SEARS FOUNDATION FOR MARINE RESEARCH
Yale University

Journal of Marine Research

Volume 28, Number 1

Detailed Temperature Cross Section of the Cold-water Belt Along the Northern Edge of the Kuroshio[1]

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ABSTRACT

On the basis of BT observations made at intervals of about one mile, a detailed temperature cross section of the cold-water belt along the northern edge of the Kuroshio is presented. Cold waters and sharp temperature inversions have been observed on the southern and northern margins of the cold-water belt. Within the cold-water belt, except in a narrow noninversion area, many temperature inversion layers have been observed, and the colder and warmer waters are arranged in a complicated pattern.

These observations suggest that the very cold waters in the cold-water belt are fed through a cold-water core parallel to and off the Sanriku coast of Honshu, Japan.

Introduction. With the development of *in situ* temperature and salinity recorders, the small-scale structure of the ocean has attracted the attention of many oceanographers (Hamon 1967, Stommel and Fedorov 1967). I have studied shallow temperature inversion layers in the sea to the east of Honshu,

1. Accepted for publication and submitted to press 26 July 1969.
Contribution from the Scripps Institution of Oceanography.
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Japan, by using data from BT (bathythermograph) observations (Nagata 1967, 1968). Small-scale temperature inversions often appear in the mixing zone between the Kuroshio and Oyashio. The horizontal scale of the inversions is of the order of 10 miles, and the vertical scale is usually less than 50 m; the shape seems to change considerably within a day or so.

The Kuroshio, flowing near the 37th parallel, forms the southern boundary of the area where temperature inversions are abundant. Some temperature cross sections near the Kuroshio have been shown, but the interval between the BT observations was too large (about 10 miles) to determine the relationship between the inversion layers observed at successive stations (Nagata 1967: figs. 4a–4e). However, those cross sections do show that strong temperature inversions are apt to occur inside of the cold-water belt just north of the Kuroshio. Also, statistical analysis of the inversion layers indicates the existence of strong inversions just north of the Kuroshio (Nagata 1968).

In order to ascertain more accurately the structure of the strong inversion layers and their relationship to the cold-water belt, observations more closely spaced than before were made by the Geophysical Institute on board the TANSEI-MARU of the University of Tokyo. Because of approaching typhoons, only two days of observations (from 1400 August 4 to 0900 August 6, 1967) are available for this study. However, despite the limited observations, the closely spaced observations, at intervals of about one mile, have revealed the very complicated and vivid features of the cold-water belt along the northern edge of the Kuroshio.

Data and Analysis. First, in order to determine the positions of the cold-water belt and the Kuroshio, the BT was lowered at intervals of 30 minutes, or intervals of about four miles, along a transect extending southeastward from just off Ofunato Bay to 38°N 143°E, thence southward along the 143°E meridian to the current axis of the Kuroshio. The transect is shown in Fig. 1, which also includes the surface-temperature field and the general location of the Kuroshio. The position of the current axis can be estimated from the location of the water temperatures, which ranged from 13°C to 15°C at a depth of 200 m. Then, working northward, the observations along the 143°E meridian were repeated; on this section the BT was lowered at intervals of 10 to 15 minutes inside the cold water belt, and the speed of the ship was 5 knots, so the minimum spacing was less than one mile. During all of the observations, the position of the ship was determined by Loran every 30 minutes. The positions of the observations are shown in detail in Fig. 5.

About 7 minutes were needed for each BT observation. Consequently, with 10 minute intervals, the upper part of the down-trace on each BT slide is closer spatially to the up-trace on the preceding slide than to the up-trace on the same slide. Although it might be possible to identify the up-trace from the down-trace on each BT slide by means of comparison with the slides taken

