Revised XCTD Fall-Rate Equation Coefficients from CTD Data*

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1. Introduction

The ocean physical state variables are salinity, temperature, and pressure. For a long time, ships of opportunity have employed expendable bathythermographs (XBTs) to make upper-ocean measurements. These probes measure temperature and infer depth from time through a fall-rate equation. Pressure can be computed from depth and latitude (Fofonoff and Millard 1983). Salinity must be estimated from an independent dataset and is often merged with XBT data using temperature–salinity (T–S) relations.

The use of XBT data for water mass studies, climate studies, and ocean circulation studies is hampered by the lack of salinity measurements. Salinity is a conservative water mass property in the ocean interior and is often a useful water mass tracer. Salinity is also a valuable climate diagnostic, especially with regard to precipitation and evaporation (Jacobs 1948), the role of the oceans in the global water cycle (Schmitt and Wijffels 1993), and the thermohaline circulation (Bryan 1986). In addition, the accurate calculation of density (hence geostrophic velocity) requires salinity measurements.

Recently, expendable conductivity–temperature–depth probes (XCTDs) have become commercially available from Sippican. XCTDs allow measurements of the ocean physical state variables to 1000-m depth. Routine XCTD use could improve the usefulness of ship-of-opportunity data for water mass, climate, and circulation studies.

Past studies comparing temperature–depth profiles from various models of Sippican XBTs, to more accurate CTD (conductivity–temperature–depth) profiles have revealed systematic temperature errors of 0.1°–0.2°C and systematic depth errors at or exceeding the 2% accuracy specification (Seaver and Kuleshov 1982; Heinmiller et al. 1983). The temperature errors were estimated by examining temperature discrepancies in shallow regions of small vertical temperature gradients (thermostads). Once these biases were corrected the XBT temperature–depth profiles were compared to CTD profiles to find the depth errors by matching temperatures. Temperature and depth errors of similar magnitudes have also been found by comparing Sippican expendable current profile (XCP) data to CTD data (Prater 1991). This careful effort at revising depth coefficients for expendable probes focused on matching finescale vertical features from 20 to 200 m in length from pairs of bandpassed XCP and CTD temperature profiles collected close in space and time. Both XBTs and XCPs reported temperatures too warm and depths too shallow.

Here XCTD performance is evaluated by comparisons with CTD data. The XCTD temperatures are assumed to be accurate to within specification. This assumption is implicitly supported a posteriori through salinity comparisons. Nominal fall-rate equation coefficients (depth coefficients) are used to calculate nominal XCTD depth as a function of time. A significant error in the nominal XCTD depths (hence the nominal depth coefficients) is found by matching XCTD temperatures with CTD temperatures. As in previous studies of Sippican expendable probes, nominal depths for the XCTDs are shallower than the CTD depths. Here revised depth coefficients are computed and used to calculate revised XCTD depths (then pressures) to remove this bias. Salinity is calculated from conductivity, temperature, and pressure (following Fofonoff and Millard 1983), so XCTD salinities are recomputed using revised XCTD pressures before comparing them to CTD salinities. Many of the XCTDs exhibit noise in the deep conductivities. However, when the XCTD salinities are averaged sufficiently in the vertical, nearly all the probes meet the expected salinity accuracy.

2. Data

The data were taken during the World Ocean Circulation Experiment (WOCE) Hydrographic Program section P18 in April 1994 along nominal longitude

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110°20′W. A total of 19 Sippican XCTDs were dropped midway between CTD stations from 1° to 9°30′N. CTD stations used here were occupied at 20′ latitude intervals from 0° to 3°N, and 30′ latitude intervals from 3° to 10°N. Thus, XCTD drops 6–11 (1°10′–2°50′N at 20′ latitude intervals) are flanked by CTD stations 18 km distant and XCTD drops 12–24 (3°15′–9°15′N at 30′ latitude intervals) are flanked by CTD stations 28 km distant.

