Journal of Oceanography, Vol. 54, pp. 373 to 380. 1998

Short Contribution

Preliminary Results of in-situ XCTD/CTD Comparison Test

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(Received 29 October 1997; in revised form 8 April 1998; accepted 8 April 1998)

The current status of XCTD manufactured by the Tsurumi Seiki Co. is described based on XCTD/CTD comparison tests conducted in the Pacific and Indian Ocean in November 1996 and January 1997 respectively. The falling rates of used probes are generally consistent and differences between individual probes stay within a small range of +/–5 m through the full depth range (0–1000 m), although the rate is slightly different from the depth-time equation provided by the manufacturer. Temperature and salinity accuracy is estimated to be better than 0.05°C and 0.05 psu respectively. Comparison of vertical temperature/salinity sections of XCTD/CTD constructed separately along a line on which XCTD stations locate midway of CTD stations. The hydrographic structures obtained are generally consistent, and the difference of surface dynamic height (referred to 1000 db) is 0.03 dyn m in RMS.

Keywords:
- XCTD,
- VOS,
- depth-time equation,
- measurement error,
- Indian Ocean.

1. Introduction

The upper ocean (surface to permanent thermocline) stores heat and freshwater supplied from the surface and then re-distributes them due to the active current and the mixing process. Thus, monitoring of global scale thermal and salinity field is essential for the study of climate. The thermal field and its variability from seasonal to interannual scales have been detected mostly by volunteer observing ship (VOS) programmes using XBT. In the areas where the T-S relation is stable, the geostrophic velocity field can be well estimated by temperature only (Kessler and Taft, 1987). However, this method is not available in the subarctic area where salinity stratification is a major factor governing the density structure.

Although the importance of upper ocean salinity measurement is widely recognized, time/space sampling density of salinity has been undertaken far less frequently than that of temperature, because of a lack of a relevant instrument for VOS salinity measurement. So, the development of a reliable XCTD (eXpendable CTD) has long been desired.

We have been investigating the applicability of the XCTD manufactured by the Tsurumi Seiki Co. (TSK) to upper ocean observation for the past few years. During this period, the XCTD model has undergone several modifications. Among them, the change of conductivity sensor from an electrode to an inductive cell has brought a significant improvement in the precision of salinity measurement and the bubble problem at the initial stage of measurements near the surface. The shape of the probe has also been modified in order to keep the falling rate stable. This report describes the results of recent in-situ XCTD/CTD comparison tests.

2. Outline of TSK XCTD System

A sketch of the probe is shown in Fig. 1. The nose cone has a flat shape in order to keep its posture vertical in the water. The ring hood attached to the tail also helps to stabilize the posture and suppress the falling speed. The length of the wire contained in a canister allows ship speeds of up to 12 kt for 1000 m of observation.

Conductivity and temperature sensors are installed in the nose part of the probe. When the probe is falling, seawater enters into a hole at the center of the nose, passes through a Pyrex glass tube, then flows out from four side holes. A thermistor is mounted inside the hole just in front of the Pyrex glass tube. An inductive cell encircles the tube. Temperature and conductivity are measured at almost the same position. Time constants of both sensors are the same (100 ms or less) so as to suppress any salinity spike. Conductivity and temperature sensors are individually calibrated by the manufacturer (3-point calibration for temperature and conductivity) and the calibration coefficients are memorized in each probe.

Measured temperature and conductivity data are transmitted by digital signal to an on-deck digital converter at a rate of 25 data sets a second (i.e. 40 ms sampling interval). The data are eventually transmitted to a computer via an RS232C interface, and converted to physical units of