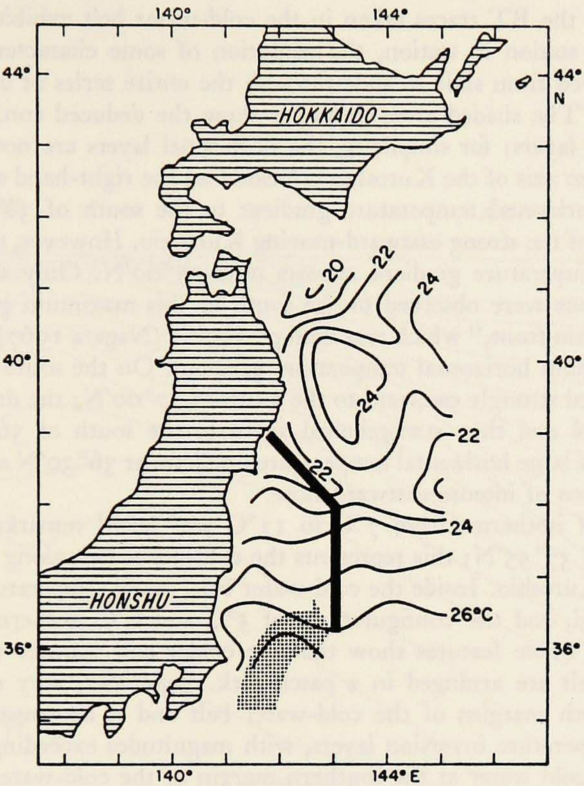

Figure 1. Site of the observations. Also shown are the surface-temperature field and the general position of the Kuroshio, from Kaiyo Sokuho No. 16, August 19, 1967 (Preliminary Report of the Oceanic State, published by the Hydrographic Office, Maritime Safety Agency, Japan).

just before and just after, only the mean of the up-trace and down-trace on each slide has been used in this paper. Therefore, the small-scale temperature structure might have been missed because of the reading procedure.

The water temperatures at standard depths (0, 10, 20, 30, 50, 75, 100, 125, 200, and 250 m) and the depths of the isotherms in increments of 1°C were read from each BT slide. Also, the depths and temperatures at the upper and lower ends of every temperature inversion and isothermal layer were read. The daytime surface temperatures recorded on the BT traces are difficult to read accurately because of the large temperature gradient near the sea surface. Therefore, since the same instrument was used throughout, the surface-temperature corrections were not made for each slide.

Detailed Cross Section of the Cold-water Belt along the Northern Edge of the Kuroshio. The detailed temperature cross section is shown in Fig. 2. Though the shapes of the BT traces taken in the cold-water belt exhibit considerable change from station to station, the evolution of some characteristic features can be followed from slide to slide through the entire series of densely spaced observations. The shaded areas in Fig. 2 show the deduced configurations of the inversion layers; for simplicity, the isothermal layers are not shown.

The current axis of the Kuroshio is located on the right-hand side of Fig. 2. The large horizontal temperature gradient to the south of 36°30'N shows the presence of the strong eastward-moving Kuroshio. However, the maximum horizontal temperature gradient appears near 37°00'N. Only small temperature inversions were observed to the south of this maximum gradient. The term "Kuroshio front," which was used previously (Nagata 1967), corresponds to this maximum horizontal temperature gradient. On the southward section, the ship drifted strongly eastward to the south of 37°00'N; the drift weakened near 36°40'N and then strengthened again to the south of 36°30'N. The two regions of large horizontal temperature gradient, at 36°30'N and 37°04'N, were in regions of intense eastward flow.

The set of isotherms from 7°C to 11°C was raised remarkably between 37°05'N and 37°55'N; this represents the cold-water belt along the northern edge of the Kuroshio. Inside the cold-water belt, many temperature inversions were observed, and the configurations of 5°C and 6°C isotherms were very complicated. These features show that the colder and warmer waters in the cold-water belt are arranged in a patchwork. Especially, very cold water is located in both margins of the cold-water belt and is accompanied by pronounced temperature inversion layers, with magnitudes exceeding 2°C.

The very cold water at the southern margin of the cold-water belt is conspicuous and covers a considerable area in the cross section. This water is located along, and just below, the sharp thermocline consisting of the Kuroshio front. At St. 68, the minimum temperature was 1.5°C at 196 m. The accompanying inversion layer at St. 68 was 58 m thick and the magnitude of the temperature inversion reached 3.0°C. These values are exceptionally large for the inversion layers observed in this region (Nagata 1968). This inversion layer could be traced horizontally for about 10 miles. An oblique tongue of this cold water extended upward along the frontal line to a depth of about 60 m, and another thin and pronounced temperature inversion layer accompanied this cold tongue. It is of interest that such a cold wall exists so close to the Kuroshio front.

