P' hydrographic time series covering 12 stations over the period April 1959–December 1986. Steric heights relative to 100 db are representative of changes in the upper seasonally influenced layer of the northeast Pacific Ocean. The 100 m depth level marks the top of the permanent pycnocline and the maximum depth of normal winter overturning and wind mixing (Dodimead et al. 1963; Tabata 1975). Although it is not deep enough to completely avoid near-surface influences through Ekman layer pumping (Tabata et al. 1986), the 1000 m level is sufficiently deep to represent deep-ocean variability and still encompass most of the oceanographic profiles.

a. Steric height anomalies

The procedure for calculating the monthly anomalies of steric height is presented in Thomson and Tabata (1987). For given pressure surfaces, P, temperatures, T, salinities, S, and specific volume, α, the monthly mean anomalies of thermosteric (Z_T), halosteric (Z_S), and total (Z_α) steric heights are given by

$$Z_T = 1/g \int_{P_0}^{P} (\partial\alpha/\partial T)\Delta T dp$$

$$Z_S = 1/g \int_{P_0}^{P} (\partial\alpha/\partial S)\Delta S dp$$

$$Z_\alpha = 1/g \int_{P_0}^{P} (\Delta\alpha) dp \approx Z_T + Z_S,$$

in which g is gravity, P_0 is the reference pressure and Δ signifies the departure of the given variable from its mean (record-averaged) monthly value. The anomalies give the departure of monthly mean steric height from the mean monthly value for the particular month (e.g., the monthly mean value for April 1979 is measured relative to the mean value for all April observations). Subtraction of the mean monthly value effectively removes the mean annual cycle from the data record. Interannual differences in the annual cycle are retained within the anomaly records. Although second order terms have been retained in the calculation of Z_α, values typically differ by only ±0.2 cm from those derived using the first order terms alone.

Monthly anomalies and trends for the 31-yr records of thermosteric, halosteric and total steric heights for the two pressure levels at Station 'P' are plotted in Figs. 2 and 3. Corresponding plots for line 'P' stations 5 and 9 are presented in Figs. 4 and 5. Station 9 is representative of sea level variability to the west of the major transition zone separating the Ridge Domain from the Subarctic Current Domain (Fig. 1) while station 5 is representative of variability within the more highly dynamic Coastal Current Domain (Thomson and Kuwahara 1981). The right-hand scale gives the anomalies in terms of the record-averaged standard deviation (listed in the lower corner of the plot) and the left-hand scale the height of the anomaly in centimeters. The standard deviation used to scale the steric anomalies is derived from the monthly time series and is typically within 0.5 cm of the standard deviations derived for time series of specific months.

A summary of the statistics for each station 'P' time series is provided in Table 1. Statistics for the total steric heights for all line 'P' stations are presented in Table 2a, b; complete results for selected line 'P' stations are presented in Table 3a, b. In all cases, the standard error of estimate for the regression lines are within 5% of the standard deviation listed in the tables. The last three columns in each table give the confidence levels for the trends based on Student-t confidence tests. Derivation of the confidence levels is described in the following section. Listings of the appropriate integral time scales T_1 and T_2 are provided in Table 4.

b. Trends and confidence levels

The steric height trends presented in the figures and tables have been obtained using standard linear regression analysis. Confidence levels for each trend have been derived in two ways: (i) using the Student-t test assuming that each monthly observation is an independent data point; and (ii) using the Student-t test in conjunction with the effective number of degrees of freedom derived from the integral time scales for the station 'P' records. Based on the presence of long-period fluctuations in the steric height records, it is obvious that derivation (i) represents a naive approach to con-