The XCTDs measure conductivity using an alumina ceramic cell and temperature using a glass bead thermistor. Neither sensor is corrected for pressure effects. However, each XCTD is subject to a three-point calibration. For the calibration, salinity is held at 35 and temperature is varied from 30° to 15° to 2°C. Thus, both sensors are calibrated over a reasonable range of temperatures and conductivities. Depth is determined using Sippican's nominal fall-rate equation. The XCTD accuracy specifications are ±0.0035 S m^{-1} in conductivity, ±0.035°C in temperature, and ±2% in depth (from Sippican product literature). Positive errors of these magnitudes in these quantities would cause errors of +0.035, −0.035, and −0.01 in salinity, respectively. (The last estimate assumes a 20-m depth error at 1000 m.) If these errors are correlated the salinity error could be as high as ±0.08. In the more likely case that they are not correlated a salinity accuracy of ±0.05 is expected. The 4-Hz sample rate and roughly 3.2 m s^{-1} fall velocity result in an XCTD data point roughly every 0.8 m.

A Sippican Mk12 PC-based system was used with a handheld launcher for XCTD data acquisition. Ship speed was reduced to below 10 kt during XCTD deployments as recommended. Data were collected to at least 1000-m nominal depth, sometimes deeper. The XCTDs used had serial numbers in the range 93110080–93110109 and were manufactured in November 1993. Two out of 19 XCTDs failed at depth. XCTD 18 (6°15′N) abruptly failed after 292 s (nominal depth 906 m). After this time the temperature and conductivity were both recorded as zeros. The cause of this failure may have been a wire break. XCTD 21 (7°45′N) failed more gradually. The salinities for XCTD 21 are questionable (but not rejected) after about 180 s (nominal depth 568 m). Temperature and conductivity fail by slowly starting to increase after about 270 and 250 s, respectively (nominal depths 840 and 780 m). The temperatures and conductivities jump abruptly to obviously unreasonable magnitudes after 283 s (nominal depth 878 m). This failure may be owing to seawater forced into the circuitry at high pressure. For XCTDs 18 and 21 only data taken prior to times of 292 and 250 s, respectively, are retained.

The CTD data are from a Sea-Bird Electronics 911plus CTD with duplicate pumped temperature–conductivity sensors. Each set of sensors underwent a precruise and postcruise calibration. The thermistor drifts are assumed to be linear between these calibrations. The conductivity sensors were calibrated in situ using salinity values from 36 water samples collected at each station. A Guildline 8400A autosalinometer was used to analyze the water sample salinities. The autosalinometer was routinely standardized with Wormley Standard Seawater Batch P114. The CTD pressures are thought to be accurate to better than 0.03% of full scale (±2 db), the temperatures to better than ±0.002°C, and the salinities (after calibration to in situ water sample data) to better than ±0.002 (equivalent to conductivities of about ±0.0002 S m^{-1}). The 24-Hz CTD data were averaged in 1-db pressure bins using standard CTD processing techniques and then smoothed and subsampled at 2-db intervals. Since these measurements are at least an order of magnitude more accurate than those from the XCTDs, the CTD data are considered a standard against which the XCTD data can be evaluated.

3. Revised fall-rate equation coefficients

An initial attempt to contour a vertical section of temperature using both the XCTD and CTD data yields a suspicious sawtooth pattern in deep isotherms. The 5°C contour (near 900 m) is on average about 20 m shallower at the locations of the XCTDs than at the CTDs (Fig. 1; interior tick marks show XCTD and CTD locations; vertical dotted lines distinguish XCTD locations). The 6° and 7°C contours (near 760 and 600 m) show similar patterns with smaller amplitude. The vertical temperature gradient at 900 m is about 0.005°C m^{-1}, so the XCTDs systematically report temperatures about 0.1°C colder than the surrounding CTD stations at this depth. One possible reason for this pattern might be a temperature error of 0.1°C at depth. For the purposes of fall-rate calculations, the XCTD temperatures are assumed to meet the ±0.035°C accuracy specification. The validity of this assumption is argued in the discussion section. If the XCTD temperatures are accurate, then the nominal XCTD depth coefficients are suspect. A discrepancy of roughly 20 m at 900 m falls outside the specified 2% depth accuracy. This systematic error is alleviated by estimating revised depth coefficients.