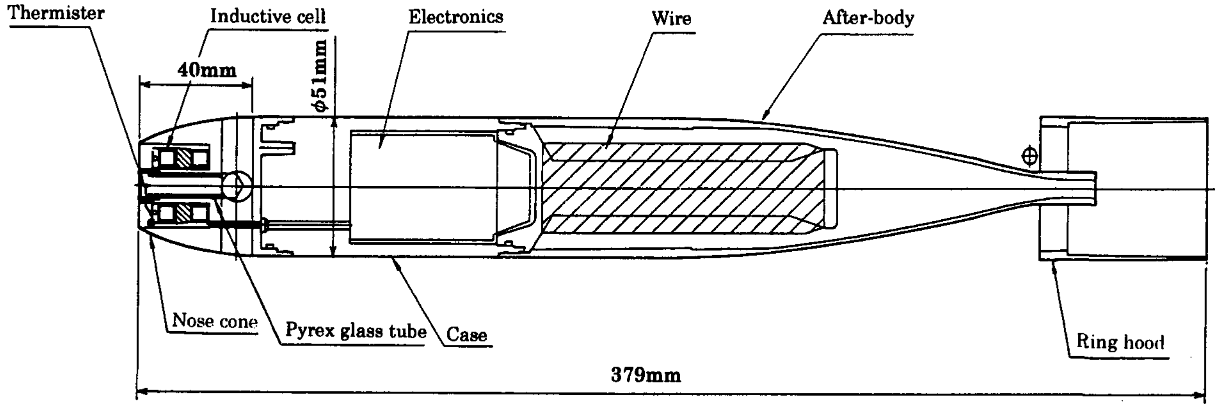


Fig. 1. Sketch of XCTD probe.

Table 1. Specifications of TSK XCTD (vendor provided).

Depth	
Range	0–1000 m
Resolution	17 cm
Accuracy	±5 m or ±2% of depth
Temperature	
Range	-2~35°C
Resolution	0.01°C
Accuracy	±0.02°C
Conductivity	
Range	0–70 mS/cm
Resolution	0.017 mS/cm
Accuracy	±0.03 mS/cm
Data sampling interval	40 msec
Dimensions	
Probe size	51 mm (Dia.) × 379 mm (L)
Probe weight	1.1 kg
Canister	T-5 size
Ship speed/Depth	12 kt/1000 m 30 kt/400 m

temperature and conductivity using calibration factors written on the memory chip in the probe. The specification of the probe as provided by vendor is shown in Table 1.

3. Field Test

Taking advantage of research cruises of *R/V Shoyo Maru* (Japan Fisheries Agency; 1,360GT), XCTD performance tests were conducted in the vicinity of Japan on Nov. 21 1996 (hereafter Experiment 1), and in the eastern Indian Ocean on the way from Sunda Strait to Fremantle during Jan. 19–23 1997 (Experiment 2). Locations of both experiments are shown in Fig. 2.

Concurrent XCTD/CTD comparison tests were conducted repeatedly. XCTD probes were launched when the CTD (Sea Bird Electronics Co. model 911 plus with Niskin bottles) reached 400 m depth. CTD salinity data were calibrated by the salinity of bottle sampled water measured by a salinometer (AUTOSAL; Guildline Co. model 8400B) on deck. The method used for the test generally followed the WHP guideline for XBT (Sy, 1991).

In Experiment 1, eleven probes were launched during CTD casts. Among eleven XCTD probes, three probes were used for concurrent comparison (P1–3). Unfortunately, salinity data of the CTD were not accurate due to sensor problems. We therefore used the temperature and pressure data for estimation of the depth-time equation.

During Experiment 2, comparison tests were conducted at three CTD stations, and one XCTD probe was launched in each station (I1–3). Additionally, XCTD probes were dropped midway between CTD stations from 9–22°S nominally occupied at each one degree of latitude along 105°E.

4. Result

4.1 Success rate

Experiment 1 was conducted on the path of the Kuroshio in rough sea conditions while the ship was stopped for the CTD cast. The XCTD wire was sometimes blown back on to the deck by the strong wind. The wire was broken before it reached maximum depth (1000 m) in five drops out of eleven. The wire was probably scratched by the hull, because the ship frequently changed its heading and speed in order to keep the CTD wire vertical in the swift northeastward Kuroshio and strong northwesterly wind.

In Experiment 2, all 27 probes obtained data to maximum depth without failure. Three probes were used for concurrent comparison tests and 24 probes were launched while steaming. In the latter case, the ship was slowed down to 10 kt to be on the safe side.

