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Note

CTD Data Processing for CREAMS Expeditions: Thermal-lag Correction of Sea-Bird CTD

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Standard CTD data processing recommended by Sea-Bird Electronics produced thermal-lag corrections larger than 0.1 psu for the data taken during the CREAMS expeditions in the northern part of the East/Japan Sea where a vertical temperature gradient frequently exceeds 1.0°C/m in the upper 100 m near the sea surface. As the standard processing is based upon a recursive filter which was introduced by Lueck and Picklo (1990), coefficients of the recursive filter have been newly derived for the CREAMS data by minimizing the difference between salinities of downcast and upcast in temperature-salinity domain. The new coefficients are validated by comparison with salinities measured by a salinometer, AUTOSAL 8400B. An accurate correction for the thermal-lag is critical in identifying water masses at intermediate depth in the East/Japan Sea.

INTRODUCTION

CTD is a basic instrument to measure temperature and salinity at sea. While CTD is a very precise instrument, great cares are required in CTD data processing to avoid spurious temperature and salinity structure. Salinity spikes are a well-known problem of CTD, which are due to the difference of time response between temperature and conductivity sensor as well as physical arrangement of sensors. They can be reduced by the optimum time shift and response matching filters. Recent studies also show that the thermal lag of the conductivity sensor due to heat stored in the body of the sensor causes the large scale differences between upcasts and downcasts (Lueck, 1990; Lueck and Picklo, 1990; Morison *et al.*, 1994).

The latest CTD system of Sea-Bird Electronics was used in the East/Japan Sea during CREAMS (Circulation Research of the East Asian Marginal Seas) expeditions. CREAMS was organized to study water masses and the circulation in the East/Japan Sea, especially with a focus on its northern part (Kim *et al.*, 1996). Seven expeditions were carried out from August 1993 to March 1997. SBE 911 plus CTD was used except in August 1993, when SBE 25 Sealogger CTD was used, and especially dual sensors of temperature and conductivity were equipped since 1996. Figure 1 shows CTD stations taken in 1994 as an example.

The SBE 911 plus CTD is widely used in the world, especially as a WOCE (World Ocean Circulation Experiments) standard equipment. It is composed of SBE 11 deck unit and SBE 9 plus underwater unit. SBE 11 deck unit supplies DC power for the underwater unit, decodes the serial data stream and passes the data to a computer. SBE 9 plus underwater unit is composed of main housing, pump, and temperature and conductivity sensors. A TC duct and pump are used to align temperature sensors with conductivity cell, providing rapid and constant flushing of the cell at 30 cm^3/s.

Application of the standard processing for the CREAMS data suggested by Sea-Bird (1995), produced two problems. Firstly, salinity spikes appear, even though SBE 11 plus deck unit was pre-set to advance conductivity 0.073 seconds and to be matched with temperature. This can be taken care of by additional alignment of conductivity with temperature during the data processing.

Secondly it was found that the step of CELLTM to correct the effect of thermal-lag error resulted in unexpectedly large corrections. Figure 2 shows the vertical profiles of potential temperature and salinity

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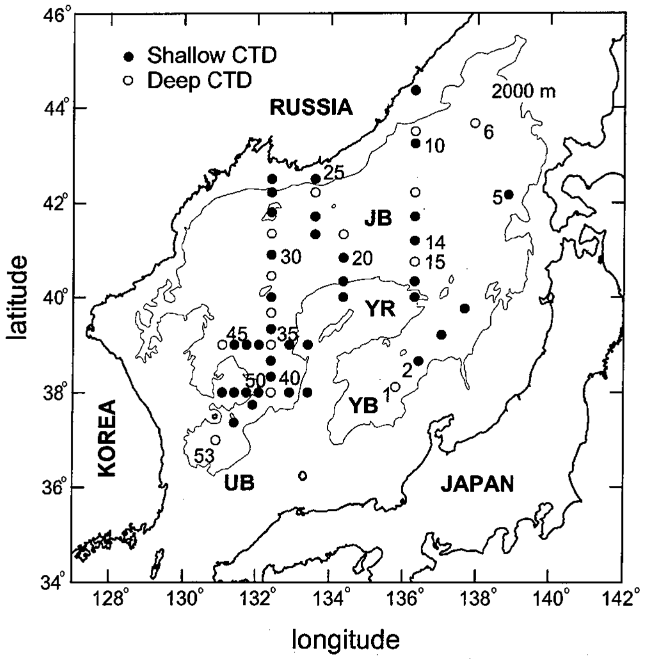

Fig. 1. CTD stations taken in 1994 during CREAMS expedition. JB, UB, YB and YR represent the Japan Basin, Ulleung Basin, Yamato Basin and Yamato Rise. Shallow and deep stations were casted down to 1000 m and the bottom respectively.

