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Interpolation Scheme for Standard Depth Data Applicable for Areas with a Complex Hydrographical Structure

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ABSTRACT

Oceanographic datasets, which are arranged for standard depths, have many applications for various users. However, oceanic observations are not always conducted exactly at standard depths, especially in the case of historical bottle observations. Therefore, interpolation for density data is usually calculated from interpolated temperature and salinity data. However, in areas such as the Kuroshio–Oyashio mixed water region, east of Japan, the oceanic conditions are extremely complex, and pseudo-density inversions are often generated during the interpolation procedure. The authors have designed a new scheme based on parabolic or cubic interpolation, to avoid the generation of pseudo-density inversions, that uses temperature and density as independent variables. If the generation of a density inversion in the parabolic or cubic interpolation is found, it is replaced by a linear interpolation. The salinity calculated from interpolated temperature and density sometimes lies outside the range between the salinities at the observed levels above and below the standard depth; therefore, the scheme is designed so as to avoid the generation of such unacceptable salinity values.

1. Introduction

Datasets based on standard depths are requested by many data users, because they are very useful for numerical model studies that require gridded data. For example, the *World Ocean Atlas 1998* (*WOA98*), which was published by the Ocean Climate Laboratory, National Oceanographic Data Center (hereafter NODC), gives various statistical results for standard depths and provides the initial conditions or boundary conditions of the numerical models.

On the other hand, the Japan Oceanographic Data Center (JODC) until 2000 provided both observed data and standard depth data via an online service; however, currently only the observed data are available, since the standard depth data can be obtained from the observed data. A further reason is that recently deployed instruments such as CTDs, XBTs, and so on can record data continuously and an observer can then select the data at the required standard depths. The Marine Information Research Center (MIRC) provides oceanographic datasets at standard depths calculated from the JODC observation datasets. Pre-2000, the standard depth data provided by JODC were constructed basically from the reported values from each organization where the data originated, with methods of interpolation differing among the organizations. It is desirable to use a unified and reliable interpolation scheme to prepare the standard depth data. The NODC applied an elaborate interpolation scheme for the compilation of the World Ocean Database 1998 (WOD98) (e.g., Antonov et al. 1998; Reiniger and Ross 1968) following the procedures set by UNESCO (1991). MIRC also followed their interpolation procedures, and after this scheme was initiated almost no pseudo–density inversions were observed in the datasets for the subtropical region and for the Kuroshio region.

However, we found that use of the NODC interpolation scheme produces occasional pseudo–density inversions, when it is applied to very complex areas such as the Kuroshio–Oyashio mixed water region east of Japan (e.g., Talley et al. 1995), shown in Fig. 1. Within the Kuroshio–Oyashio mixed water region, the area off Sanriku in the westernmost part of the region is espe-

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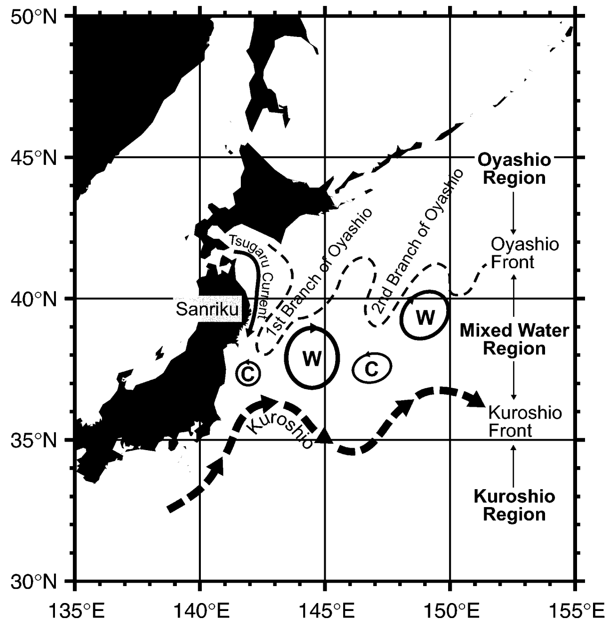

FIG. 1. Schematic view of the mixed water region between the Oyashio and Kuroshio fronts. The W indicates the warm-core ring and the C the cold-core ring.

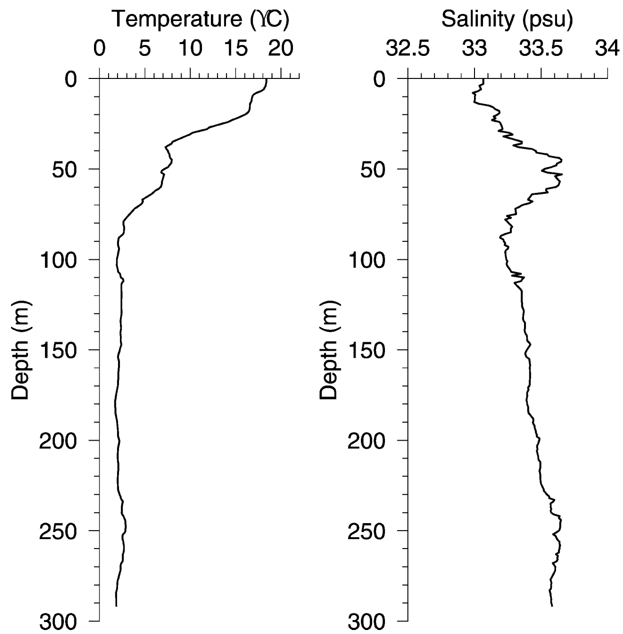

FIG. 2. CTD profile at 39°31.85′N, 143°10.95′E on 1 Sep 1993.

cially complex. In this area, the warm and saline Tsugaru Current Water encounters the cold and fresher Oyashio Water, and the much warmer and more saline water originating from the Kuroshio Water frequently intrudes (Oguma and Nagata 2002; Oguma et al. 2002). As a result, they create a very complex layered structure, and their vertical temperature and salinity profiles may form in a zigzag-shaped pattern. The CTD profile in Fig. 2 obtained by the Iwate Fisheries Technology Center suggests that the typical thickness scale of the interleaving layers is generally much less than the vertical intervals of measurements in bottle observations. Because of the coarseness of the large depth intervals, vertical profiles of temperature and salinity observed at standard depths show a somewhat smooth curve. The smooth profiles obtained in areas of complex hydrographic structure suggest that the gross features of the profiles might be reproduced by the conventional interpolation scheme.

We plan to apply the NODC interpolation scheme in order to compile an MIRC standard depth database and also to attempt to obtain an interpolation scheme that does not produce pseudo–density inversions, even in the Kuroshio–Oyashio mixed water region east of Japan. In this study, we discuss a modification to the interpolation scheme to make it applicable for such areas of complex hydrographic structure.

2. Interpolation scheme used by NODC

Before interpolation, we conducted data quality checks. We did not use any erroneous data that was in conflict with the range check or the density inversion check. In this study, a gradient check was not conducted to test the interpolation scheme for the area where temperature and salinity change markedly in the vertical direction, such as the area off Sanriku.