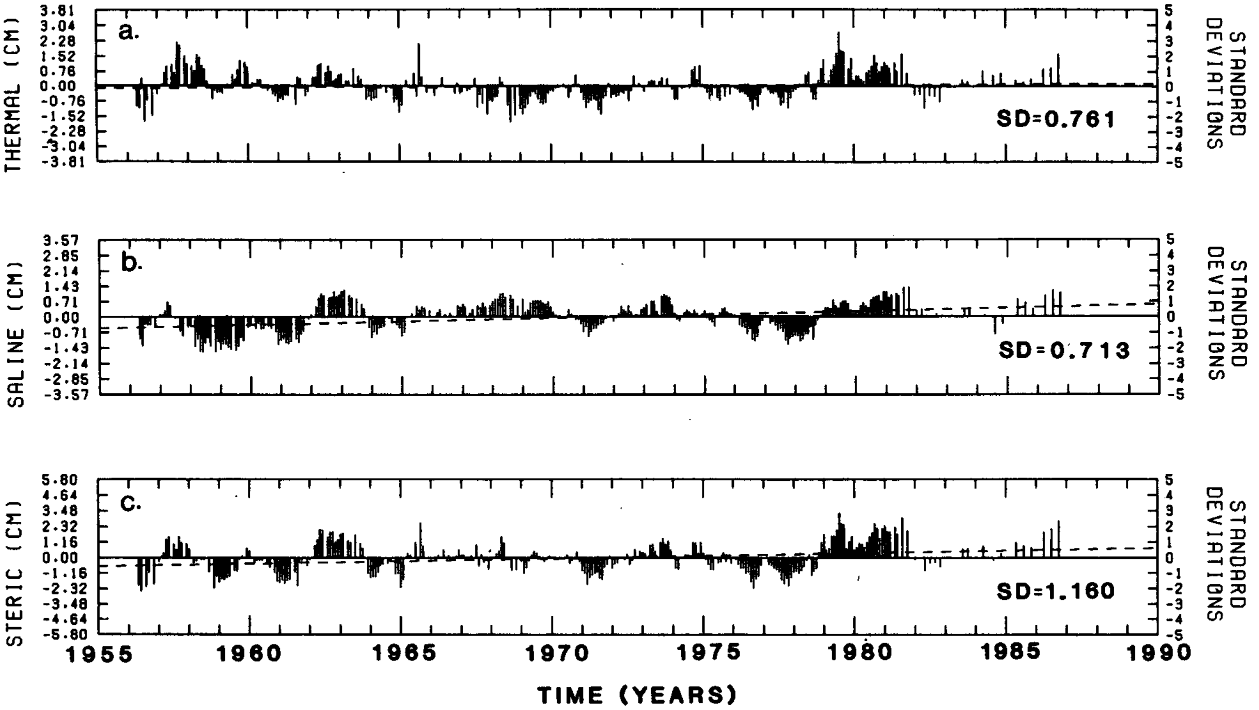

FIG. 2. Time series of monthly mean steric height anomalies at station 'P' for the period January 1956–December 1986 based on the 100 db reference level. The standard deviation for each record is written in the lower right corner. The dashed line gives the linear trend for the record. Appropriate statistics are listed in Table 1. (a) Thermosteric height anomaly, Z_T; (b) halosteric height anomaly, Z_S; and (c) total steric height anomaly, Z_α.

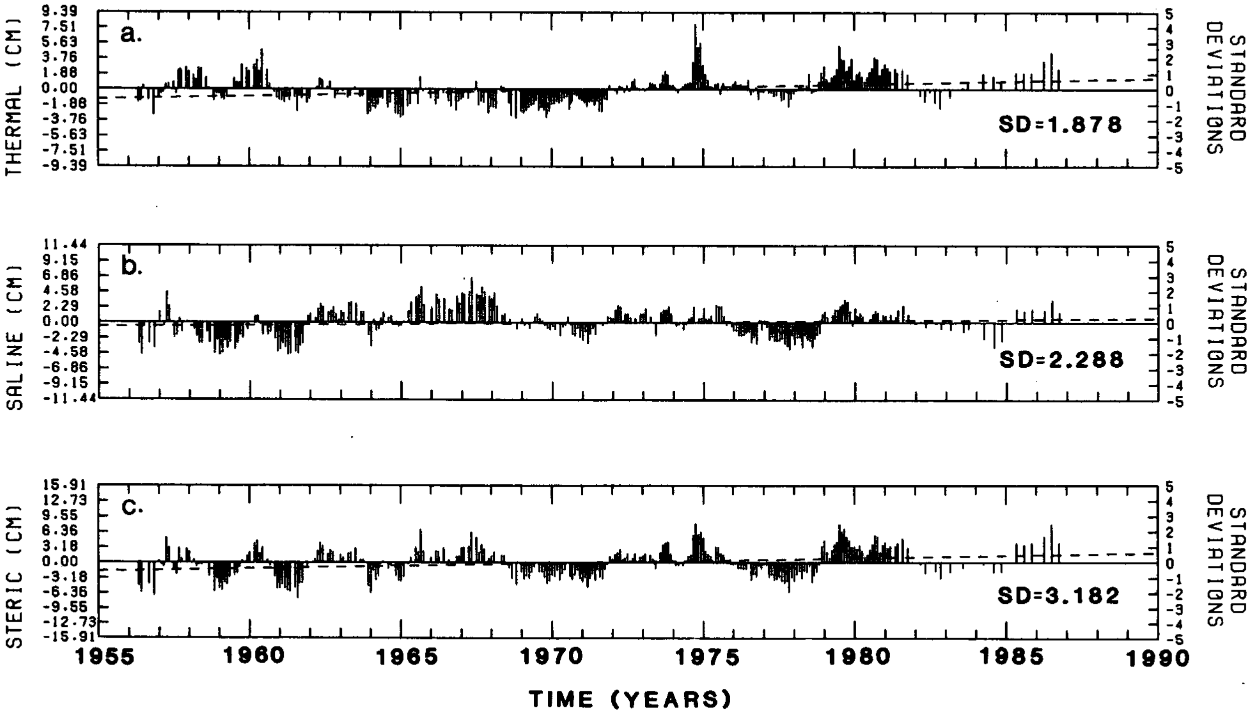

FIG. 3. Same as Fig. 2 except based on the 1000 db reference level.