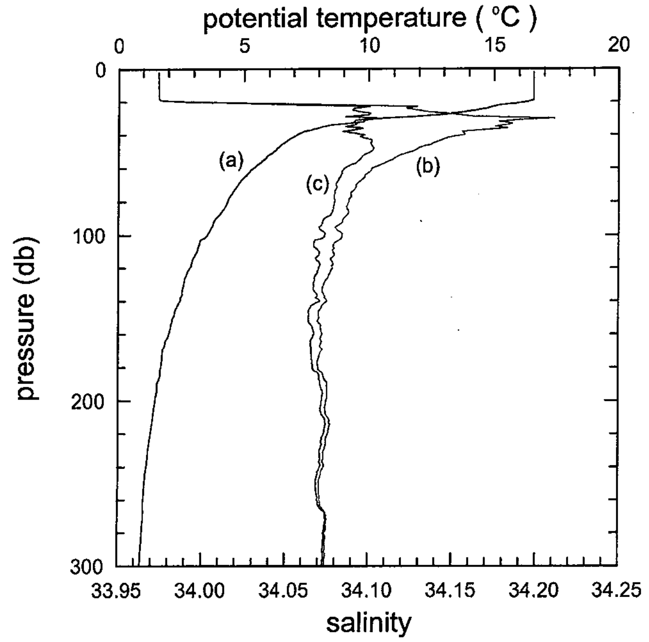

Fig. 2. Vertical profiles of (a) potential temperature and salinities (b) before and (c) after CELLTM observed at Station 6 shown in Fig. 1.

before and after the application of CELLTM at Station 6 in July 1994. The effect of CELLTM is to remove a high salinity core centered at about 30 db changing dramatically the vertical structure of upper 100 db. Kim and Kim (1999) found two kinds of intermediate waters in this layer at the northern part of the East/Japan Sea, i.e., the East Sea Intermediate Water (ESIW) and the High Salinity Intermediate Water (HSIW). The ESIW is characterized by salinity less than 34.06, while the HSIW can be defined as salinity higher than 34.07. Because they are distinguished by salinity difference, it is critical to measure salinity both precisely and accurately, and CELLTM poses a serious correction which influences the interpretation of CTD data. In this paper we examine each step of CTD data processing focusing on the correction for thermal-lag, and derive new coefficients to obtain reliable data.

PROBLEMS OF STANDARD PROCESSING AND THERMAL-LAG CORRECTION

Sea-Bird Electronics (1995) recommends a standard processing for SBE 911 plus CTD as shown in Fig. 3. The alignment between sensors is not included in this process because SBE 11 deck unit is preset to advance conductivity by 0.073 seconds and automatically for this purpose. We select several sample casts to examine salinity spikes where the temperature has a strong gradient. Nevertheless, we have found that the salinity spikes still remain despite of the preset. In order to obtain the optimal time shift, the correlation coefficients between temperatures and conductivities were calculated against various time shifts after large-scale structure of each cast had been removed by a high-pass filter with a cut-off frequency of 1 cps. Figure 4 shows that the correlation is relatively high for the time shift of –0.03 seconds and in the case of data taken in July 1994, which means that temperatures should be advanced against conductivities by 0.03 seconds. This indicates that extra alignment between sensors is necessary in ALIGNCTD during the data processing, even though the deck unit was preset to correct the mismatch due to the physical arrangement of sensors. The amount of the time shift may depend upon the lowering speed of CTD cast so that the winch should be controlled to keep a constant speed during an expedition.

Figure 2 shows that correction by CELLTM is more than 0.1 psu around 40 db where the temperature gradient is the steepest, while the order of correction according to the manual would be about 0.005 psu. Moreover, comparison of the T-S diagrams before and after CELLTM (Fig. 5) shows that salinity values