4.2 Depth-time equation and depth error

By using Hanawa's method (Hanawa *et al.*, 1995), the depth-time equation was estimated on the basis of temperature profiles for each probe used in the tests (Table 2). The differences of the depth-time equation from that given by the manufacturer are shown for each probe in the upper panel of Fig. 3. The estimated depths of probes tend to be slightly shallower in the initial stage (0–150 sec) and deeper in the final stage (250–300 sec) than the depths derived from manufacturer's equation. The differences are within the error range of their specification (see Table 1). The differences of individually estimated depths show a similar shape. This indicates that the depth-time relation does not vary very much from probe to probe. Taking the averaged depth-time equation for the six probes, the variation of individual depth difference is much smaller than the manufacturer's equation and the depth difference is well within 1% (Fig. 3, lower panel). Therefore, we use the averaged equation for the analysis hereafter.

4.3 Temperature/salinity comparison (Experiment 2, I1–3)

The CTD used in the comparison tests was calibrated by the manufacturer within a month of the test. The accuracy of temperature and depth of CTD were followed by the manufacturer's calibration sheet. The accuracy of salinity was estimated to be 0.001 psu by comparison with bottle sampled seawater salinity measured by a salinometer. The CTD accuracy is one order of magnitude higher than that of the XCTD evaluated here, and is accurate enough to take its data as "true data" for the test.

Starting with XCTD raw temperature/conductivity data sampled every 40 ms (i.e. approximately 14 cm interval in depth), time-depth conversion was applied by using the averaged depth-time equation, then salinity was calculated from the depth/temperature/conductivity data set. These data were smoothed by a 13 data-point running mean and were interpolated into every 1 m depth, and the 1 m interval data set eventually obtained was used for temperature/salinity evaluation.

The accuracy of salinity is not given explicitly in Table 1. However, it can be estimated by calculating the salinity

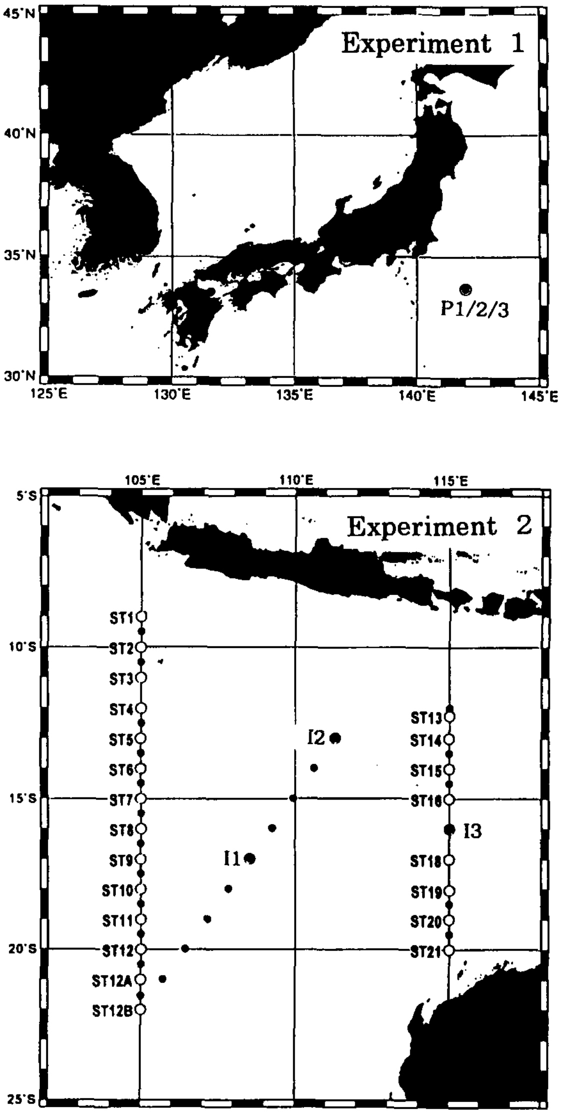
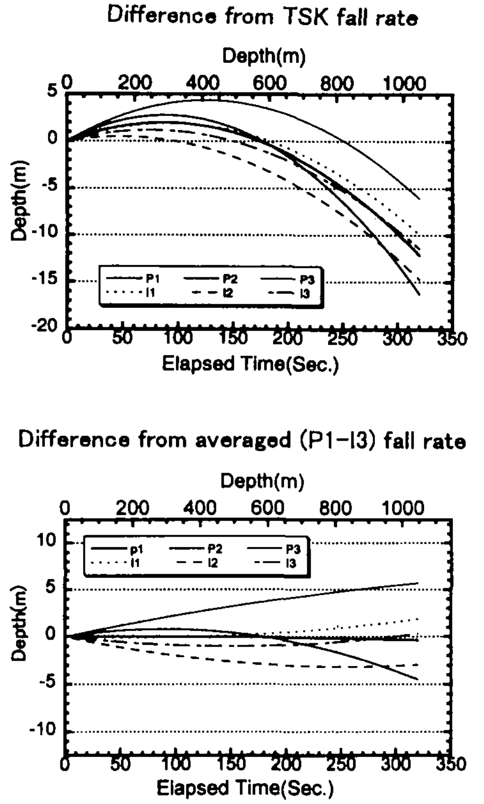