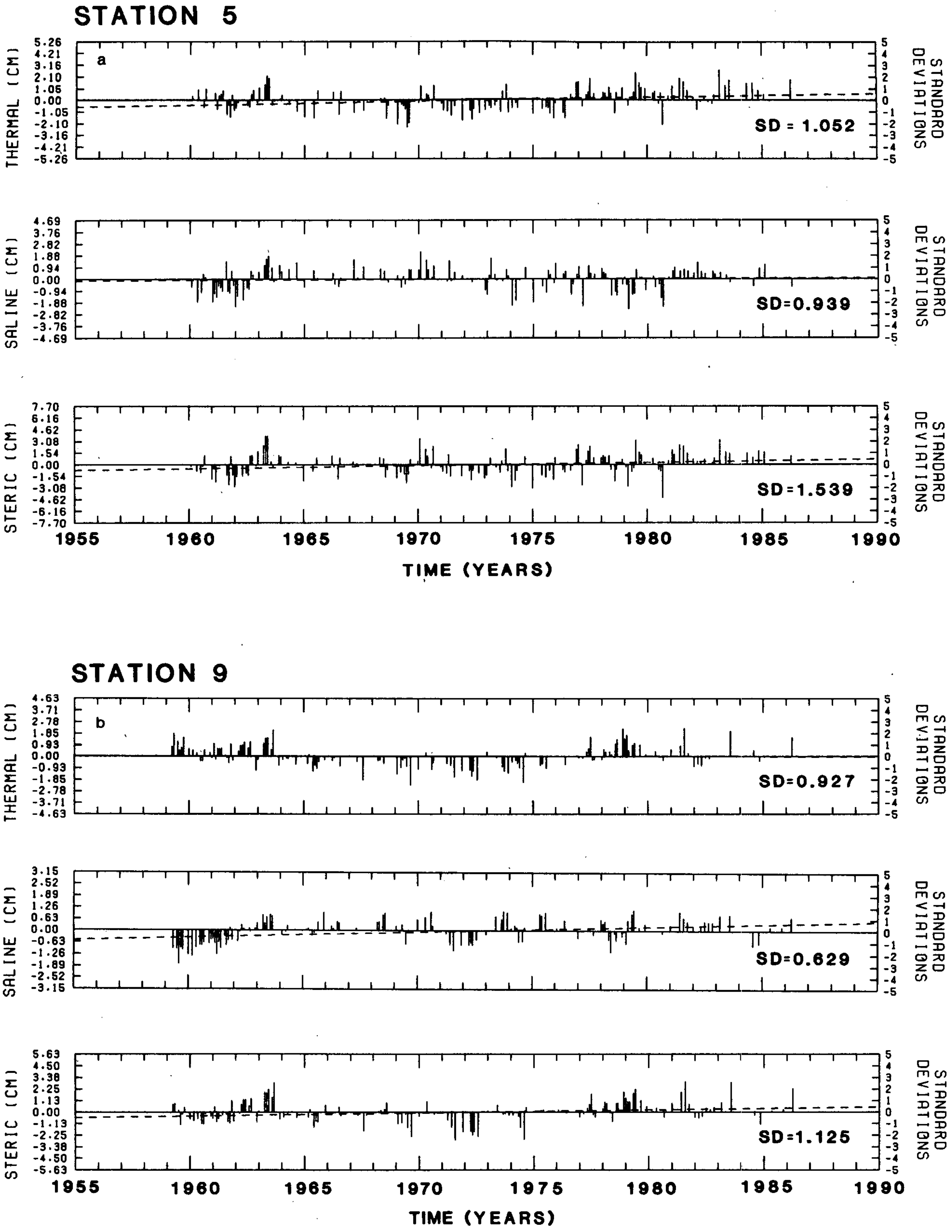

FIG. 4. Time series of monthly mean thermosteric (Z_T), halosteric (Z_S) and total steric (Z_a) anomalies at two line 'P' stations for the period August 1956–December 1986 based on the 100 db reference level. (a) station 5; and (b) station 9.