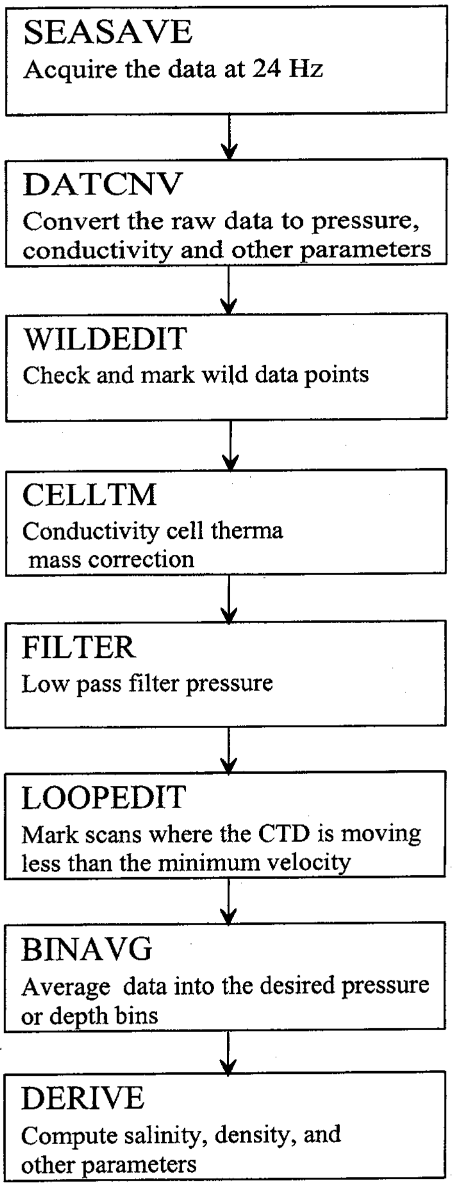

Fig. 3. The standard processing for SBE 911plus CTD recommended by Sea-Bird Electronics. Alignment between sensors is excluded, while CELLTM is included for the correction of thermal-lag error.

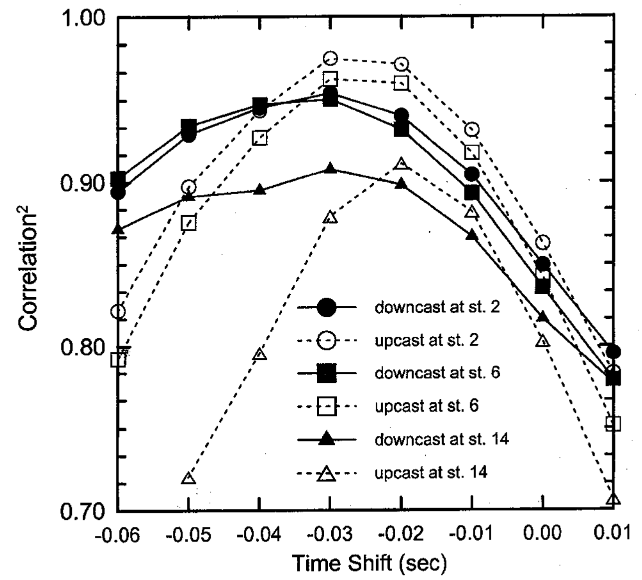

Fig. 4. Correlation between temperature and conductivity after a high-pass filter with cut-off frequency of 1 cps for 3 stations observed in July, 1994 against time shifts (conductivity time-temperature time).

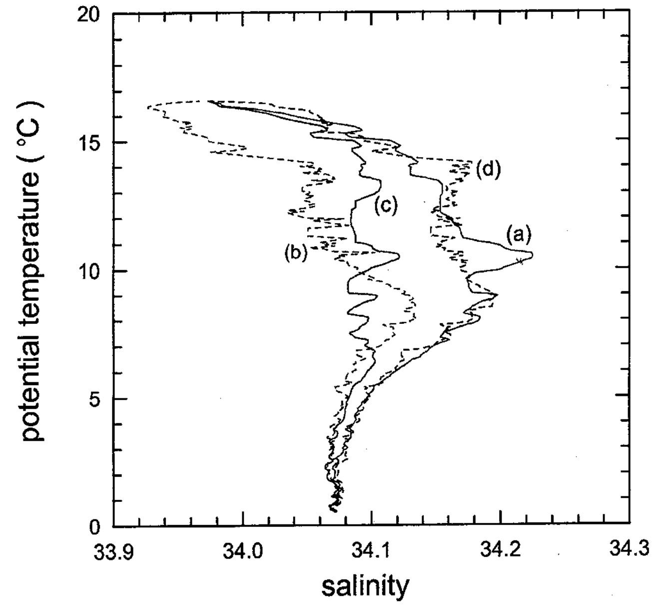

Fig. 5. T-S diagram for Station 6; (a) downcast and (b) upcast before CELLTM, (c) downcast and (d) upcast after CELLTM with $\alpha = 0.030$ and $\tau = 9.0$ s.

of upcast after CELLTM become even larger than those of downcast after CELLTM, suggesting that CELLTM yields excessive corrections. Therefore, validity of CELLTM in the standard processing is suspected. As CELLTM provided by Sea-Bird (1995) has been programmed based on the work by Lueck and Picklo (1990) as well as SeaBird's own research, we reexamine previous works on thermal-lag correction step by step to find any cause for the overestimation.