In the present case, XCTDs were dropped midway between CTD stations to increase horizontal resolution of the hydrographic section in the top 1000 m of the water column. Thus each XCTD profile is 18–28 km from the nearest CTD profile. This spatial separation prevents matching finescale vertical features following Prater (1991), since these features almost certainly do not have horizontal coherence over such distances (Munk 1981). For instance, a near-inertial internal wave (frequency twice the local Coriolis parameter) at 5°N, 900 m (buoyancy frequency $N \sim 2.5 \times 10^{-3}$ s^{-1}) with vertical wavelength 200 m would have a horizontal wavelength of about 20 km. Smaller vertical wavelength or higher-frequency waves would have shorter

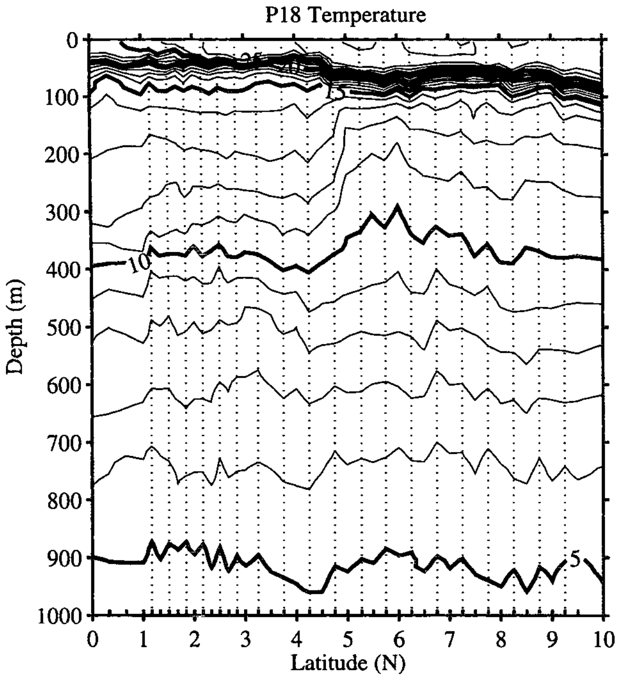

FIG. 1. Vertical section of temperature (°C) combining CTD stations with XCTD drops using nominal XCTD depths. Data taken 13–19 April 1994 along 110°W during WOCE Hydrographic Program Section P18. The data are smoothed and subsampled at 10-m intervals before contouring. Isotherms are contoured at 1°C intervals and labeled at 5°C intervals (thick contours). Inward tick marks show CTD and XCTD locations. XCTD locations are distinguished by dotted vertical lines. Nominal vertical exaggeration is 1250:1. The sawtooth pattern visible in the 5°, 6°, and 7°C isotherms reveals that XCTDs nearly always report colder temperatures than surrounding CTDs at depth. This discrepancy is owing to a systematic error that results in a nominal XCTD depth shallower than the CTD depths in the bottom half of the depth range. By 1000 m the nominal XCTD depth error reaches 25 m.

horizontal wavelengths. However, the WOCE Hydrographic Program sections are designed to oversample the large-scale field and resolve much of the mesoscale eddy field. The first baroclinic Rossby deformation radius exceeds 100 km at 10°N and increases toward the equator so the section easily oversamples the mesoscale eddy field in the region of interest. This oversampling means that it is possible to use the large-scale and mesoscale temperature field to revise XCTD depth coefficients.