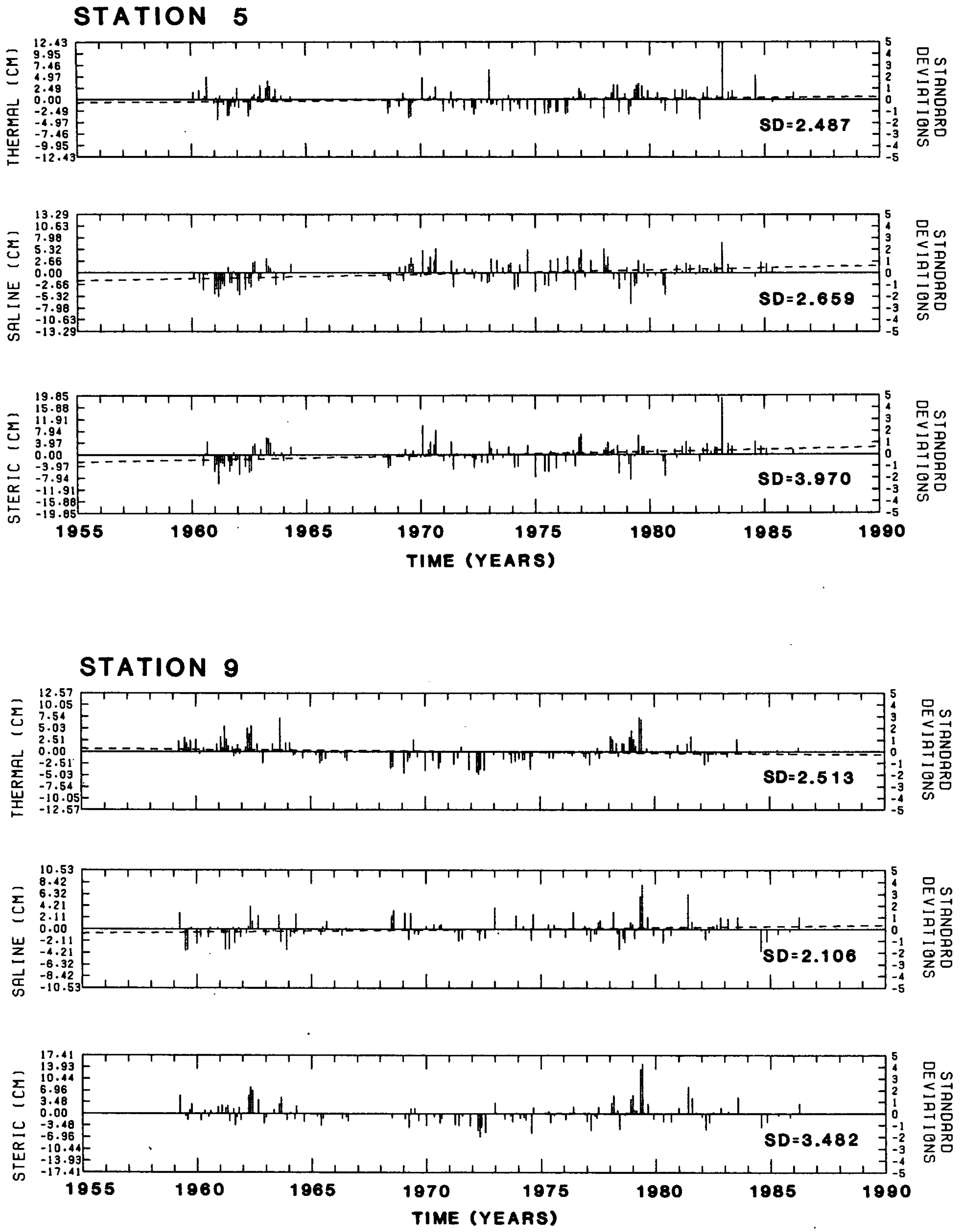

FIG. 5. Same as Fig. 4 except based on the 1000 db reference level.

TABLE 1. Station ‘P’ means, standard deviations, linear trends and confidence levels for thermosteric (Z_T), halosteric (Z_S) and total steric (Z_α) anomalies. Monthly values for January 1956–December 1986. All trends are positive. “∞” is based on assumption that all monthly values are independent; other levels use the integral time scales T_1 and T_2 (Table 4).

Level	Function	Number of records	S.D. (cm)	Trend (mm yr^{-1})	Confidence levels		
					∞	T_1	T_2
100 db	Z_T	282	0.76	0.08	0.90	—	—
	Z_S	282	0.71	0.32	0.99	0.90	0.90
	Z_α	282	1.16	0.39	0.99	0.95	0.90
1000 db	Z_T	278	1.88	0.73	0.99	0.80	0.70
	Z_S	278	2.29	0.37	0.95	0.60	—
	Z_α	278	3.18	1.10	0.99	0.95	0.90

fidence level estimation. We justify inclusion of this approach on the basis that it helps emphasize the need for caution when interpreting relatively short climatological datasets.

We further note that the number of data points used in each monthly anomaly estimate varies from month to month. As a consequence, some monthly records are derived from several independent ship surveys while others may be derived from only one survey. The question then arises whether it is more appropriate to use monthly mean values or the individual data points when calculating the trends. Except near the ends of the time series, the first half of each data record contains approximately two observations per month whereas the second half of the record contains a steadily increasing number of observations per month. A trend based on the individual data points would, therefore, be heavily weighted toward the more recent segment of the time series and would not be representative of the data sequence as a whole. As a consequence, we assume that observations collected within a given month are representative of that month so that trends are derived from monthly mean values regardless of the numbers of data points.

TABLE 2a. Trends of total steric height relative to 100 db for line ‘P’. Table shows means, standard deviations, linear trends and confidence levels for Z_α. Monthly values for January 1956–December 1986. Confidence levels are based on the integral time scales for station ‘P’ (Table 4). Levels less than 0.50 are not shown.