Ranges used are in the function of depth, and are the same as those used by NODC at the compiling stage of WOD98 (Antonov et al. 1998). For the density inversion check, the in situ density

$$\rho = \rho(T, S, p)$$

was applied, which were calculated from the in situ temperature T, salinity S, and pressure p. NODC applied acceptable values as a function of depth for the density inversion: the density of the upper level is over 0.03 kg m^{-3} heavier than that of the lower level for the depth range from 0 to 30 m, or over 0.02 kg m^{-3} heavier for the depth range from 30 to 400 m, or over 0.001 kg m^{-3} heavier for the depth range deeper than 400 m. Note that these values are not for the density gradient, but for the density difference between two adjacent observed depths no matter how far the two depths are separated. It should be noted that the in situ density is used only for the data quality check. To discuss the generation of pseudo–density inversions, the potential density

$$\sigma_\theta = \rho(\theta(T, S, p), S, 0) - 1000$$

will be used.

After the data quality check, we interpolated the data to the standard depths (see Table 1), using data obtained at the observation points. In the NODC interpolation scheme, observed data at as near to a standard depth as possible are selected to interpolate data to the standard depths. Table 1 lists the acceptable distances (m), which

TABLE 1. Acceptable distances (m) for defining the interior and exterior values used in the NODC scheme [Reiniger and Ross (1968) scheme] for interpolating observed levels data to standard levels (after Antonov et al. 1998).

Standard level no.	Standard depths (m)	Acceptable distances (m) for interior values	Acceptable distances (m) for exterior values
1	0	5	200
2	10	50	200
3	20	50	200
4	30	50	200
5	50	50	200
6	75	50	200
7	100	50	200
8	125	50	200
9	150	50	200
10	200	50	200
11	250	100	200
12	300	100	200
13	400	100	200
14	500	100	400
15	600	100	400
16	700	100	400
17	800	100	400
18	900	200	400
19	1000	200	400
20	1100	200	400
21	1200	200	400
22	1300	200	1000
23	1400	200	1000
24	1500	200	1000
25	1750	200	1000
26	2000	1000	1000
27	2500	1000	1000
28	3000	1000	1000
29	3500	1000	1000
30	4000	1000	1000
31	4500	1000	1000
32	5000	1000	1000
33	5500	1000	1000

are used for defining the interior value and the exterior value [hereafter I stands for interior value and E for exterior value, defined by Antonov et al. (1998)] of the distance between the objective standard depth and the observed data depth. The data at a standard depth are not extrapolated and hence must be bracketed by at least one observation on each side. There must be at least one interior observation in the bracketing of the standard depth. No more than one exterior point, which are located $z < S - E$ or $z > S + E$, (where z is depth of the point and S is the depth of the objective standard depth), is used on either side of the standard depth. The nearest two to four points that bracket the standard depth are used in the interpolation.

Although I and E for the sea surface (0 m) and 10-m depth are defined by NODC, we did not make interpolations or extrapolations for these depths. If observed data at a depth shallower than 5 m are available, we use these value as the data at the sea surface, because the definition of the surface is not clear for either the bucket water sampling or for the CTD observations. Also, the temperature of the intake water to the ship engine can

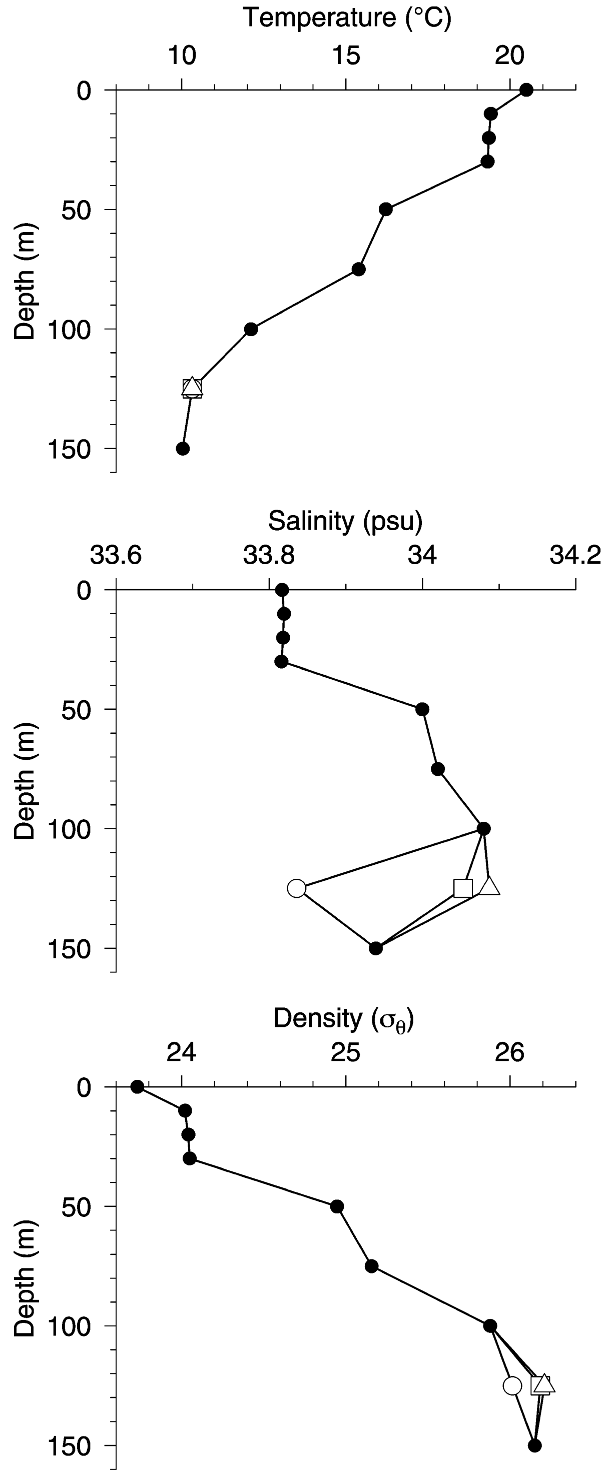

FIG. 3. An example of the generation of a pseudo–density inversion at the 125-m standard depth. The observed values are shown with black circles. The results of the parabolic interpolation applied for the temperature and salinity are shown with white squares, and for temperature and density the results are shown with white triangles. White circles indicate data based on linear interpolation. Observation data in this case were obtained on 5 Sep 1986 at 39°15′N, 142°4′E.

TABLE 2. Typical example of the generation of unacceptable salinity values at the objective standard depth. Interpolation was conducted at 30-m depth, and its results are shown in italics. Results of the cubic interpolation are shown in the left columns (2d–4th columns), those of the linear interpolation in the middle columns (5th–7th columns), and those of the salinity readjustment in the right columns (8th–10th columns). Observation data in the case below were obtained on 24 Sep 1971 at 39°00′N, 142°59′E.