Fig. 2. Location of experimental site off Japan (Experiment 1) and south of Java (Experiment 2). For Experiment 2, solid (open) circles denote the locations of XCTD (CTD) observation.

Table 2. Depth-time equation.

Manufacturer (TSK) provided equation		$D = 3.380t - 2.14 \times 10^{-4}t^2$
Exp. 1	Probe No.	
P1	9611007	$D = 3.426t - 4.75 \times 10^{-4}t^2$
P2	9611008	$D = 3.443t - 5.69 \times 10^{-4}t^2$
P3	9611013	$D = 3.450t - 4.90 \times 10^{-4}t^2$
Average (P1–3)		$D = 3.440t - 5.12 \times 10^{-4}t^2$
Exp. 2	Probe No.	
I1	9612014	$D = 3.422t - 4.41 \times 10^{-4}t^2$
I2	9612018	$D = 3.400t - 4.21 \times 10^{-4}t^2$
I3	9612022	$D = 3.412t - 4.25 \times 10^{-4}t^2$
Average (I1–3)		$D = 3.411t - 4.29 \times 10^{-4}t^2$
Total average		$D = 3.426t - 4.70 \times 10^{-4}t^2$


Difference from TSK fall rate

Difference from averaged (P1–I3) fall rate

Fig. 3. Upper panel; Differences of individual depth-time relation from that provided by manufacturer. Depth-time equation for each probe is calculated by Hanawa's method (Hanawa *et al.*, 1995). Lower panel; Differences of individual depth-time relation from averaged equation (P1–3 and I1–3). Depth scale derived from manufacturer's equation is also added on the upper side of the frame in both panels.

error numerically using the algorithm given by UNESCO (1983). The temperature error of 0.02°C yields a salinity error of 0.02 psu within the observed temperature, salinity and pressure range (i.e. 5–29°C, 34–36 psu, 0–1000 db). Meanwhile, the conductivity error of 0.03 mS/cm yields a salinity error of 0.03 psu, and the depth error (i.e. pressure error) of 2% yields 0.01 psu at most. A squared sum of these data gives the total variance of salinity error, and the salinity accuracy is finally estimated to be 0.04 psu.

Vertical temperature and salinity profiles of XCTD/CTD show good agreement, even in detailed profiles in each case (Fig. 4), and no outstanding salinity spikes are found in XCTD profiles. Near-surface XCTD salinity data are systematically smaller than those of CTD due to the bubble effect. However, initial larger differences decrease rapidly within 10–20 m and the value settles within or around the specified error range at deeper depths, except in the halocline depths. It is noted that differences of salinity below the halocline down to maximum depth tend to increase slightly with depth.

Table 3. XCTD/CTD comparison of 600–1000 m T/S data of I1–I3.