Station	Number of records	S.D. (cm)	Trend (mm yr^{-1})	Confidence levels		
				∞	T_1	T_2
1	84	2.66	0.72	0.95	0.60	0.50
2	86	2.40	0.20	—	—	—
3	166	2.02	0.20	0.70	—	—
4	146	1.47	0.18	0.60	—	—
5	149	1.54	0.42	0.95	0.70	0.50
6	154	1.35	0.32	0.95	0.70	0.50
7	134	1.18	0.13	0.60	—	—
8	124	1.19	0.39	0.99	0.70	0.60
9	135	1.13	0.29	0.99	0.70	0.60
10	109	1.02	0.32	0.95	0.60	0.50
11	109	1.00	0.31	0.99	0.60	0.50
12	132	1.27	0.20	0.90	—	—

1) ALL DATA INDEPENDENT

Confidence levels for each trend listed under “∞” in Tables 1 through 3 are based on a Student-t test for an infinite number of degrees of freedom. This presents no difficulties in the interpretation of the results since values for the confidence limits based on the actual numbers of monthly data points differ only by a few percent from values based on an infinite number of degrees of freedom. If the magnitude of the confidence limit exceeds that of the linear slope, the slope is considered unreliable at that confidence level.

2) EFFECTIVE DEGREES OF FREEDOM

A major problem with interpreting the trends in terms of global-scale climate warming or changes in basin-scale circulation is that the large interannual fluctuations in steric height anomaly (range ≈ 10 cm, standard deviation ≈ 3 cm) make it difficult to obtain accurate estimates of any small secular rise in sea level. As in (1), standard tests for confidence intervals in linear regression analysis frequently assume that individual datum is statistically independent whereas the long-term variability in the monthly steric height records (e.g., Figs. 2–5) suggests that the data are correlated over much greater time scales. The concern in such cases is that frequency components within the

TABLE 2b. Trends of total steric height relative to 1000 db (cf. caption of 2a). Stations 1 and 2 are too shallow to be included in the analysis.

Station	Number of records	S.D. (cm)	Trend (mm yr^{-1})	Confidence levels		
				∞	T_1	T_2
3	140	4.05	1.12	0.99	0.70	0.70
4	134	3.74	0.64	0.90	—	—
5	127	3.97	1.14	0.99	0.80	0.70
6	148	3.33	0.98	0.99	0.80	0.70
7	110	2.65	−0.31	0.60	—	—
8	97	2.75	0.09	—	—	—
9	118	3.48	0.03	—	—	—
10	87	2.32	0.18	0.50	—	—
11	103	2.53	0.39	0.80	—	—
12	113	2.78	0.57	0.90	—	—

TABLE 3a. Thermosteric, halosteric and total steric anomaly trends for line 'P' stations, relative to 100 db reference level. Also listed are the confidence levels for the trends based on an infinite number of degrees of freedom (∞) and on the integral time scales T_1 and T_2.

					Confidence levels		
Station	Function	Number of records	S.D. (cm)	Trend (mm yr^{-1})	∞	T_1	T_2
3	Z_T	166	1.15	0.17	0.90	—	—
	Z_S	166	1.31	0.03	—	—	—
	Z_α	166	2.02	0.20	0.70	—	—
5	Z_T	149	1.05	0.35	0.99	0.70	0.60
	Z_S	149	0.94	0.07	0.50	—	—
	Z_α	149	1.54	0.42	0.95	0.70	0.50
8	Z_T	124	0.95	0.24	0.95	0.60	—
	Z_S	124	0.63	0.16	0.95	0.50	—
	Z_α	124	1.19	0.39	0.99	0.70	0.60
11	Z_T	109	0.72	0.11	0.80	—	—
	Z_S	109	0.64	0.21	0.99	0.60	0.50
	Z_α	109	1.00	0.31	0.99	0.60	0.50

low-frequency portion of the spectral band can be aliased into the trend. To obtain reliable confidence limits on the trends, we require realistic estimates of the effective number of degrees of freedom.

A variety of methods exist for determining the degrees of freedom for nonstochastic time series. In our previous analysis (Thomson and Tabata 1987), we used a maximum entropy technique to obtain the frequencies of the dominant interannual signals in the steric height fluctuations. The spectral peak centered in the 5–7 yr band for the 1000 db records suggested a maximum decorrelation time of about 6 yr which was then divided into the total record length to determine the effective number of degrees of freedom in each time series. Physically, the 6-yr time scale appears to be linked to large-scale El Niño–Southern Oscillation (ENSO) events in the north Pacific.

Although the ENSO time scale continues to dominate the time series of monthly steric heights, we now believe it yields a much too conservative estimate of the degrees of freedom and that a more realistic (and objective) estimate can be obtained through use of the integral time scale

$$T = 1/C(0) \int_0^{\tau_0} C(\tau)d\tau,$$

in which $C(\tau)$ is the autocorrelation function for lag time, τ, and τ_0 is some upper limit determined by the length of the dataset. (Once τ_0 begins to exceed approximately 10% of the record duration, the statistical significance of the autocorrelation estimates diminishes appreciably.) Because the upper limit of the integral is not always well defined (i.e., the integral does not reach a constant value or oscillates about a "mean" level), we have calculated two values of the integral time scale, T, for each station 'P' time series. The smaller value, T_1, corresponds to the lag for which the integral time scale first reaches a local maximum. This value is typically associated with a "flat" portion of the curve and occurs for lags of 1–3 yr (Fig. 6). The longer value, T_2, is associated with the global maximum of the integral time scale and gives rise to the minimum number

TABLE 3b. Same as Table 3a except based on the 1000 db reference level.