At the beginning of CTD cast, the wall of the glass conductivity cell retains heat absorbed from the water (a function of the cell's thermal inertia). As the cell is lowered from warm water to colder water through a steep temperature gradient, the heat stored in a glass is shed back into the water inside the cell, raising the temperature at which the conductivity measurement is made and therefore inducing an error. This is called the thermal-lag effect. The characteristic time scale of the thermal-lag error can be long compared with salinity spikes. Salinity differences between the upcast and downcast result mainly from this effect.

Lueck (1990) examined the theory of the thermal-lag problem and showed that the response of measured conductivity to a step change in temperature of unit magnitude is

$$C(t) = \gamma(1 - \alpha e^{-\beta t})\ u(t) \qquad (1)$$

where γ is the proportionality factor of conductivity to temperature, $\partial C/\partial T|_{S,P}$, $u(t)$ is the Heaviside step function ($u(t) = 0$ for $t<0$ and $u(t) = 1$ for $t \geq 0$), $\beta = \tau^{-1}$ is the inverse relaxation time. After the application of the step change, the measured conductivity rises immediately to the value $\gamma(1 - \alpha)$ and then relaxes to its asymptotic value of γ with an e-folding time of $\tau = \beta^{-1}$. Lueck and Picklo (1990) developed a recursive filter scheme for the discrete time-domain,

$$C_T(n) = -bC_T(n-1) + \gamma a[T(n) - T(n-1)] \qquad (2)$$

which converts the lag and lag-lead corrected temperature T into the negative of the conductivity error, C_T. Here, n is the sample index, $a = 4f_n\alpha\beta^{-1}(1 + 4f_n\beta^{-1})^{-1}$, $b = 1 - 2a\alpha^{-1}$ and f_n is the sample Nyquist frequency (24 Hz in our data). The conductivity error must then be added to the measured conductivity to obtain a longterm corrected conductivity.

Lueck and Picklo (1990) determined coefficients for a pumped Sea-Bird CTD mounted in a towed profiler by comparing the temperature and conductivity responses of up and down cast through large thermocline steps and found $\alpha = 0.028$ and $\tau = \beta^{-1} = 9.0$ s. Morison *et al.* (1994) also tried to determine coefficients, using high-frequency yo-yo CTD data measured by Sea-Bird SBE 9 CTD unit with pumped and ducted sensors. They found that $\alpha = 0.025$ and $\tau = 9.5$ s minimize the down-up separation in the T-S space. It should be noted that coefficients, α and τ, are not unique but a function of flow rate through the cell (Morison *et al.*, 1994).

CELLTM calculates the conductivity correction error using the recursive filter scheme of Lueck and Picklo (1990), and recommends $\alpha = 0.03$ and $\tau = 9.0$ s. Since correction by CELLTM is determined entirely by the coefficients α and τ, we have tried to find the correct coefficients independent of the previous estimates as follows.

(1) Run CELLTM for each α, τ pair.

(2) Average salinity for the downcast and upcast respectively with a 0.05°C temperature bin.

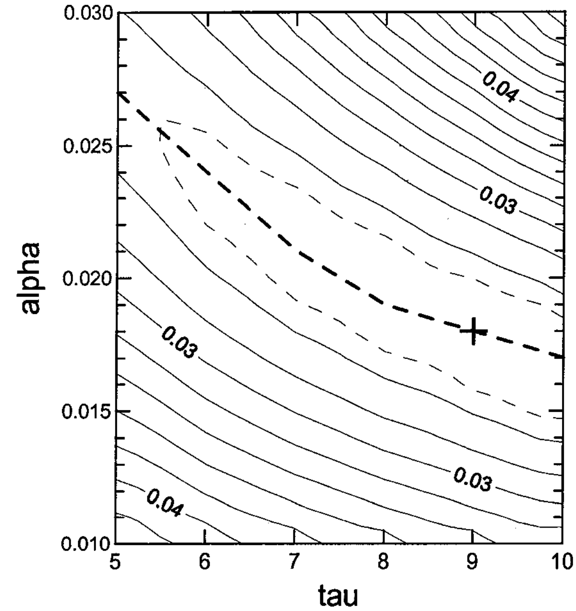

Fig. 6. The RMS of salinity differences between downcast and upcast averaged for 42 stations taken in July, 1994. Dashed line represents a trough of small salinity difference and a cross indicates the minimum difference.