The procedure for refining the depth coefficients is straightforward. First, temperatures for the pair of CTD stations flanking each XCTD drop are averaged on pressure surfaces. Then the depths for the resulting mean CTD temperature profile are calculated from pressure and the average latitude. The mesoscale horizontal temperature gradient between CTD stations should be roughly linear so the resulting mean CTD temperature–depth profile should be similar to that of the XCTD dropped midway between the CTD stations. The same assumption has been used for more widely spaced XBT profiles (Heinmiller et al. 1983). Next, the mean CTD temperatures are sorted to remove any inversions so that temperature monotonically decreases with increasing depth (following Thorpe 1977). Very little sorting is required (64 out of over 10 000 temperatures are assigned new depths), but this step is necessary to obtain a mean CTD profile where each temperature is associated with a unique depth. Then the time base is reconstructed for the XCTD profile by inverting the quadratic fall-rate equation

$$d = z_0 + z_1 t + z_2 t^2$$

to find time, t, from depth, d, where z_n are the fall-rate equation coefficients. Finally, each XCTD time is paired with a CTD depth. This match is made by taking each XCTD temperature, finding the depth in the sorted mean CTD temperature–depth profile at which that XCTD temperature occurs, and associating the XCTD time with the CTD depth.

These XCTD-time/CTD-depth pairs are compiled for all 19 XCTDs. There is considerable scatter in the individual values of the differences between nominal XCTD depths and CTD-derived depths (Fig. 2; dots). Means and standard deviations of these differences

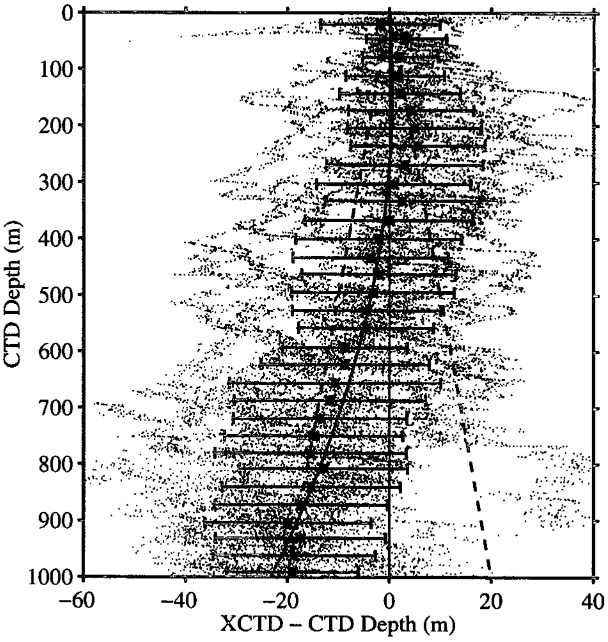

FIG. 2. Difference of nominal XCTD depths and CTD-derived depths plotted against CTD-derived depths for all 19 XCTD drops. The dots are individual differences. The asterisks with error bars are the means and standard deviations of these differences calculated in 10-s time (about 30-m depth) bins. The thick solid line is the difference between nominal XCTD depth and revised XCTD depth from the two sets of fall-rate equation coefficients (Table 1). The dashed line is an error envelope of 2%. Nominal XCTD depths depart increasingly from revised XCTD depths and CTD-derived depths with increasing depth. The differences approach the 2% error envelope in the bottom few hundred meters.

TABLE 1. XCTD fall-rate equation coefficients. The first column contains nominal coefficients and the second column contains revised coefficients. The first row contains XCTD depth offsets, the second row initial velocities, and the third row accelerations. The revised deceleration is about 40% of the nominal deceleration.

Coefficient	Nominal	Revised
z_0, offset (m)	0	0
z_1, velocity (m s^{-1})	3.254	3.227
z_2, acceleration (m s^{-2})	-5.33×10^{-4}	-2.17×10^{-4}

are computed in 10-s time bins (Fig. 2; asterisks with error bars). Mean differences between nominal XCTD- and CTD-derived depths reach 20 m at 1000 m. Mean differences exceed their standard deviations below 840 m.