At the northern margin of the cold-water belt, the very cold water was more diffuse and was split into several cores. However, in Fig. 2 this water can be traced from the bottom left (St. 129) to a depth of 40 m at St. 102. At St. 128, the minimum temperature was 2.6°C and occurred at 240 m. In the cross section, the area of the temperature inversion layer accompanying this minimum temperature is much smaller than the area of the corresponding inversion layer at the southern margin of the cold-water belt. At the northern

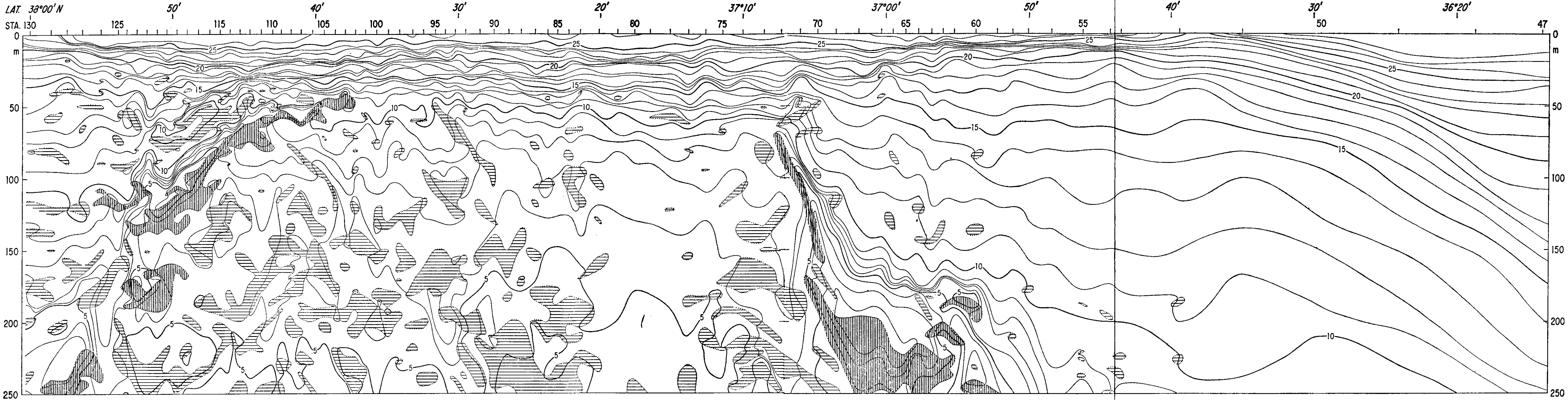

Figure 2. Detailed vertical section of temperature, Celsius, along 143°E on August 5–6, 1967. The section crosses the cold-water belt along the northern edge of the Kuroshio. Minimum intervals of the observations were less than one mile. Shaded areas show positions of inversion layers. Deep shades indicate that the magnitude of the temperature inversion is more than 2°C.

margin, the most notable inversion layer appears to have been shallower than 150 m. This thin but very sharp inversion was traced for 16 miles, from St. 102 through St. 124, and its depth changed from 40 m to 140 m. This inversion seems to correspond to the inversion that accompanied the cold wall at the southern margin. The slope of this northern inversion layer, 1/320, was less than the slope of the corresponding inversion layer at the southern margin, where the slope was about 1/170. Inversion layers at the northern margin had ragged and complicated shapes while those at the southern margin had simple shapes. These differences between the very cold water at the northern and southern margins suggest that the southern water is young and that the northern water is old and in a state of decay due to mixing.

It must be noted that few inversions were observed between St. 75 and St. 82. This noninversion area seems to have divided the cold-water belt into two parts. The temperature structure in the northern part may be considered as a diffused mirror image of that in the southern part. As the current direction seems to have been eastward in the southern part of the cold-water belt and westward in the northern part, it is possible that the very cold water and its surrounding water in the southern margin travels eastward to the eastern end of the cold-water belt and then travels westward along the northern margin of this belt. Though we cannot derive any conclusive results from a series of single observations, this assumption seems to explain the temperature distribution shown in Fig. 2.

The large horizontal temperature gradient at the Kuroshio front may represent the boundary between a highly turbulent area and a less turbulent area. If the Kuroshio area is highly turbulent because of the high-speed current and if the cold-water belt is less turbulent, then the large temperature gradient may result from a process similar to the formation of seasonal thermoclines (Turner et al. 1967). In such formations, water is always transferred from less turbulent into more turbulent regions, where it is quickly mixed.

Density Structure of the Temperature Inversion Layer. Near 250 m at 37°58′N, 142°54′E, the vertical distributions of salinity and temperature in the inversion layer were measured with closely spaced Nansen bottles. This inversion layer corresponds to that which accompanied the temperature minimum in the northern very cold water. The results are shown in Fig. 3. Salinity shows a marked reversal where temperature shows an inversion. This salinity reversal counteracts the effect of the temperature inversion on the vertical distribution of density, and throughout the temperature inversion the density increases linearly with depth. No more observations of the density structure could be made owing to another approaching typhoon. However, in Fig. 2 the results suggest that at least the larger inversion layers have stable density structures.