(3) Calculate root mean square (RMS) differences between salinities of downcast and upcast for the same temperature bin.

(4) Repeat (1)–(3) for all α, τ pairs.

Figure 6 shows the RMS salinity differences averaged for 42 stations taken in July 1994. A trough of small salinity differences is well established as denoted by a dashed line. To obtain optimal values of α, τ within the trough, the frequency of their combinations where the minimum salinity difference was observed from each cast was examined. The minimum difference appears most frequently for $\alpha = 0.018$ and $\tau = 9.0$ s, which are chosen as the best coefficients. Another experiment for 39 casts taken in July 1995 gives almost same trough of small salinity differences and minimum difference is found at $\alpha = 0.017$ and $\tau = 9.0$ s. This test proves that our results are stable because the difference of 0.001 in α does not generate meaningful difference in the vertical structure of salinity. T-S curves of downcast and up-cast with $\alpha = 0.018$ and $\tau = 9.0$ s follow each other very closely (Fig. 7), demonstrating that the new coefficients improve the correction significantly as compared with the over-correction shown in Fig. 5.

In order to verify our analysis further, CTD salinities are tested against salinities measured independently by a salinometer, AUTOSAL 8400B manufactured by Guildline Co., for water samples taken in

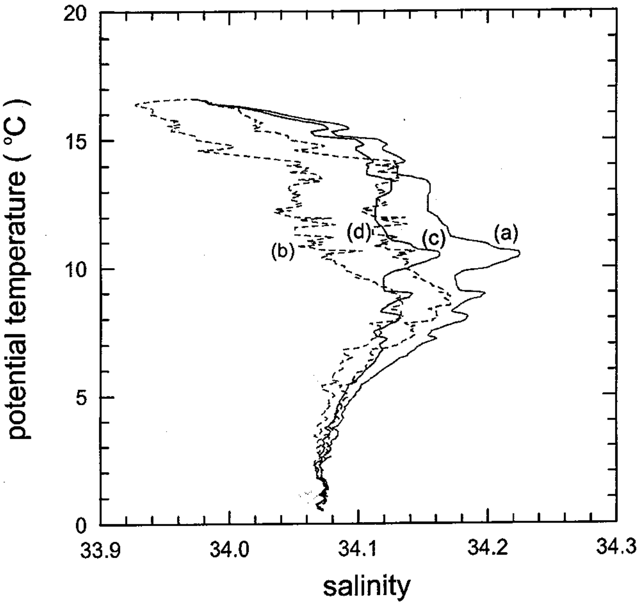

Fig. 7. T-S diagram for Station 6; (a) downcast and (b) upcast before CELLTM, (c) downcast and (d) upcast after CELLTM with $\alpha = 0.018$ and $\tau = 9.0$ s.

the upper 500 m during the CREAMS expedition in August 1996 (Fig. 8). Most salinities for downcast before correction of CELLTM are significantly larger than those of AUTOSAL due to the effect of thermal lag, except in the range of 34.06–34.10 psu. Salinities in the range of 34.06–34.10 psu are found at depths deeper than 300 m, where the temperature gradient is very small, so that the correction does not make any meaningful difference in vertical profiles. Application of CELLTM with $\alpha = 0.018$ and $\tau = 9.0$ s draws salinities close to those of AUTOSAL and reduces the root mean square of misfits against AUTOSAL salinities from 0.031 to 0.018 psu, excluding the range between 34.06 and 34.10 psu. This confirms that new coefficients derived in this study give more reliable estimates of salinity.