Revised fall-rate equation coefficients z_n (Table 1) are found from a least squares fit of the XCTD-time/CTD-depth pairs to the quadratic fall-rate equation. All data for times less than 325 s (nominal XCTD depth 1000 m) are used in the fit except for XCTDs 18 and 21. (See the data section.) Since data acquisition starts directly after the XCTD hits the water, no offset is expected, so z_0 is constrained to be zero. The difference between the depths from the revised and nominal fall-rate equation coefficients (Fig. 2; solid line) exceeds the 2% accuracy specified for depth (Fig. 2; dashed lines) below 900 m.

The nominal XCTD fall-rate equation coefficients give too slow a descent, as did those for XBTs (Heinmiller et al. 1983) and XCPs (Prater 1991). The revised initial XCTD velocity is only 0.027 m s^{-1} slower than the nominal initial XCTD velocity. However, the revised XCTD deceleration is about 40% of the nominal XCTD deceleration. Therefore, after about 84 s (nominal depth 270 m) the revised XCTD depth exceeds the nominal XCTD depth (Fig. 2; solid line). After 325 s (nominal depth 1000 m), the revised XCTD velocity is 0.179 m s^{-1} faster than the nominal XCTD velocity and the revised XCTD depth is about 25 m greater than the nominal XCTD depth (Fig. 2; solid line). There may be some aspect of the Sippican method for calculation of depth coefficients that biases their nominal decelerations high.

4. Salinity evaluation

The third property measured by the XCTD is conductivity. The conductivity sensors are individually calibrated during XCTD manufacture to be accurate to ±0.0035 S m^{-1}. The XCTD temperatures are assumed to conform to specifications. Subject to this assumption, nominal XCTD depths have been shown to be systematically shallow of CTD depths by as much as 25 m at 1000 m. Since salinity is calculated from conductivity, temperature, and pressure, a systematic error in pressure will result in a systematic error in salinity. A pressure that is 25 db too low yields a salinity that is about 0.01 too high. An error of 0.01 in salinity is about one-fifth the expected XCTD accuracy. Such an error could be noticeable in regions with small salinity gradients. Hence, before comparing XCTD and CTD salinities the pressures are recalculated from the revised depths. Then XCTD salinities are recalculated from the conductivity, temperature, and revised pressure values.

Salinity has very small vertical and horizontal gradients at about 800-m depth (5.5°C) in the region where these data were taken. As a result, this dataset is an excellent one with which to examine the accuracy of XCTD salinities. To compare XCTD and CTD salinities at depth, the portion of each profile with 5° < T < 6°C (about 900–750-m depth) is found. The means and standard deviations of the salinities within this temperature range are calculated and plotted against latitude (Fig. 3; asterisks for XCTD means, open circles for CTD means, error bars for standard deviations). While there is significant probe-to-probe variability, the XCTD salinities have standard deviations on the order of ±0.02, an order of magnitude greater than those of the CTD salinities. This difference is owing to noise in the XCTD conductivities that grows with depth below about 600 m. This conductivity noise