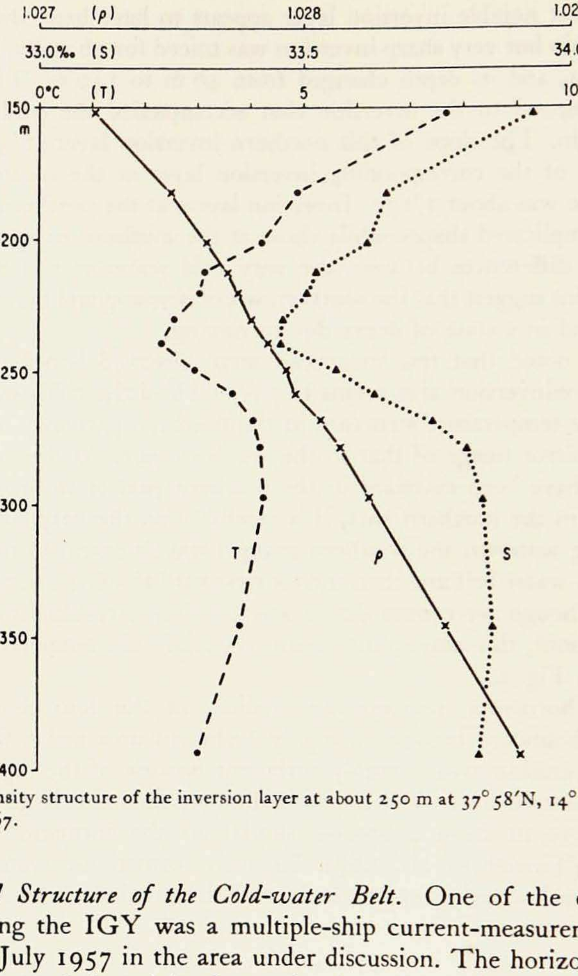

Figure 3. Density structure of the inversion layer at about 250 m at 37° 58′N, 14° 55′E on August 6, 1967.

Horizontal Structure of the Cold-water Belt. One of the oceanographic projects during the IGY was a multiple-ship current-measurement program in June and July 1957 in the area under discussion. The horizontal structure of the cold-water belt and its fluctuation have been discussed by Masuzawa (1958). In Fig. 4 are shown two examples of the horizontal structure derived from Masuzawa (Operations GS_1 and GS_3 in the original paper). Fig. 4 shows that the cold-water belt along the northern edge of the Kuroshio is variable in time and that the belt sometimes appears as a train of cold-water patches. Masuzawa considered that the coldest water in Fig. 4a (B) corresponds to the coldest water in Fig. 4b (B′). The indicated advective velocity of the coldest water agrees with the results obtained by direct current measurements with parachute drogues at 100 to 200 m. The correspondence of B to B′ is not evident because operation GS_2, which was conducted between GS_1 and GS_3, shows only narrow strips of the cold water and does not indicate that any of the