	Temperature (°C)		Salinity (psu)	
	Mean	S.D.	Mean	S.D.
I1				
XCTD	5.916	0.553	34.676	0.016
CTD	5.957	0.549	34.639	0.015
Diff.	–0.041	0.010	0.036	0.004
I2				
XCTD	6.083	0.662	34.615	0.007
CTD	6.086	0.657	34.611	0.005
Diff.	–0.003	0.011	0.004	0.003
I3				
XCTD	6.108	0.650	34.642	0.005
CTD	6.147	0.656	34.620	0.004
Diff.	–0.039	0.012	0.022	0.003

For temperature error estimation, a small vertical temperature gradient is favorable. In the case of I1–3, no thermostad can be found. The thermal gradient below 600 m is still large (>0.01°C/m), and a depth error of merely 2 m causes a difference of greater than 0.02°C which eventually causes salinity error. However, quantitative temperature/salinity errors are conservatively estimated by using the data from deeper than 600 m for simplicity (Table 3).

Each vertical profile of difference deeper than 600 m tends to have a certain bias with high frequency noise. Since the noise amplitude is much smaller, and can be smoothed out, the bias is a problem. The averaged temperature error of I1 (0.041°C) is larger than the error specified by the manufacturer, but the salinity error (0.036 psu) is within the error range. However, the errors are quite small for I2 (–0.003°C/0.004 psu) well within the range. For I3, the errors are –0.039°C and 0.022 psu respectively. Therefore, the manufacturer's specification is reasonable, taking account of the severe conditions under which the comparison was conducted.

4.4 Comparison of vertical section along 105°E

In order to check the performance of XCTD, vertical sections of temperature and salinity along 105°E were constructed for XCTD and CTD separately, with their differences (Fig. 5).

Although depicted large scale thermal structures are consistent, discrepancies can be found for smaller scale structures. A similar pattern occurs in salinity structure (Fig. 6). Large temperature differences tend to appear in the upper 400 m. The spatial patterns of temperature/salinity anomaly tend to be patchy. If significant systematic depth error existed, a spatially consistent anomaly pattern would appear