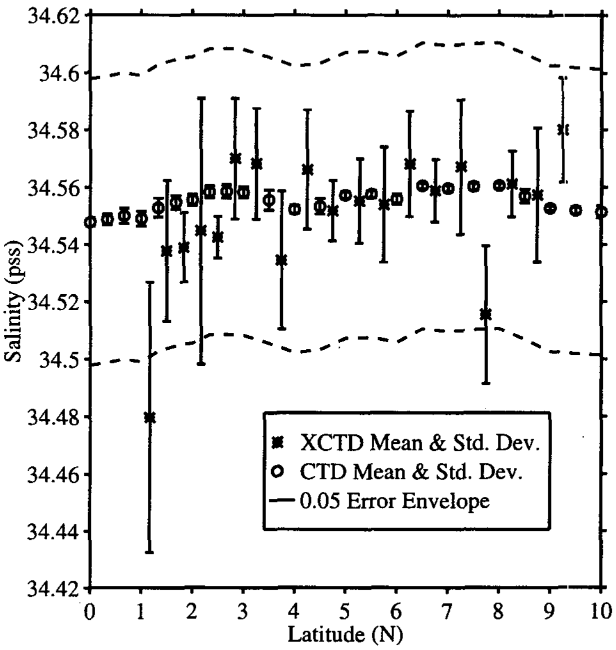

FIG. 3. Means and standard deviations of deep salinities for 5° < T < 6°C plotted against latitude. Asterisks show XCTD means using revised pressures. Open circles show CTD means. Error bars show standard deviations. XCTD standard deviations (roughly ±0.02) are an order of magnitude larger than CTD standard deviations. This discrepancy is owing to noise in the deep XCTD conductivities. The dashed line shows a ±0.05 envelope about the mean CTD salinities. Only one XCTD has mean deep salinities outside of this error envelope.

has a standard deviation of around ±0.002 S m^{-1} between 800 and 1000 m. This noise requires the XCTD salinities to be averaged for comparison or plotting. Sippican claims the problems causing this noise have been ameliorated in subsequent production runs.

The dashed lines on Fig. 3 delineate an envelope of ±0.05 about the mean CTD salinities. The XCTD salinities are sufficiently noisy so that their standard deviations (hence their individual values) sometimes fall outside this expected error envelope. However, of the 19 mean XCTD salinities, only 1 lies outside of this envelope. XCTD 6 (1°10′N) reports salinity too low throughout much of the water column. Thus, 18 of 19 XCTDs (95%) nominally conform to specifications for salinity accuracy when the data are averaged sufficiently in the vertical.

In an overall sense, the deep XCTD salinity accuracy is quite good. There is little systematic bias between the mean XCTD and CTD salinity values in Fig. 3. Mean XCTD salinities (excluding the outlier) are 0.003 low of adjacent mean CTD salinities. This agreement would not be so good if the salinities had been calculated using nominal pressures. Mean XCTD salinities would be 0.008 high of adjacent mean CTD salinities if the nominal pressures were used. The standard deviation of the differences of mean XCTD salinities and adjacent CTD salinities is ±0.02.

This same set of comparisons was also performed for 1°C temperature bins from 6° to 12°C (680–250 m). Above 12°C *T–S* comparisons are difficult because vertical temperature and salinity gradients are large, as is the natural variability of these properties. The mean XCTD salinity data agree with the mean CTD data to within the error specifications of ±0.05 in all the bins (ignoring the outlier XCTD 6). The standard deviation of the differences of mean XCTD salinities and adjacent CTD salinities is ±0.02 or better. Progressing from the 5°–6°C bin to the 11°–12°C bin (deep to shallow), mean XCTD salinities (excluding XCTD 6) trend gradually from 0.003 low to 0.007 high of adjacent mean CTD salinities, a systematic error of uncertain origin. However, the error has a mean of only +0.004 and is only 0.01 in total range (roughly one-twelfth and one-fifth of the error specification, respectively), so no correction is attempted.

5. Composite vertical sections

The vertical section of temperature including XCTD data with revised depths (Fig. 4) is smoother in the bottom few hundred meters than that including XCTD data with nominal depths (Fig. 1). The deep systematic sawtooth pattern resulting from nominal XCTD depths being shallower than actual depths is gone. About half of the roughly 20-m standard deviation of remaining vertical displacements is attributable to high-frequency small-scale processes such as internal waves that are not correlated over the distances between the XCTD drops and flanking CTD stations (Munk 1981). Even if all the rest of the scatter were attributable to variations in individual XCTD fall rates, the revised XCTD depths would be within specification.