Depth (m)	Cubic interpolation			Linear interpolation			Salinity adjustment		
	Temp	Density	Salinity	Temp	Density	Salinity	Temp	Density	Salinity
10	17.70	23.865	33.065						
25	17.20	24.173	33.311	17.20	24.173	33.311			33.311
30	*15.37*	*24.501*	*33.181*	*14.47*	*24.633*	*33.104*	*15.18*	*24.633*	*33.298*
50	3.57	26.434	33.247	3.57	26.434	33.247			33.247
70	2.43	26.582	33.307						

be reported as the sea surface temperature. The accuracy of the sea surface temperature is in general limited as discussed by Nagata et al. (1999). Since the interpolated value for the 10-m standard depth can be strongly affected by the surface temperature, we used data that were observed between 9- and 11-m depths as 10-m depth data.

In the NODC interpolation schemes or other compatible schemes, interpolation is usually applied to temperature and salinity values, and the density value at the objective standard depth is calculated from the interpolated temperature and salinity values. However, if we apply the NODC interpolation scheme to data taken in areas of complex hydrographic structure, such as the Kuroshio–Oyashio mixed water region, pseudo–density inversions may be generated; namely, the density calculated from interpolated temperature and salinity values may be denser than the observed density at a deeper depth, or be lighter than that observed at a shallower layer. We discuss this problem in the next section.

3. Generation of pseudo–density inversions

In order to check how frequently pseudo–density inversions are generated by the NODC interpolation scheme, we use data for the area off Sanriku, the westernmost part of the Kuroshio–Oyashio mixed water region (see Fig. 1). The dataset we used was obtained by the Iwate Fisheries Technology Center during 1971–95. Data obtained before 1970 are also available; however, the low quality of the salinity data in this period may cause excessive pseudo–density inversions. During the 1970s, the quality of the oceanographic observations conducted by the prefectural fisheries agencies in Japan was much improved, because accurate salinometers (manufactured by Auto-Lab Industries Pty. Ltd., Australia) were installed by many of the agencies (Nagata et al. 1999; Oguma et al. 1999). After the 1990s, STD or CTD devices allowed measurement of data exactly at the standard depths, and few interpolations were needed thereafter. To assess the interpolation scheme for density, only observation points including both temperature and salinity data were used.

As mentioned in the previous section, we first conducted a range check and inversion check of the density (for in situ density) for the observed data in the area off Sanriku. Acceptable ranges for range checks are the same as in the NODC quality check scheme. The acceptable values for a density inversion used here are the same as the values used by NODC. The criterion 0.001 kg m^{-3}, which is applied for depths deeper than 400 m, is used to assess the manner of how pseudo–density inversions appear at all depths. The profiles that fail the density inversion check are excluded from the interpolation procedure.

Concerning the range-checked, 25-yr (1971–95) dataset in the area off Sanriku obtained by the Iwate Fisheries Technology Center, the total number of observation stations was 9382; however, 3555 stations were eliminated from the interpolation procedure after the density inversion check described above. Additionally, the potential density (σ_θ) was estimated before the assessment of the interpolation scheme. There were 1590 stations that include potential inversions; namely, their density profile was statically unstable. This may indicate the complexity of the area off Sanriku, where water masses of the Kuroshio, Oyashio, and Tsugaru currents intrude into each other. These stations were also eliminated from the interpolation procedure. Finally the 4237 observation stations remaining were used for the assessment of the interpolation scheme.

In this section, temperature and salinity were selected as independent values, and were interpolated to assess the objective standard depths following the NODC interpolation scheme discussed in the previous section. At the 4237 stations, 30 029 potential density data points were obtained as observed data at the standard depths. Temperature and salinity interpolations were conducted at the objective standard depths, where no observed data occurred. As a result, 12 583 potential density data points were calculated using the interpolated temperature and salinity. For all 4237 interpolated stations, a pseudo–density inversion check was performed. There are some cases where the interpolated temperature or salinity values may lie outside the range between the values directly above and below the observation depths because of the parabolic or cubic interpolation. Following the NODC procedure, the interpolation scheme is replaced by linear interpolation, if the interpolated value lies outside of the range between the values directly

TABLE 3. Same as in Table 2 except that an observation was not conducted at 125-m depth and that the parabolic interpolation was applied first. Observations data in the case below were obtained on 7 Nov 1985 at 39°15′N, 142°4′E.

Depth (m)	Parabolic interpolation			Linear interpolation			Salinity adjustment		
	Temperature	Density	Salinity	Temperature	Density	Salinity	Temperature	Density	Salinity
75	16.80	24.686	33.821						
100	16.43	24.808	33.856	16.43		33.856			33.856
125	*13.31*	*25.399*	*33.749*	*11.93*	*25.634*	*33.712*	*12.48*	*25.634*	*33.844*
150	7.43	26.460	33.831	7.43		33.831			33.831

above and below the observation depths. After we made this replacement by linear interpolation, the number of pseudo–density inversions decreased to 160, or 1.3%. It should be noted that a pseudo–density inversion can be created even by the linear interpolation of temperature and salinity, when density differences between the upper and lower observed depths are significantly smaller and the vertical temperature (salinity) gradient is larger (cabbeling effect).

On the basis of these results, we have tried to use temperature and potential density as independent variables, and the interpolation is applied for these two values. The reason is that the accuracy of the temperature measurements is generally better than that of the salinity, and that the pseudo-density inversion may not be generated, at least in the linear interpolation of potential density values.

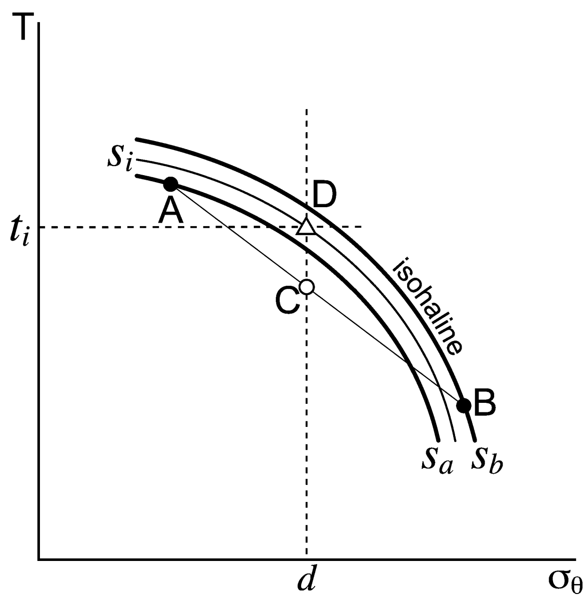

FIG. 4. Schematic explanation of the generation of an unacceptable salinity value in the procedure of the linear interpolation of temperature and density. Curvatures in the T–σ_θ plane indicate isohalines. The observed temperature and density values at the depths directly above and below are shown with A and B in the T–σ_θ plane. Salinity values of A and B are s_a and s_b. The result of the linear interpolation of temperature and potential density is denoted with C (white circle), and its density value is denoted with *d.* The finally readjusted value s_i in our scheme is denoted with D (white triangle), and the newly calculated temperature is t_i.