					Confidence levels		
Station	Function	Number of records	S.D. (cm)	Trend (mm yr^{-1})	∞	T_1	T_2
3	Z_T	140	2.40	0.50	0.95	—	—
	Z_S	140	2.56	0.71	0.99	0.60	—
	Z_α	140	4.05	1.12	0.99	0.70	0.50
5	Z_T	127	2.49	0.38	0.80	—	—
	Z_S	127	2.66	1.00	0.99	0.70	—
	Z_α	127	3.97	1.38	0.99	0.80	0.70
8	Z_T	97	2.34	−0.05	—	—	—
	Z_S	97	2.12	0.14	—	—	—
	Z_α	97	2.75	0.09	—	—	—
11	Z_T	103	1.61	0.30	0.80	—	—
	Z_S	103	2.09	0.09	—	—	—
	Z_α	103	2.53	0.39	0.80	—	—

TABLE 4. Integral time scales T_1 and T_2 for station ‘P’ time series. T_1 is integral time scale where integral first reaches a plateau; T_2 is worst case (max) integral time scale where $T_2 \sim T_{\max}$ for computed lags.

Level	Function	T_1 (mo)	Lag (mo)	T_2 (mo)	Lag (mo)
100 db	Z_T	7.09	34	10.74	96
	Z_S	10.72	33	13.62	87
	Z_α	5.89	32	9.77	94
1000 db	Z_T	12.91	37	20.28	89
	Z_S	10.12	33	—	—
	Z_α	6.07	14	7.81	96

of degrees of freedom for a given time series. Typical lags for T_2 are in the range of 7–8 yr and, as expected, are comparable to the ENSO time scales derived using a spectral analysis technique. We note that it is not the lag that determines T_2 but rather the integrated contribution from all shorter lags up to that period. In effect, we have assumed that steric fluctuations become decorrelated at time scales significantly shorter than the time between ENSO events.

Listings of the integral time scales and corresponding lags for the station ‘P’ time series are presented in Table 4. Because of the large gaps in most of the line ‘P’ time series, we have chosen to use the integral time scales for station ‘P’ when calculating the appropriate confidence levels for the line ‘P’ trends. These time scales allow us to avoid problems with interpolation of the line ‘P’ time series and are assumed to give acceptable estimates of the effective numbers of degrees of freedom.

3. Results

Maximum confidence levels are obtained when each data point is treated as an independent sample. In this case, the positive trends obtained from the station ‘P’ time series are significant at the 99% confidence level. Exceptions are the thermosteric record relative to 100 db which is significant at the 90% level and the halosteric record relative to 1000 db which is significant at the 95% level. Significant (95%) trends for the line ‘P’ time series occur at a few selected stations only (cf. Tables 2 and 3).

More realistic confidence levels are obtained using the integral time scales. In this case, the 100 and 1000 db total steric trends are considered statistically significant at the 95% confidence interval for the shorter time scale, T_1, and remain statistically significant at the 90% level for the maximum time scale, T_2. The halosteric trend relative to 100 db is significant at 90% while the thermosteric trend relative to 1000 db is reliable at the 70%–80% level. With the possible exceptions of stations 5 and 6 relative to 1000 db, trends at line ‘P’ stations are no longer considered significant. This lack of consistent significant trends along line ‘P’ is possibly related to the relative sparseness of the time series records (which typically have fewer than half the number of data values of the station ‘P’ time series) or to differences in the regional physical oceanography. If the latter is true, it would suggest that observed secular trends at station ‘P’ and along line ‘P’ are indicative of changes in large-scale circulation rather than global sea level rise.