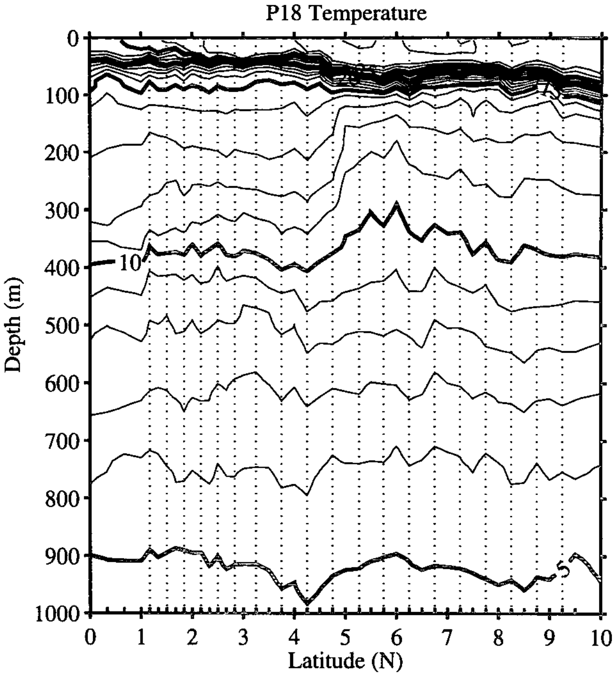

FIG. 4. Vertical section of temperature (°C) as in Fig. 1 but including XCTDs with revised depths. The systematic bias in the deep XCTD depths that created a sawtooth pattern in the deep isotherms of Fig. 1 is eliminated by using the revised fall-rate equation coefficients to recalculate XCTD depth.

The vertical section of salinity reveals the XCTD with outlying salinities (Fig. 5). XCTD 6 (1°10′N) clearly reports low salinities throughout the water column. The 10-m smoothing and subsampling is sufficient to suppress much of the XCTD salinity noise at this contour level. However, there are very few contours below 600 m, where the XCTD salinities are noisiest. The isohalines exhibit larger vertical displacements than the isotherms. These enhanced isohaline displacements probably arise because vertical salinity gradients are one or two orders of magnitude less than vertical temperature gradients throughout nearly all of the water column. Thus errors of similar magnitudes in the two fields will result in vertical isohaline displacements much larger than isotherm displacements.

6. Discussion

Systematic biases in XCTD data have been attributed to the nominal fall-rate equation coefficients. Revised coefficients have been calculated by matching XCTD temperatures with flanking CTD temperatures. The deep sawtooth pattern in the isotherms that occur when XCTD data were combined with CTD data (Fig.