4. Interpolation using temperature and potential density values

We interpolated the temperature and potential density for the 25-yr dataset as well in the interpolation for temperature and salinity detailed in the previous section. Salinity values are back-calculated using interpolated temperature and density values by the bisection method with the equation of state of seawater (UNESCO 1991). The number of standard depths to be interpolated was 12 559. First, the parabolic and cubic interpolations caused 133 pseudo-density inversions, or 1.1% of the objective standard depths. As discussed in the previous section, parabolic and cubic interpolations of temperature and salinity generated 176 pseudo–density inversions. If the interpolated temperature or density lies outside of the range of the observed values directly above and below, the parabolic or cubic interpolation was replaced by a linear interpolation. Consequently, 24 (0.19%) pseudoinversions were generated. These inversions were generated among the interpolated values, while they were not outside of the range of values observed directly above and below. These cases can occur if the observed data directly above and below are at a long distance and several standard depths between them are interpolated.

Examples of generation of pseudo–density inversions are shown in Fig. 3. In Fig. 3, there is no observation for the 125-m depth; therefore, we interpolated from the observed values at 75, 100, and 150 m according to the criterion shown in Table 1 and Fig. 3. The results of the parabolic interpolation applied for temperature and salinity are shown with white squares. The calculated density value at 125-m depth is denser than the observed density at 150-m depth. When we applied the interpolation for temperature and density, the interpolated density at 125 m also exceeded the observed density at 150 m, as is shown with white triangles. In this case, the generated density inversion in our scheme is a little larger than that produced by the conventional scheme. This example indicates that the generation of pseudo–density inversions is not always suppressed by simply replacing salinity with density, and explains why some pseudo–density inversions are newly generated in an interpolation applied to temperature and density. After the linear interpolation, the potential density profile becomes reasonable as is shown in Fig. 3 with white circles.

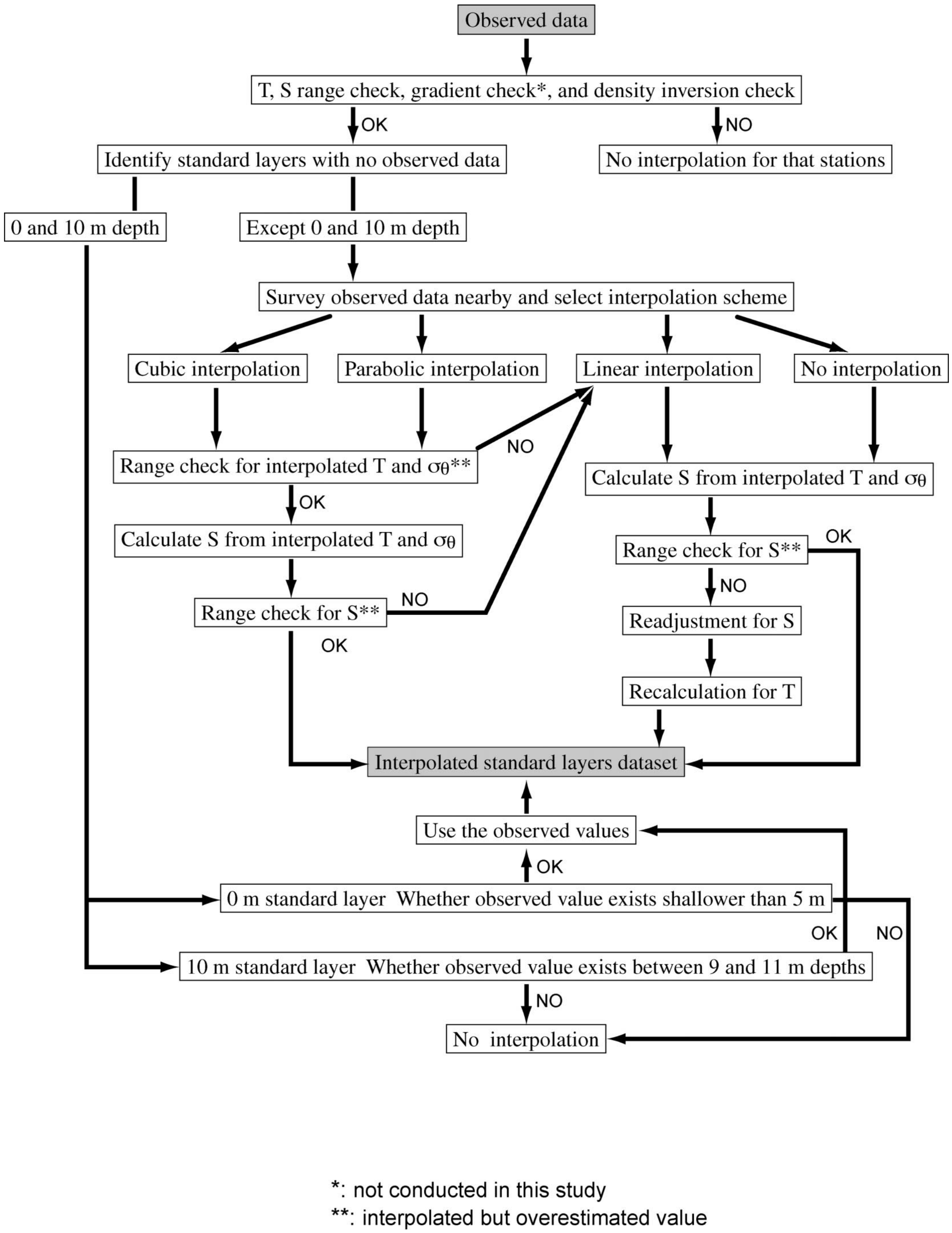

FIG. 5. Flow diagram of the MIRC interpolation scheme. Asterisk (*) indicates that the gradient check was not conducted in this study. Double asterisks (**) show the interpolated value that is overestimated compared to the values at just above and below layers.

However, Fig. 3 indicates another problem. The salinity value calculated from the interpolated temperature and potential density is outside of the values for the data observed directly above and below (termed as outside values). At first, after the parabolic or cubic interpolation of the temperature and density, the resultant outside salinity values appeared at 2511 objective depths, or 20.0% of the interpolated salinity values (12 569). This result was considerably larger than that of the pseudo–density inversion (133). After replacement of the cubic or parabolic interpolation with a linear interpolation for temperature or potential density, 2106 (16.8%) outside

TABLE 4. Occurrence frequency of pseudo–density inversions generated by the NODC interpolation scheme in three subregions shown in Fig. 6. Percentage is a ratio of pseudo–density inversion in the interpolated density data, which are comparable with data at adjacent standard depth.