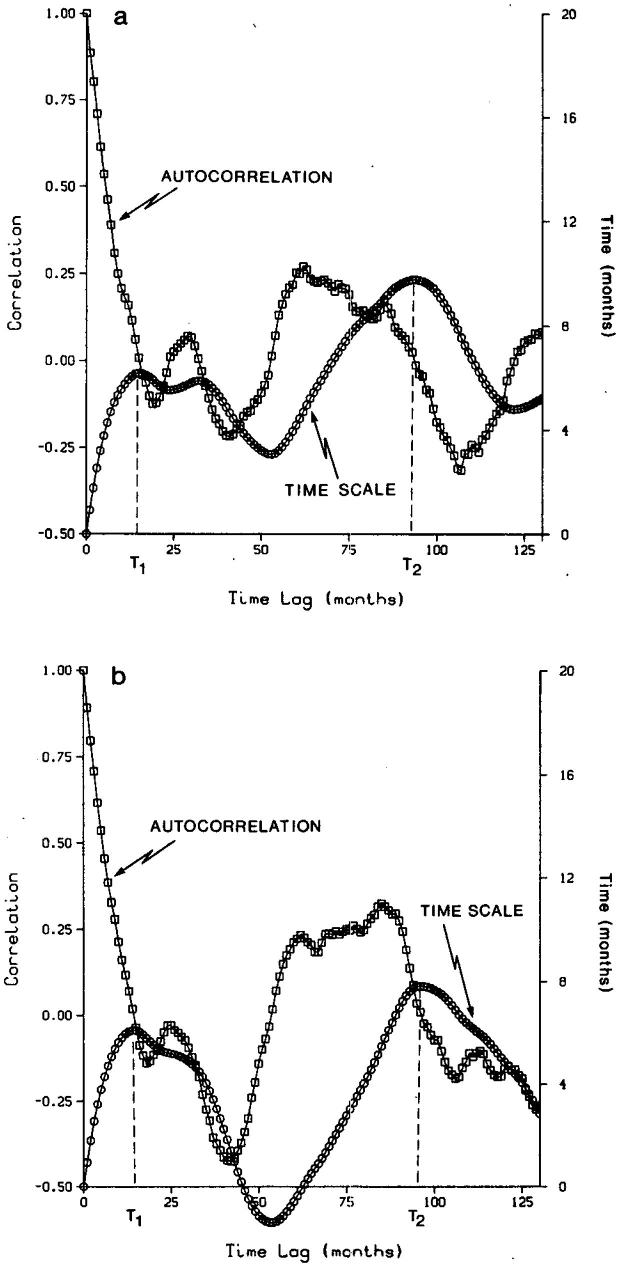

FIG. 6. Autocorrelation functions and associated integral time scales for the station ‘P’ monthly mean time series of total steric height. (a) 100 db reference level; and (b) 1000 db reference level.

a. *Station PAPA*

Based on the integral time scales, the positive 0.39 mm yr^{-1} trend in the 100 db steric height is significant at the 90%–95% confidence levels and is due almost entirely (81%) to the halosteric component of sea level (Table 1). The thermosteric component is not significant above the 50% confidence level and contributes little to the net sea level rise relative to 100 db. The positive 1.10 mm yr^{-1} trend in the 1000 db steric height is also significant at the 90%–95% level but, in contrast to the shallower reference level, is due mainly to the 0.74 mm yr^{-1} trend in the thermosteric component. The halosteric trend relative to 1000 db is similar to that relative to 100 db. According to data presented in Tabata (1989), the positive thermosteric trend relative to 1000 db coincides with a 0.05°C rise in temperature at 1000 m depth over the past 30 yr. This rise is considerably greater than the absolute temperature measurement accuracy of roughly ±0.01°C. In contrast, the salinity decrease at 1000 m of about 0.015 ppt over the same period is close to the approximate accuracy of ±0.01 ppt for absolute salinity measurement.

Qualitatively, the above results are almost identical to those presented in Thomson and Tabata (1987). The primary effect of adding three years to the time series is to increase slightly the trends of the total steric height records and to increase the contribution from the halosteric component for the two reference levels. Specifically, the respective trends for total steric height for the 100 and 1000 db reference levels increase from 0.31 to 0.39 mm yr^{-1} and from 0.93 to 1.10 mm yr^{-1}.

b. *Line 'P': 100 db reference level*

Use of the station 'P' integral time scales from Table 4 indicates that the positive steric height trends relative to the 100 db reference level along line 'P' are only marginally significant at the 70% confidence level for selected sites. According to Table 2a, maximum confidence levels are observed at stations 5 and 6, and stations 8–11. Only at station 8 do both the thermosteric and halosteric components appear to contribute to the overall steric height trend (Table 3a).

c. *Line 'P': 1000 db reference level*

As with the 100 db reference level, confidence levels for the positive steric height trends relative to the 1000 db reference level are only marginally significant above the 70% level at selected sites (Table 2a). Maximum confidence levels are obtained at stations 3, 5 and 6, where contrary to the situation at station 'P', the trends are completely dominated by the halosteric effect.

4. Discussion

Based on the extensive hydrographic time series for station PAPA, there has been a mean steric sea level rise of approximately 1 mm yr^{-1} within the upper 1000 m of the central northeast Pacific over the past 31 years. This value is similar to sea level rises estimated from the analysis of selected coastal tide gauge records (Barnett 1984; Pirazzoli 1986) but, unlike the tide gauge trends, is not contaminated by tectonic and glacio-isostatic processes. Thermal effects account for approximately 67% of the long-term steric rise at station 'P' but appear to be confined to the intermediate layer at depths greater than 100 m. The remaining 33% arises from a decreasing trend in salinity within the upper 100 m. As indicated by Table 1, the halosteric trend relative to 100 db is considerably more reliable (90% confidence level) than the thermosteric trend relative to 1000 db (70%–80% confidence level).