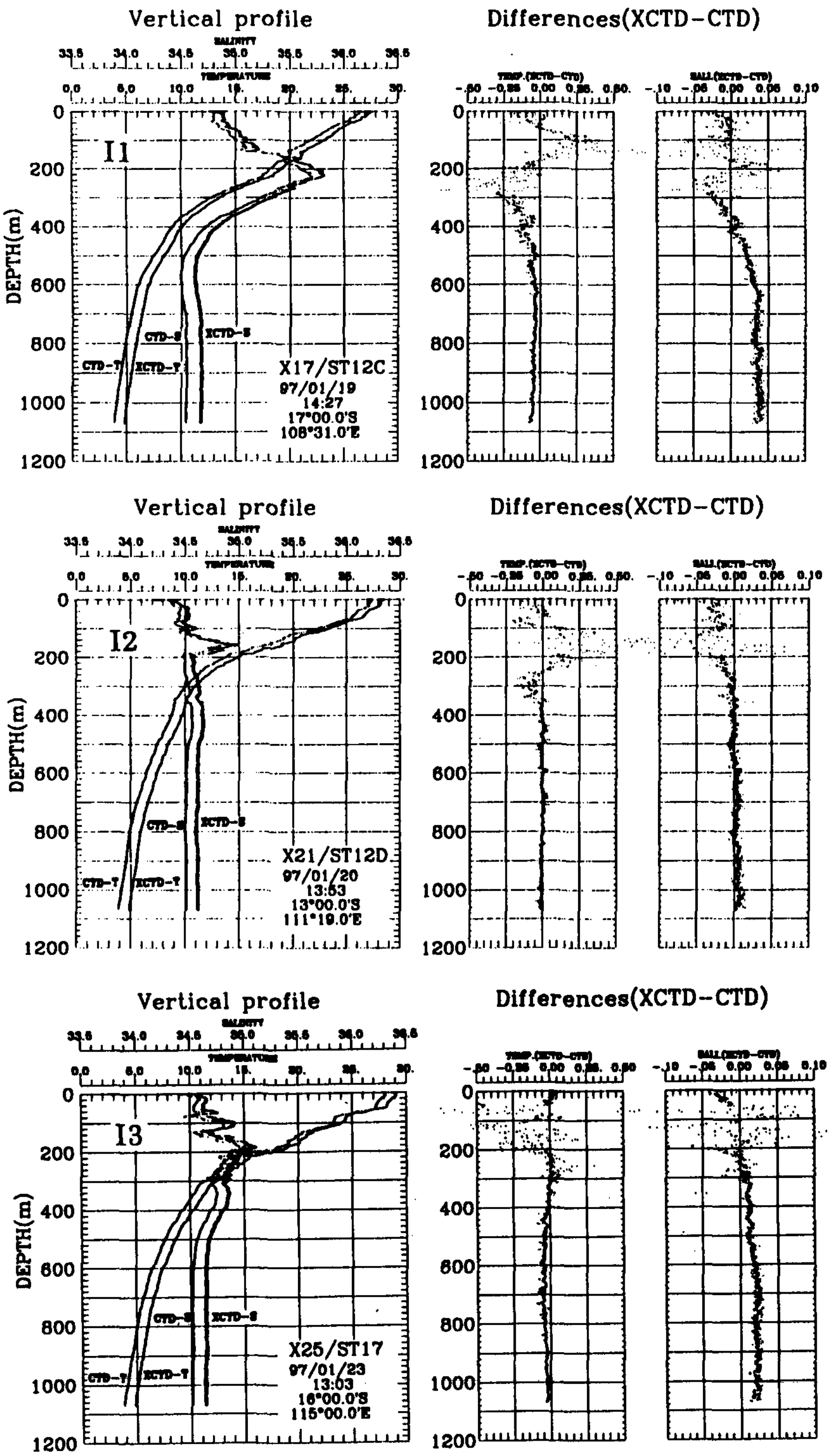


Fig. 4. Vertical temperature and salinity profiles of XCTD/CTD and their differences for I1–3. Temperature and salinity values of CTD data are subtracted by 1 °C and 0.1 psu respectively.

for the same reason as the "XBT wave" pattern (Hanawa and Yasuda, 1992) depicted by CTD/XBT mixed data. Therefore, the depth-time equation used is capable of significantly suppressing the systematic depth error.

The observed interval for CTD stations are 60 miles in space and 4–6 hours in time, and XCTD stations are between the CTD stations. Temperature/salinity structures having smaller scales than these time/space intervals can possibly