	Interpolated density data	Pseudo–density inversion
Kuroshio–Oyashio mixed water region	49 646	479 (0.96%)
(Iwate Fisheries Technology Center)	(12 218)	(160) (1.3%)
Japan Sea	40 159	195 (0.49%)
Subtropical region	5829	3 (0.051%)

interpolated salinity values remained like the outside salinity value in Fig. 3.

For this problem, we discuss the salinity readjustment method in the next section.

5. Readjustment of salinity values

In the area off Sanriku, salinity profiles with a zigzag pattern such as in Fig. 2 are not unusual. Among 30 033 observed standard depth salinity data points at 4237 observation stations, 10 754 observed salinities (35.8%) were outside of the range of salinity values directly above and below the observation depths. Calculated salinity values at the standard depths, which were estimated from the interpolated temperature and density values in our scheme, may also lie outside of the range; however, they seem unnatural, as is shown in Fig. 3. To improve the results of the salinity interpolation, linear interpolations were conducted for both temperature and density, if the interpolated salinity value was still outside of the values directly above and below. The problem suggested in Fig. 3 is reduced by this method, and the number of outside salinity values decreased to 457, or 3.6%.

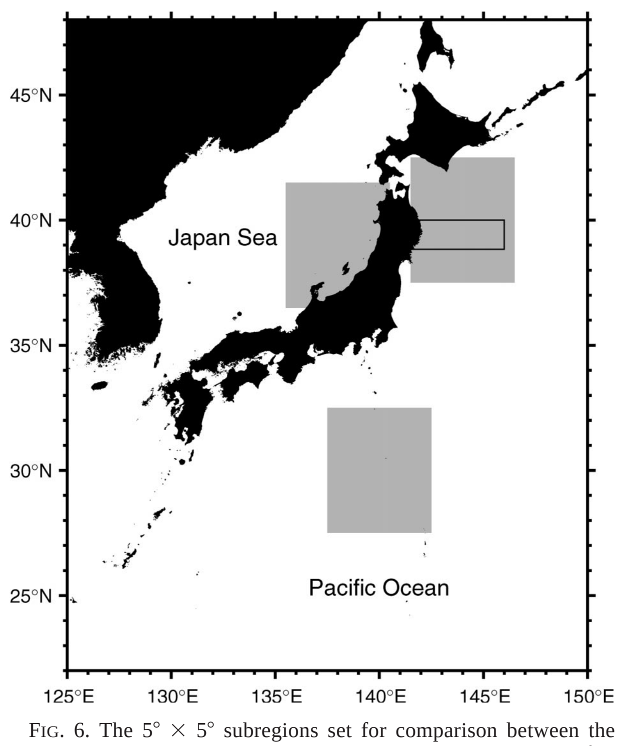

FIG. 6. The 5° × 5° subregions set for comparison between the two interpolation schemes. Hatched subregions are centered at 40°N, 144°E in the Kuroshio–Oyashio mixed water region, at 30°N, 140°E in the subtropical region, and at 39°N, 138°E in the Japan Sea. Inside of the subregion of the Kuroshio–Oyashio mixed water region, the observation area of the Iwate Fisheries Technology Center is shown as a smaller square.

For the remaining 457 outside salinity values, two typical examples of outside salinity generations are shown in Tables 2 and 3 for the parabolic and cubic interpolations, respectively. In the case of Table 2, observations were lacking at 30-m depth, and the cubic interpolation was applied for temperature and density, then the salinity was calculated from the interpolated temperature and density values. The obtained salinity value lies outside of the range between the salinities at the 25- and 50-m observation levels. Cubic interpolation was replaced by linear interpolation; however, in this case the value still remained outside of the range. Therefore, we readjusted the salinity value, replacing it with the averaged value of those at just above and below the observation depths, and then the temperature was recalculated from the density and salinity values. In the case of Table 3, almost the same process was performed for the outside salinity value at 125-m depth calculated by parabolic interpolation.

In these cases, no pseudo–density inversion is generated, but the calculated salinity values lie clearly outside of the salinity range between the upper and lower observed depths. The situation is not improved in these typical cases, even if we use a linear interpolation for temperature and density; the salinity values shift to lower salinity values and become less acceptable. These cases explain why unacceptable interpolated salinity values occur even in the case of linear interpolation of temperature and density. As shown in these cases, they can occur when the temperature gradient between the observed depths directly above and below the objective standard depth is large. Actually, these cases would be flagged as ‘‘profile holding large gradient (of temperature, etc.)’’ if we apply the gradient check used by NODC. However, such large temperature gradients are often observed in the Kuroshio–Oyashio mixed water region, and occur as real phenomena, not erroneous ones.

The mechanism for the generation of outside salinity values is schematically shown in Fig. 4. The isohalines curvature is shown in the T–σ_θ diagrams in the figure.