Results for the considerably less extensive line 'P' datasets are ambiguous in that only the inner stations 3, 5 and 6 suggest possible long-term trends with respect to the 1000 db level. No significant trends are observed at midocean stations such as 11 and 12 which lie within comparatively close proximity to station 'P' and presumably lie within the same general water mass (cf. Fig. 1). However, where the trends relative to 1000 db are marginally significant, values agree closely with the order 1 mm yr^{-1} trend at station 'P'. The principal difference is that the 1000 db trends at the line 'P' stations are due mainly to the halosteric component while at station 'P' the trend is due mainly to the thermosteric component. A majority of the line 'P' stations indicate marginally significant trends relative to the 100 db level but halosteric effects do not appear to dominate as they do at station 'P'.

a. *Climate-induced change*

Although the effects of regional circulation change cannot be ruled out, it is feasible that the positive sea level trend at station 'P' is indicative of an eustatic rise in global sea level linked to climatic warming. The fact that steric sea level increases relative to 1000 db is primarily due to thermal expansion of the subsurface layer might indicate an increased vertical transfer of heat to the deeper waters of the northeast Pacific Ocean. This is supported by observed warming to 4000 m at station 'P' and by the absence of a coinciding change in salinity (Tabata 1989). Any corresponding change in the upper 100 m would be difficult to detect because of the presence of large amplitude seasonal variability. Large-scale modification of precipitation patterns that is expected to accompany climate warming could account for the significant halosteric contribution to the upper 100 m of the water column at station 'P'. For our results to be consistent with climate warming, there will have been increased rainfall over the open ocean over the past few decades.

The cause of the observed warming of the intermediate waters at station 'P' is unknown since the North Pacific does not appear to be ventillated at the surface at high latitudes. We further note that the observed temperature increase is not consistent with downward transport rates expected on the basis of vertical diffusion coefficients derived from C_{14} data and the presence of a low oxygen layer near 1500 m depth in the northeast Pacific Ocean (R. W. Stewart, personal communication).

b. *Circulation-induced change*

Secular redistribution of the temperature and salinity fields could also account for the positive steric height trends in the northeast Pacific. For example, a gradual poleward displacement of the Alaska Gyre through a change in the mean (climatic) wind field, would be accompanied by northward movement of relatively warm, low salinity water. This would coincide with a downward displacement of isopycnal surfaces and would lead to an increase in steric levels at station 'P' and adjoining stations. The fact that such increases are not observed at offshore line 'P' stations in the general vicinity of station 'P' (e.g., stations 10–12) presumably reflects inadequate sampling in time. A strong argument against circulation-induced change is the absence of a large halosteric component at station 'P'. Since the density field in the northeast Pacific is mostly controlled by salinity, we would expect the halosteric component and not the thermosteric component to dominate changes in total steric height. Also, a careful study of the temperature, salinity and dissolved oxygen fields on fixed density surfaces at station 'P' (Tabata 1989) failed to find any discernible effect of the horizontal displacement of the center of the Alaska Gyre on the water properties at station 'P'.

Although of marginal significance, the positive steric trends in the vicinity of line 'P' stations 5 and 6 would appear to be related primarily to modification of the subsurface currents and associated water masses rather than to climatic changes in water density. Intensification or expansion of the poleward mean flow off the west coast of North America (Fig. 1) would lead to increased steric sea levels over the eastern portion of the line. The lack of corresponding sea level rise to the west of station 6 may reflect relatively weak zonal transport in this region.

5. Summary

An analysis of steric height trends for the station/line 'P' data sets suggests that sea levels in the northeast Pacific have been rising at an average rate of approximately 1 mm yr^{-1} over the past 31 yr. The addition of 3 yr to the time series analyzed by Thomson and Tabata (1987) and a recalculation of the significance intervals based on integral time scales has somewhat increased our confidence in the observed rise at station 'P'. However, we continue to caution that the order 1 mm yr^{-1} trends are subject to considerable error due to the large O(1–10 cm) seasonal and interannual fluctuations. If we assume that the observed trends at station 'P' are indicative of climate-induced sea level change, then roughly 67% of the total steric rise relative to 1000 m depth is due to warming of the ocean below surface wind-mixed layer (depths < 100 m). The remaining 33% of the rise in total steric height is mainly associated with reduced salinities in the surface oceanic layer and may be linked to climate-induced changes in open ocean precipitation. Alternatively, the secular trends may be related to gradual poleward displacement of the regional water masses and associated circulation patterns.

Observed trends at the twelve line 'P' stations are not inconsistent with those at station 'P' but appear to be far too inadequately sampled in time to provide reliable estimates of possible sea level rise. The confinement of marginally significant trends to water mass transition zones on the eastern half of the line indicates that steric sea level rise may be associated with long-term changes in the subsurface circulation and water mass boundaries rather than with secular climate-induced variability. For both the steric and coastal tide-gauge records, such an effect would make it more difficult to separate secular climate-induced eustatic changes from long-term oceanographic fluctuations (cf. Pirazzoli 1986).

Determination of the eustatic component of long-term sea level change remains a challenging problem. Studies based on oceanographic time series are invariably limited by the brevity of the records and by the small signal-to-noise ratios associated with the presence of annual and interannual variability. Similarly, studies based on coastal tide gauge records face the formidable task of separating the weak eustatic component from tectonic, glacio-iostatic, oceanographic and atmospheric effects. Both approaches will benefit from extended measurements over the next half century during which time the climate-induced signal will clearly begin emerging from the signal noise.

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