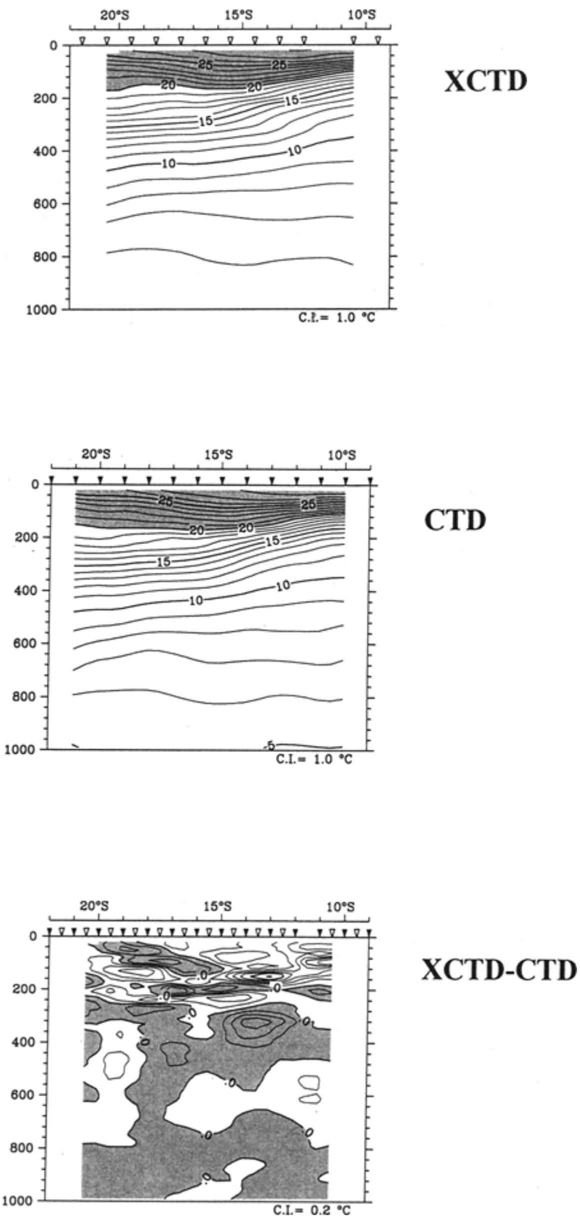


Fig. 5. Vertical temperature sections along 105°E observed by XCTD (upper panel) and CTD (middle panel), and their differences(lower panel). Triangles at surface level indicate the observation points. The spatial interval is almost 1 degree in latitude for upper and middle panels, and the data are interpolated into every 0.5 degree in latitude. Contour interval is 1°C for the upper two panels, but 0.2°C for the lower panel.

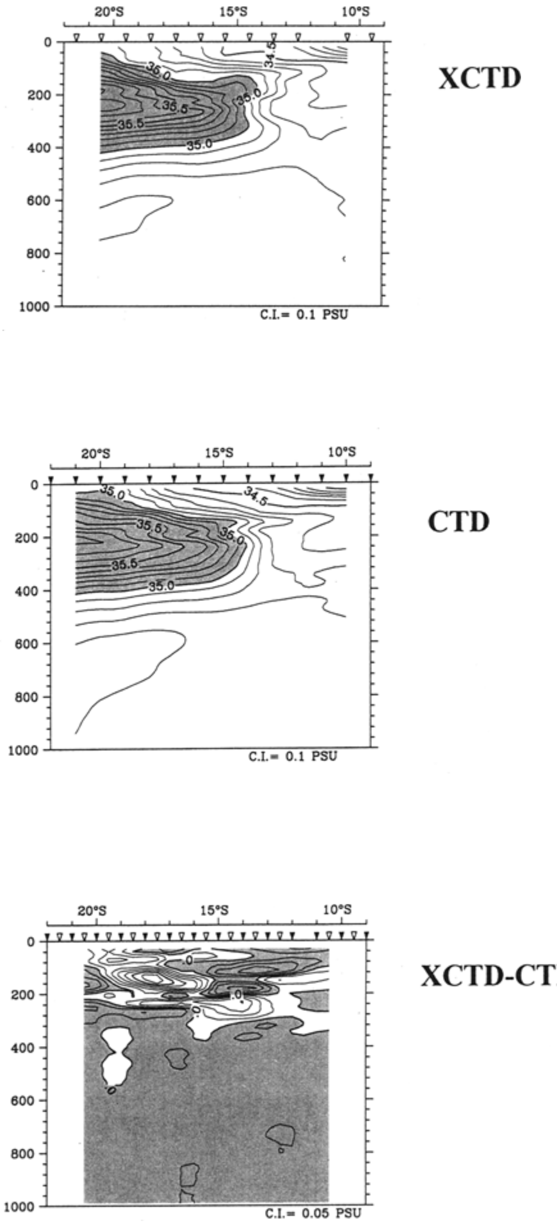


Fig. 6. Vertical salinity sections along 105°E observed by XCTD (upper panel) and CTD (middle panel), and their differences (lower panel). Triangles at surface level indicate the observation points. The spatial interval is almost 1 degree in latitude for upper and middle panels, and the data are interpolated into every 0.5 degree in latitude. Contour interval is 0.1 psu for the upper two panels, but 0.05 psu for the lower panel.

generate such patchy anomalies. Eddies or internal waves are possible causes, although they have not been identified so far.

Deeper than 600 m, the differences decrease and settle to small values around zero for both temperature and salinity. For the quantitative evaluation of the differences between the fields, statistical characteristics were calculated, as shown in Table 4. The averaged XCTD thermal field for 600–1000 m is higher than that of CTD by 0.008°C, and their variations are both approximately 0.1°C. In terms of salinity field, mean XCTD salinity is slightly higher than that found by CTD by 0.034 psu and both have similar standard deviations (0.024 and 0.028 psu).

Finally, dynamic height based on the 1000 db reference

Table 4. XCTD/CTD section comparison of thermal/salinity field along 105°E (calculated by every 0.5 degree grided data).