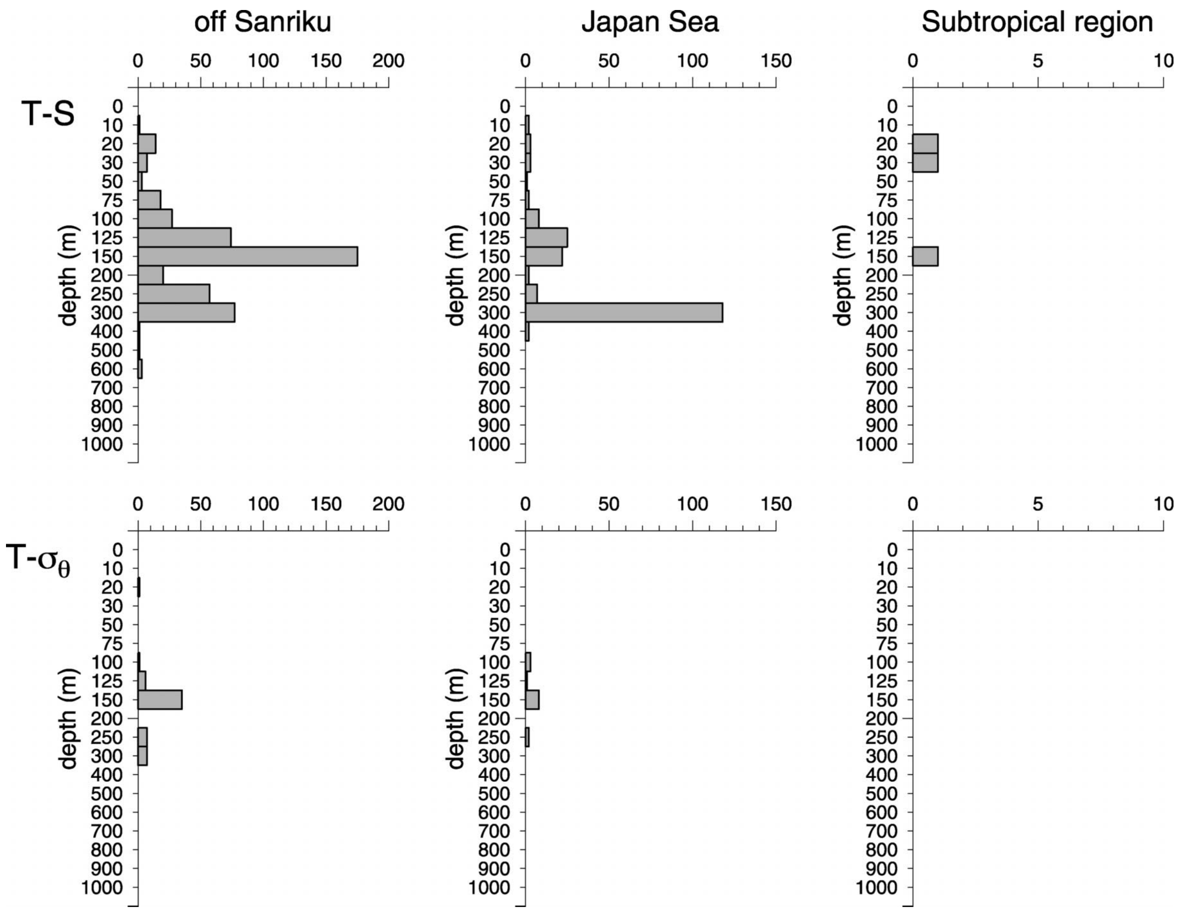

FIG. 7. Occurrence frequency distribution of pseudo–density inversions in the three subregions. Results of the NODC scheme are shown in the upper row and of our scheme in the lower row.

If the temperature difference is large between the values directly above and below the observed depths, and if the salinity difference is small, the density difference becomes large. The water types directly above and below are shown schematically with black circles A and B, respectively. The linearly interpolated value is given at point C and is shown with a white circle. The resultant salinity value is lower than the salinity values of both the directly above and below observed depths. The situation is just the same as the cabbeling effect in the *T*–*S* diagram.

Although a zigzag salinity profile such as in Fig. 2 is not unusual, readjustment of interpolated salinity is needed to be inside of the range between the upper and lower observed depths. To readjust the salinity value, first the linear interpolation for salinity at the objective standard depth, using salinities s_a at the depth directly above and s_b at the depth directly below, while the density value d is kept equal to the result of the linear interpolation. As shown with the white triangle D in Fig. 4, the readjusted salinity value is s_i and the temperature value recalculated from density and adjusted salinity is t_i. Here, t_i is estimated using d and s_i by the bisection method with the equation of state of seawater (UNESCO 1991). The recalculated temperature t_i lies within the range between the observed temperatures at just above and below the observed levels, as the temperature difference is large and the salinity difference is small.

A calculation process of our interpolation scheme is summarized in Fig. 5. As mentioned above, a gradient

TABLE 5. As in Table 4 except using our interpolation scheme.

	Interpolated density data	Pseudo–density inversion	Temp recalculation
Kuroshio–Oyashio mixed water region	49 617	57 (0.11%)	286 (0.58%)
(Iwate Fisheries Technology Center)	(12 185)	(24) (0.20%)	(23) (0.19%)
Japan Sea	40 047	14 (0.035%)	81 (0.20%)
Subtropical region	5607	0 (0%)	26 (0.46%)

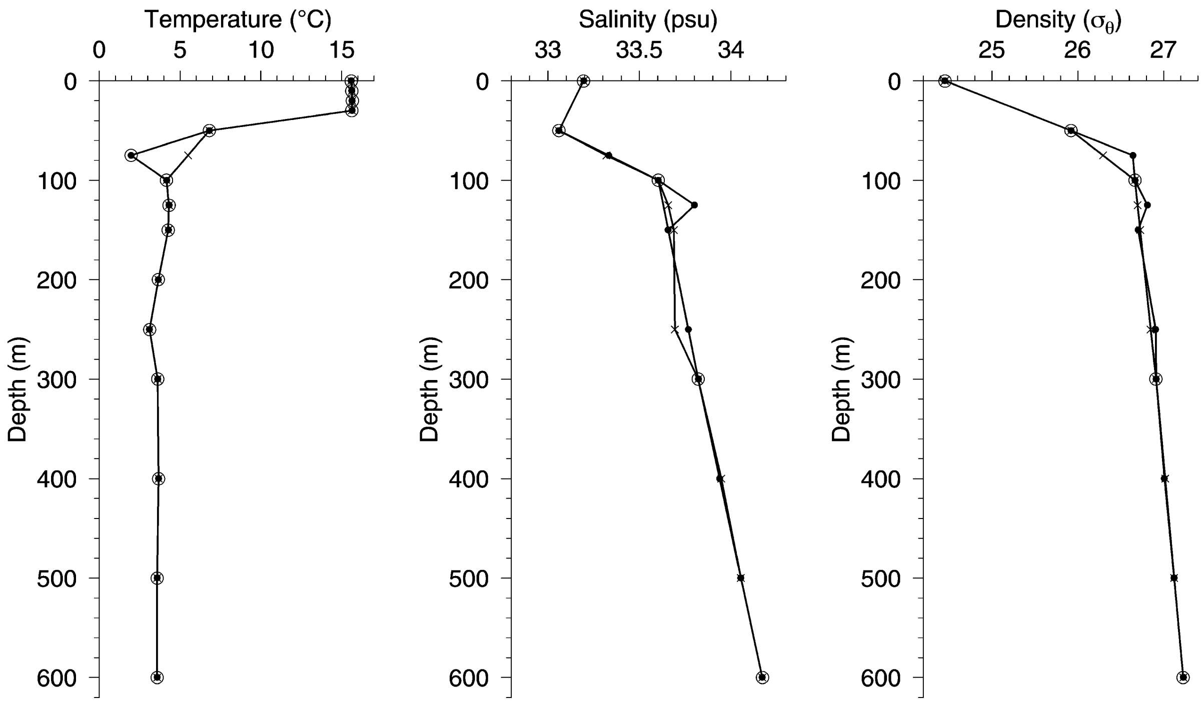

FIG. 8. Vertical profiles of observed and interpolated data. Large circles indicate observed data. Black bullets and crosses indicate interpolated data calculated by the NODC scheme and our scheme, respectively. Observation data were obtained at 40°41′N, 142°5′E on 21 Jul 1982.

check was not conducted to test the interpolation scheme, while it was one of the processes of the data quality check.