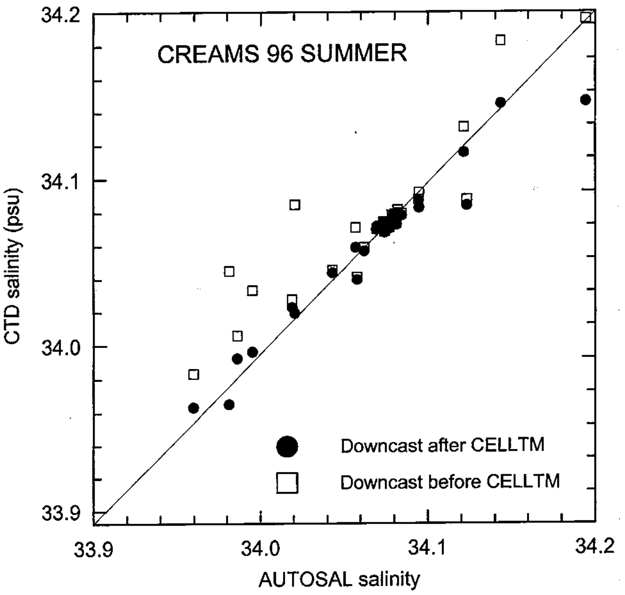

Fig. 8. Comparison between AUTOSAL salinities and CTD salinities for the upper 500 m. Squares and circles denote downcast before and after CELLTM with $\alpha = 0.018$ and $\tau = 9.0$ s.

DISCUSSION AND CONCLUDING REMARKS

According to Lueck and Picklo (1990), α and τ depend upon only the hardware of CTD such as the conductivity cell material and the average velocity of the water through the cell. Morison *et al.* (1994) calculated curve fits of α and τ with respect to the average velocity of flow, V, through the cell by incorporating previous works including Lueck and Picklo (1990). The equations of fits are

$$\alpha = 0.0264/V + 0.0135$$
$$\tau = b^{-1} = 2.7858/V^{1/2} + 7.1499 \qquad (3)$$

As the SBE 911plus CTD used in 1994 has a TC duct with 0.4 cm diameter opening and a pump which forces the seawater flow at a constant speed of 30 cm^3/s, the average velocity through the cell is 2.4 m/s, which gives $\alpha = 0.025$ and $\tau = 9.0$ s according to Morison's formula. If so, why are our coefficient of a different from this? We have examined two possibilities.

A possible cause is that the scheme of Equation (2) used by Lueck and Picklo (1990) may not be good enough to correct thermal-lag effect universally. Lueck and Picklo (1990) derived the recursive filter scheme of Equation (2) by expanding Lueck's (1990) theoretical Equation (1) taking into account only the first order term of the temperature difference. So a possibility has been examined that the effect of higher order terms may affect α, τ depending on the temperature gradient. To test this possibility, 39 pairs of down-up casts observed in 1995 were divided into two groups, one has a very steep temperature gradient more than 1.0 °C/meter and the other has a relatively smooth temperature gradient less than 1.0°C/meter. Figure 9 shows the average of root mean squares similar to Fig. 6 for α and τ of each group. Troughs of small salinity difference between downcast and upcast coincide with each other, although their minima appear at different pairs of α, τ which may be due

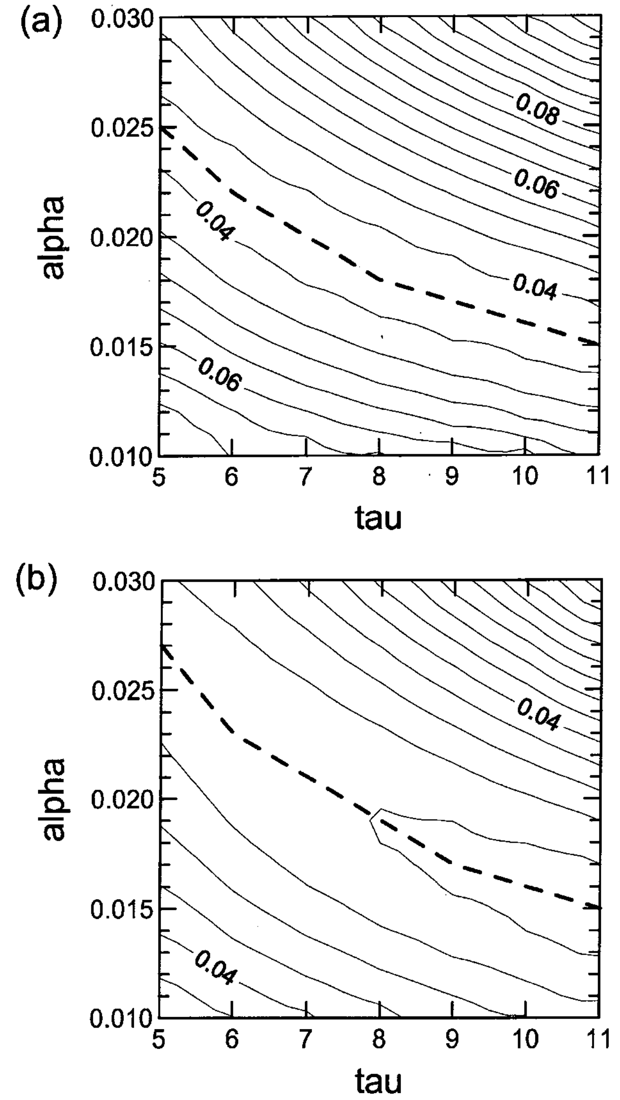

Fig. 9. The RMS of salinity differences between downcast and upcast for (a) a steep temperature gradient group, and (b) a smooth temperature gradient group taken in July, 1995.