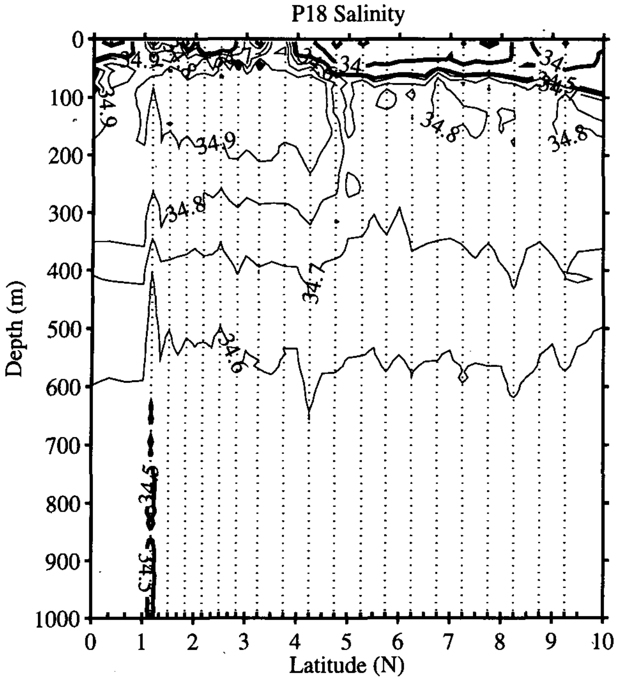
P18 Salinity

FIG. 5. Vertical section of salinity (pss) as in Fig. 4. Thick contours are isohalines at intervals of 0.5 and thin contours are isohalines at intervals of 0.1 from 34.6 to 34.9. XCTD 6 (1°10'N), reports salinities consistently low throughout the water column. The isohalines show more vertical displacement than the isotherms in Fig. 4. The vertical salinity gradient is an order of magnitude smaller than the vertical temperature gradient, so noise of similar magnitudes in the two fields results in isohaline vertical displacements larger than those of isotherms.

1) could have been caused by XCTD temperatures 0.1°C too cold or XCTD depths 20 m too shallow. Correcting the XCTD depths by assuming the XCTD temperatures are accurate throughout the water column results in deep XCTD salinities that agree with deep CTD values to better than ±0.01 in an overall sense with a scatter of ±0.02. Attributing the pattern to XCTD temperature error and adding a −0.1°C bias to the XCTDs would have resulted in deep XCTD salinities about 0.1 low of CTD values, well outside of specification. The relative success of the depth correction argues that the nominal fall-rate coefficients are the largest source of error. The good salinity comparisons are an implicit a posteriori validation of XCTD temperature accuracy since calculation of salinity depends on temperature and suggest that XCTD temperatures have at least an individual accuracy of around ±0.02°C and an overall accuracy of ±0.01°C.

This argument does not exclude the possibility of compensating errors in the XCTD. An evaluation of a similar glass-bead thermistor showed a pressure dependence of the right sign and magnitude (Millard et al. 1980) to account for the sawtooth pattern in Fig. 1 (0.065°C at 1000 db). Such a tendency might combine with a compensating error in conductivity or the electronics to give salinities that would suggest that depth, not temperature, was in error. However, studies of Sippican XBTs suggested that they read too warm by 0.1°–0.2°C in the North Atlantic 18°C thermostad (Seaver and Kuleshov 1982; Heinmiller et al. 1983). A recent study has shown XCPs also read too warm with the error increasing from 0.1°C at the surface to 0.2°C by 1000 m (Prater 1991). The positive mean depth difference (Δz = 5 m; Fig. 2) in the weak tropical thermostad ($\Delta T/\Delta z = 0.013°\mathrm{C\ m^{-1}}$) in the present study region (11°–12°C at 250 m; Fig. 4) is reminiscent of those used to infer temperature errors in the XBT studies and comprises marginal evidence for a bias of $\Delta T = +0.07°\mathrm{C}$ in the XCTD data. These warm biases are in the wrong sense to account for the observed discrepancies (Fig. 1). In addition, an error analysis of the possible temperature bias at the tropical thermostad implied by Fig. 2 suggests that it is not statistically different from zero. Hence, depth error remains the most likely cause of most of the discrepancies between XCTD and CTD data. Comparisons of XCTD profiles made directly after CTD stations following Prater (1991) would aid in separating depth error from possible temperature error.

A final concern is the effect of the error in nominal depth on density and geostrophic velocity calculations. For the region sampled the potential density calculated with nominal depths is about 0.02 kg $\mathrm{m^{-3}}$ denser than that calculated with revised depths at around 1000 m. Geopotential anomaly at the surface relative to 1000 m is in error by about 0.07 $\mathrm{m^2\ s^{-2}}$ (0.7 dynamic centimeters). This error is about 3% of the total change in geopotential anomaly from the equator to 10°N. Of course, the pycnocline in the tropical Pacific is very close to the surface. The error in geopotential anomaly would be larger in a region with a deeper pycnocline. Geostrophic calculations using XCTD nominal depths might contain significant errors with a deep thermocline when CTD and XCTD data are combined.

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