6. Discussion

In this section, we discuss the occurrence frequency of pseudo–density inversions in other regions using the MIRC Ocean Dataset 2001 (MODS2001). MODS2001 is a quality controlled dataset, which is flagged following the data quality check procedures of NODC (Marine Information Research Center 2001). The data source of MODS2001 is the oceanic data of the JODC, and most of these data points have been observed around Japan. We calculated the standard depth data from MODS2001 using the two interpolation schemes. For the same purpose as outlined in section 2, the gradient check flag of temperature and salinity was ignored. As is the case in the sea off Sanriku, the Japan Sea also shows large vertical gradients of temperature and salinity between surface water and deeper water, which is termed the Japan Sea Proper Water (e.g., Uda 1934). Such large gradients of temperature and salinity are important properties in these regions, and these are flagged by the vertical gradient criteria of NODC. To study how pseudo–density inversions are generated in the sea around Japan with different oceanic conditions, three 5° × 5° subregions were selected for data analysis. As shown in Fig. 6, these subregions are centered at 40°N, 144°E in the Kuroshio–Oyashio mixed water region, at 30°N, 140°E in the subtropical region, and at 39°N, 138°E in the Japan Sea. The observation area of the dataset obtained by the Iwate Fisheries Technology Center, which is used in the former section, is also shown in Fig. 6.

a. Occurrence frequency of pseudo–density inversions

The occurrence frequency of pseudo–density inversions was counted when adjacent interpolated or observed density data were on the next standard depth. Numbers of total interpolated density data points comparable with adjacent standard depth data points and numbers of the occurrence frequency of pseudo–density inversions generated by the NODC scheme are summarized in Table 4. As in Table 4, equivalent numbers based on our scheme are summarized in Table 5, except for the rightmost column, which shows numbers of the temperature recalculation conducted for the salinity adjustment. Both schemes generate few pseudo–density inversions in the subtropical region, where seawater is moderately stratified. Differences of the interpolated data between two interpolation schemes in this subregion are much smaller than in the other subregions. As shown in Table 4, the NODC scheme generates pseudo–density inversions over 8 times the number observed using our scheme in all subregions. These results suggest that conventional data interpolation using temperature and salinity independently can generate greater pseudo–density inversions than when using temperature and potential density. In the Kuroshio–Oyashio mixed water region, the NODC scheme produced a high rate (0.96%) of pseudo–density inversions. Especially in the

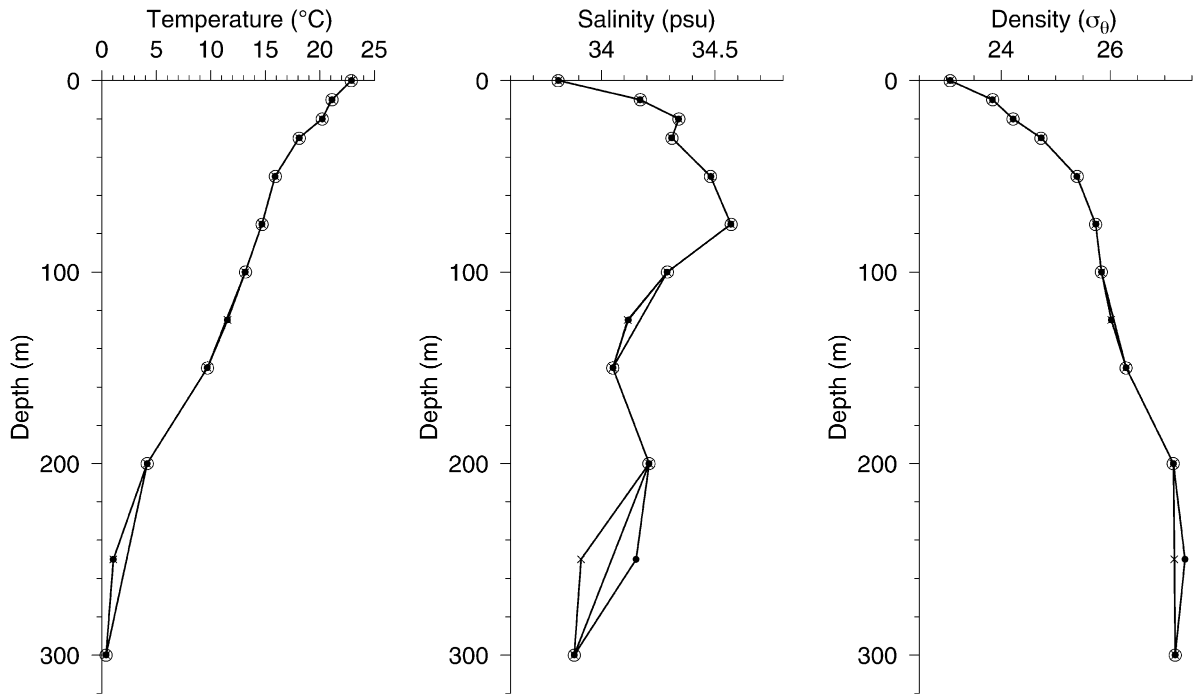

FIG. 9. As in Fig. 8 except at 37°N, 136°25′E on 2 Jul 1973.

observation area of the Iwate Fisheries Technology Center, pseudo–density inversions seem to occur more frequently than in the other subregions. Although our scheme was developed to prevent pseudo–density inversions, some inversions occurred in the Kuroshio–Oyashio mixed water region and the Japan Sea. These are caused by two adjacent interpolated values, and they are difficult to forecast only by checking the observed values.

Figure 7 shows the vertical distribution of the occurrence frequency in each subregion. The peaks of occurrence frequency differ among the subregions. It seems that pseudo–density inversions are most apt to occur at 150 m (i.e., between the 125- and 150-m standard depths) in the Kuroshio–Oyashio mixed water region, or occur at 300 m (i.e., between the 250- and 300-m standard depths) in the Japan Sea. These results are relevant with routine observations operated by prefectural fisheries experimental stations, in which the observation depth is not set at each standard depth. For example, in the subregion in the Japan Sea, the number of temperature data point observed at 250 m is one-sixth of that at 200 or 300 m. Accordingly, interpolations to 250-m depth are operated much more than the adjacent standard depths. Even if no density inversion occurred between the 200- and 300-m depths, the interpolated value at 250 m may cause a pseudo–density inversion. However, pseudo–density inversions are also caused by complex oceanic conditions, such as the interleaving of different kinds of water masses.