	Temperature (°C)		Salinity (psu)	
	Mean	S.D.	Mean	S.D.
For 600–1000 m				
XCTD	6.043	0.086	34.659	0.024
CTD	6.035	0.112	34.625	0.028
Diff.	0.008	0.082	0.034	0.017

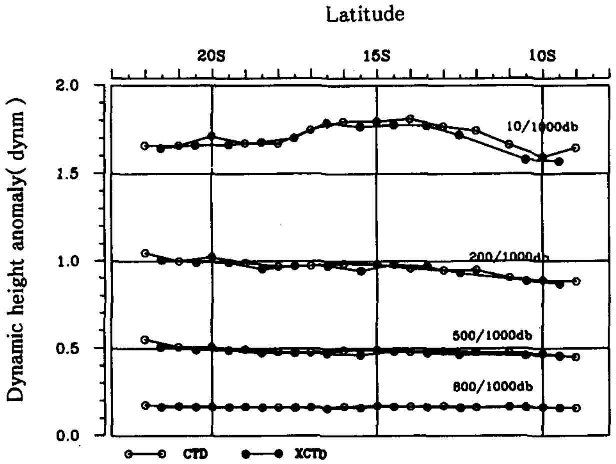


Fig. 7. Dynamic height anomaly (dyn m) along 105°E for typical isobars based upon 1000 db reference level. Solid (open) circles denote the anomalies obtained by XCTD (CTD).

level is calculated from XCTD/CTD data separately (Fig. 7). Generally, both topographies are consistent. At the 10 db isobaric surface, where the difference is most intensified, the difference is 0.03 dyn m RMS.

5. Discussion and Conclusions

A stable depth-time relation is the most important requirement for XCTD, because depth error smears not only temperature/salinity profiles but also causes error in salinity itself via pressure error (Johnson, 1995). Actually, a pressure error of 25 db is responsible for 0.01 psu. Depth-time equations obtained by the experiments were considerably stable, but were systematically different from the equation provided by manufacturer. Therefore, we may tentatively propose a revised depth-time equation using the averaged equation in the experiments. The equation is $D = 3.426t - 4.70 \times 10^{-4}t^2$, where D is the depth and t is the elapsed time after hitting the sea surface.

Concurrent comparison tests showed that near surface salinity data settled within the specified error range within 10–20 m depth immediately after the probe hits the sea surface. The near-surface bubble problem is considerably suppressed compared to the previous probe model having a long electrode cell (Mizuno *et al.*, 1996). The small inductive cell with a short Pyrex glass tube probably mitigated the bubble problem. This has the advantages of holding fewer bubbles in the tube and of flushing them quickly.

In terms of subsurface salinity profile, salinity spikes are inconspicuous. This indicates matching of temperature/conductivity sensors: they have the same response time and they are placed almost in the same position. The accuracy of temperature and salinity estimated by the field tests almost satisfied the specification given by the manufacturer. However, systematic error in salinity was detected in deeper depths, the cause of which is not clear at this time. It is in the nature of expendable equipment that XCTD cannot be calibrated after use. Therefore, temperature/conductivity sensor calibration by the supplier is important in order to keep the data unbiased and of constant quality.

Although XCTD has many technical difficulties, especially in salinity measurement, it also has some favorable properties. Its stable falling speed helps give a constant water flushing rate in the conductivity cell. Also the probes are free from self-generated turbulence, unlike the case of CTD, due to its frame.

Since available data for XCTD/CTD comparison are quite inadequate for statistically confident evaluation, the above-mentioned values of accuracy are preliminary ones. Therefore, many more comparison tests are necessary. Actually, we are continuing comparison tests, hoping that a more statistically reliable evaluation can be provided in the future.

Acknowledgements

This study was financially supported by the Science and Technology Agency under the "Japanese Experiment on Asia Monsoon" project. We express our appreciation to Professor Kimio Hanawa at Tohoku University who kindly made available his software for depth-time equation calculation for this study, and prvided us useful comments on this paper. Appreciation is also extended to Captain Kan'ichi Yamanaka and the crew of *R/V Shoyo Maru* for their cooperation in the field work, and to Mr. Michio Sekimoto at TSK for his useful and helpful comments and discussion.

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