to short number of the pairs compared. This confirms Lueck's (1990) theoretical estimation neglecting higher order terms.

Another possibility is that the difference in α may be related to flow rates, V in Equation (3). Morison *et al.* (1994) obtained coefficients, $\alpha = 0.025$, $\tau = 9.5$ s using SBE 9 CTD unit pumped with the flow rate of 1.75 m/s. On the other hand, Lueck and Picklo (1990) found another pair of $\alpha = 0.028$, $\tau = 9.0$ s from a test using the towed body instead of a pumped CTD. According to Larson (1995), the flow speed, $V = 2.4$ m/s, estimated by Lueck and Picklo (1990) was uncertain so that it should have been overestimated. It is most likely that the coefficients derived by Lueck and Picklo (1990) correspond to a flow rate around 1.75 m/s for which Morison *et al.* (1994) obtained $\alpha = 0.025$, $\tau = 9.5$ s. Since Equation (3) was derived based on works including Lueck and Picklo (1990), it should be revised. Larson (1995) also analyzed the data from customers for the past several years and found that CELLTM parameters $\alpha = 0.017$ to 0.019, $\tau = 9.0$ s are required for data from 911plus CTDs with a TC-duct and a 3000 rpm pump which is the same as ours.

The thermal-lag effect had not been corrected for SBE 25 Sealogger CTD data taken in 1993 as CELLTM is not a part of standard processing. At first, a core of high salinity appeared at the intermediate layer in the entire East/Japan Sea, which was suspected as the effect of thermal-lag. The 1993 data hence was re-processed and the high salinity core was removed except in the Eastern Japan Basin, which is consistent with results in other years. This implies that the thermal-lag correction is also essential for SBE 25 in the East/Japan Sea. The coefficients for CELLTM from 62 down-up casts are $\alpha = 0.039$, $\tau = 9.0$ s.

The East/Japan Sea is unique in that it has very steep thermocline, which poses a problem in estimating salinity. We have found new coefficients for thermal-lag correction of SBE 911plus CTD to measure salinity accurately in the East/Japan Sea. The CTD data can produce spurious vertical structure and lead a misinterpretation of the distribution of water masses in the East/Japan Sea without an appropriate thermal-lag correction (Kim, 1996). The East Sea Intermediate Water is defined by salinity lower than 34.06 psu whereas the High Salinity Intermediate Water has salinity higher than 34.07 psu in an almost same range of temperature. The thermal-lag correction is particularly important because temperature decreases very rapidly and salinity varies more than 0.1 psu due to thermal-lag correction at the intermediate layer as shown in Fig. 2. Especially it is critical in identifying the High Salinity Intermediate Water defined by high salinity core in the vertical structure.

We introduce a sequence of data processing for SBE 911 plus CTD applied to the CREAMS data (Fig. 10). SEASAVE is the program to acquire the real time data at 24 Hz on board and the data are converted to pressure, temperature and conductivity by DATCNV. And selecting a sample cast we examine the wild point and the salinity spikes to determine parameters for WILDEDIT and ALIGNCTD. SEASOFT supports WILDEDIT to mark wild points dif-