Figures 8 and 9 are examples of vertical profiles in the Kuroshio–Oyashio mixed water region and the Japan Sea, respectively. In Fig. 8, the salinity data are observed only at 0, 50, 100, 300, and 600 m. In the NODC scheme, the salinity value at 125 m seems to be affected by the salinity minimum at 50 m and the large gradient between 50-m and 100-m depths. As the estimated salinity is not outside of the range between the 100- and 300-m salinity values, then it is accepted as an interpolated value. However, the salinity value at 150 m is interpolated linearly, because of the limitations of distance among observation data, *I* and *E*, which are defined as shown in Table 1. Therefore, it is not influenced by the vertical gradient change among the surface layers. As a result, a pseudo–density inversion is generated between the 125- and 150-m standard depths. In Fig. 9, both temperature and salinity are interpolated at the 250-m depth by parabolic interpolation. In this case, the temperature decreases simply in the vertical direction; however, the salinity changes in a more complicated manner. This complex structure may be caused by the interleaving of the Tsushima Current Water and the upper portion of the Japan Sea Proper Water (e.g., Senju and Sudo 1994) in to the coastal area. It seems that the salinity value interpolated by the NODC scheme at the 250-m standard depth is influenced so much by the upper layers that it is overestimated, and then a pseudo–density inversion may occur between the 250- and 300-m standard depths.

b. Salinity adjustment and temperature recalculation

On the other hand, density values calculated by our scheme do not show any pseudo–density inversions in

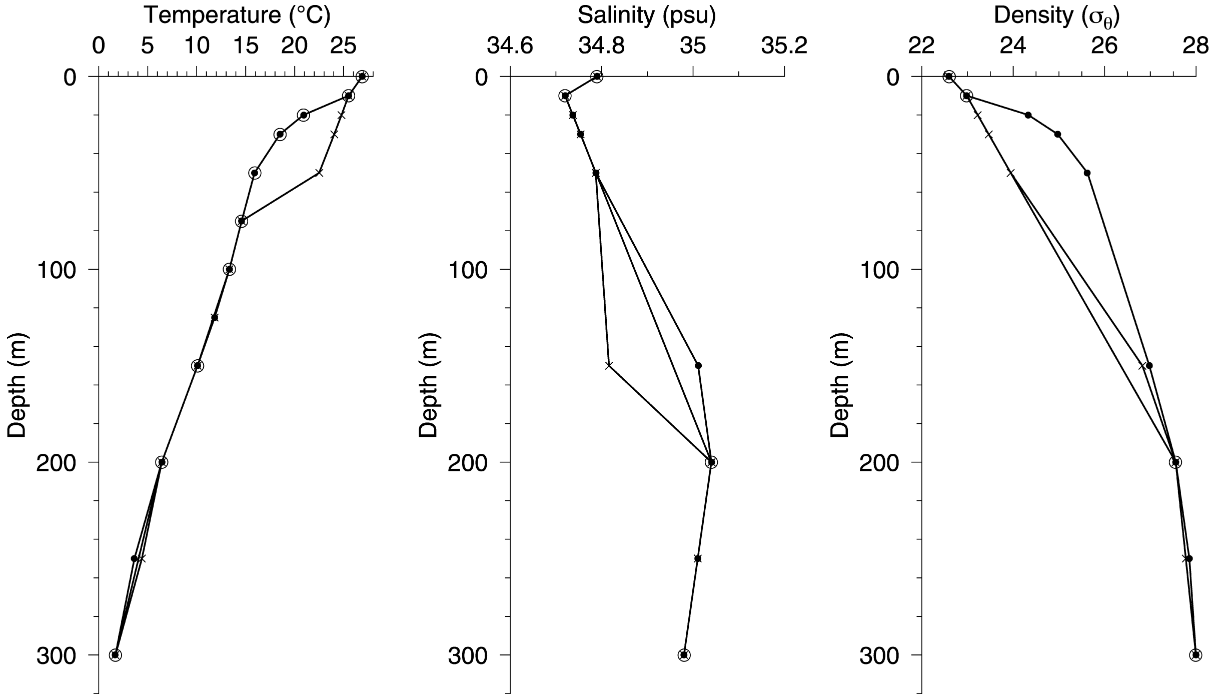

FIG. 10. As in Fig. 8 except at 39°15′N, 143°3′E on 30 Sep 1982.

Figs. 8 and 9. As shown in Fig. 9, salinity adjustment is operated at the 250-m standard depth in the Japan Sea to avoid pseudo–density inversion. The adjusted salinity value is not outside of the range between the 200- and 300-m salinity values, and no temperature recalculation is needed. However, as is shown in Fig. 8, a temperature recalculation is used at 75 m, and the temperature value is changed to an underestimated value though there is an observed value. This underestimated temperature is recalculated using the adjusted salinity value and the formerly interpolated density value. The rightmost column of Table 5 indicates that such temperature recalculations are operated in large numbers in the subregions of the Kuroshio–Oyashio mixed water region and the Japan Sea. Moreover, the number of temperature recalculations is larger than the number of pseudo–density inversions.

The salinity adjustment and the temperature recalculation are mostly applied when the observation depths are dispersed. Observations at more than one standard depth are skipped, although temperature or salinity values vary greatly in the vertical direction. Figure 10 is a typical example of temperature recalculation. In this profile, salinity values are observed at 0, 10, 200, and 300 m. There are no data at the standard depths between 10- and 200-m depths, while the temperature at these depths shows a large gradient, particularly between 10- and 75-m depths. To adjust the temperature values to linearly interpolated salinity and density values at 20, 30, and 50 m, temperature values are recalculated and become higher. In this case, the density values at these depths are underestimated by our scheme, compared with the distribution of temperature values. Temperature and density profiles interpolated by the NODC scheme seem ''real'' rather than the profiles linearly smoothed by our scheme.

As given in Table 5, the interpolated datasets in the subregions calculated by our method include some problems for temperature recalculation, which causes unnatural profiles as is shown in Fig. 10. Each interpolated profile can seriously affect the horizontal distribution or vertical section of a one-time observation cruise. However, the percentage of occurrence frequency of the temperature recalculation looks trivial, and these results will not dramatically influence the statistical analysis study using a long-term dataset, such as seasonal variations of monthly mean temperature and salinity. Oguma et al. (2002) used a standard depth dataset interpolated by our scheme, which was the same dataset used in the earlier sections of this study. Their results showed a clear seasonal variation of the sea off Sanriku at 100-m depth. There are four recalculated temperature data points at the 100-m depth in their dataset; however, these temperature values did not cause any unnatural distributions in monthly mean fields.

7. Concluding remarks

We have designed a reliable interpolation scheme by selecting temperature and potential density values as independent variables, and salinity values as the dependent variable. The scheme is effective at preventing pseudo–density inversions in areas with a complex hydrographic structure such as the Kuroshio–Oyashio mixed water region. Also, our scheme gives almost the same results as does the conventional scheme, which selects temperature and salinity as independent variables, for seas of moderate conditions such as the subtropical regions and the Kuroshio region. However, the interpolation process of our scheme has a problem related to the temperature recalculation; interpolated values may be substituted even though observed data exist at the standard depth. Its occurrence frequency is higher than that of pseudo–density inversions; however, it is mainly caused at stations that have relatively little dispersed salinity data. Basically our scheme can obtain stably stratified density profiles, even if the temperature or salinity varies complicatedly in the area, such as the Kuroshio–Oyashio mixed water region and the Japan Sea. MIRC will adopt our scheme to create the MIRC standard depth database of temperature and salinity. In the discussion of this paper, the acceptable density inversion criterion was set as 0.001 kg m^{-3}, which is strict for shallow depths. In real applications, we shall use the criterion used by NODC for convenience's sake.

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