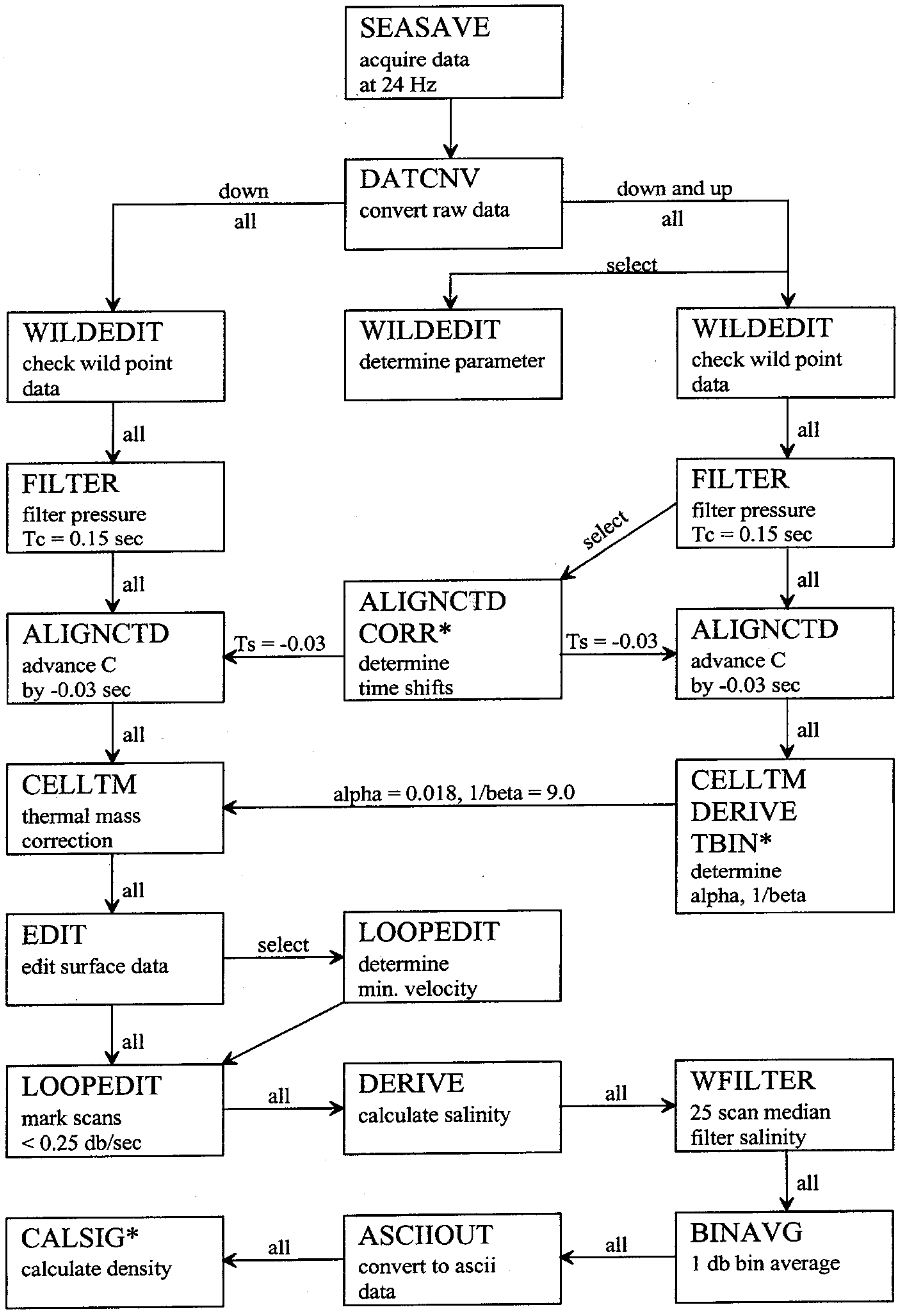

Fig. 10. Recommended process of SBE 911 CTD including steps to remove wild data and to correct pressure. All programs are supported by SEASOFT except programs marked by*, which are coded by the first author. CORR is to remove a large-scale structure of temperature and conductivity and to calculate correlation coefficients between them. TBIN is to calculate root mean square (RMS) differences between salinities of downcast and upcast for a 0.05°C temperature bin. CALSIG is to calculate densities.

ferent from the mean by more than given times standard deviation within a moving block. The coefficients α and τ for the thermal-lag correction are calculated using CELLTM as described previously after WILDEDIT, FILTER and ALIGNCTD. Returning to the raw data, the downcasts are separated and re-processed using the coefficients determined. In addition, the data around surface must be edited because the measurements change in the large range when CTD is staying at the sea surface for sensor adjustment.

For the correction for pressure dither, which is due to count resolution and fluctuations in dynamic pressure around the pressure port, FILTER and LOOPEDIT can be used. FILTER is a low pass filter to increase the pressure resolution. LOOPEDIT removes scans where CTD is moving less than fixed velocity in order to reduce the pressure dither. Time constant 0.15 sec was used for FILTER and velocity 0.25 db/s for LOOPEDIT in processing the CREAMS data. Toward the end of final process, WFILTER is the most useful in removing salinity spikes still alive, which replaces the salinity value at the center point of the window by the median value.

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