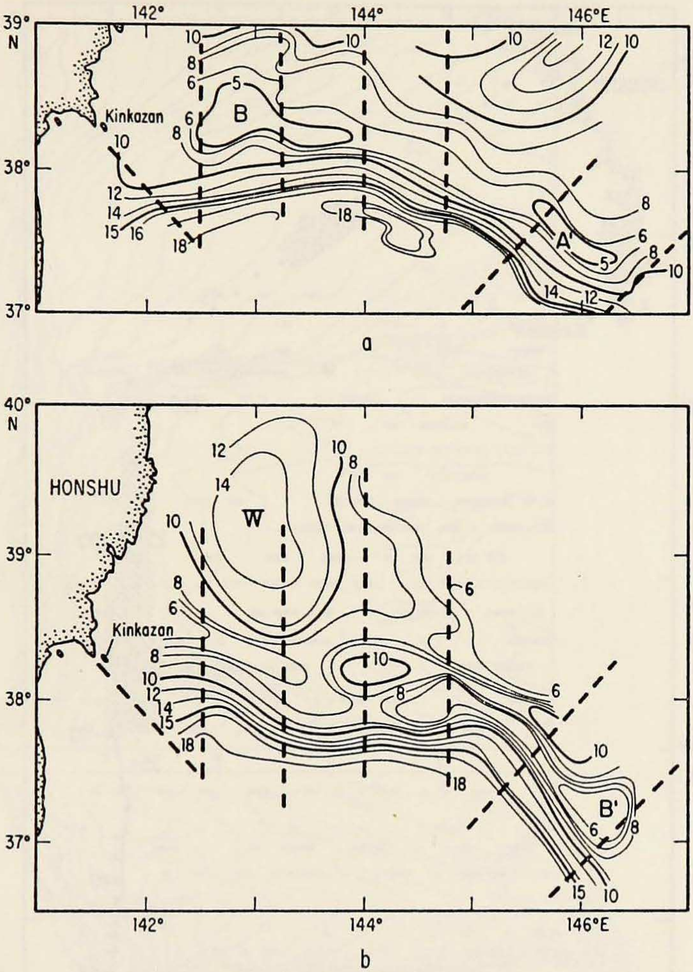

Figure 4. Mean temperature, Celsius, of the upper 200-m layer: a, on June 17–19, 1957; b, on June 28–30, 1957 (from Masuzawa 1958). Dashed lines show the standard observation lines adopted for the multiple-ship current-measurement survey in 1957.

coldest water corresponds to B or B'.[3] However, it seems possible that the cold waters in the cold-water belt have their origin in the sea near Kinkazan.

The surface temperature in August 1967 (Fig. 1) indicates the existence of a remarkable occlusion of warm water in the vicinity of 39°30'N, 143°00'E,

3. Because of the large space intervals between the observation lines, it is possible that the coldest water was not observed in this operation. Furthermore, the parameter adopted by Musuzawa, the mean temperature in the upper 200-m layer, may not be suitable for a study of the cold-water belt because of its complicated structure.

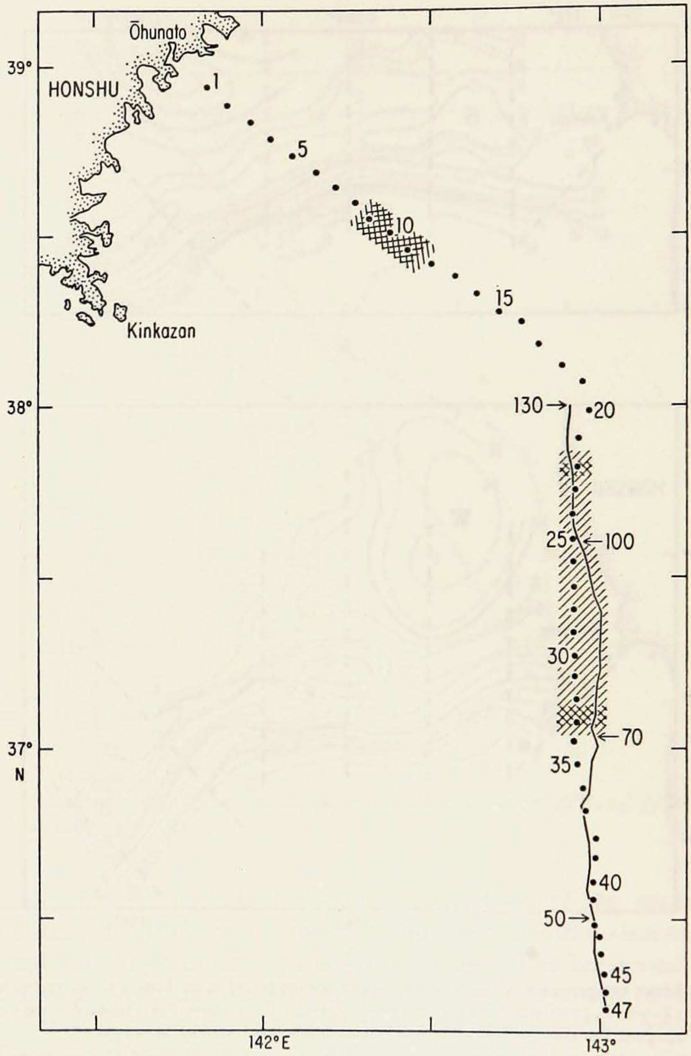

Figure 5. Station map of the observations on August 4–6, 1967. Dots show the positions of the preliminary observations. The solid line represents the section on which the detailed temperature cross section was made. The diagonally lined portions indicate that the water temperature at 100 m was less than 8°C, the hatched portion less than 6°C.

and the cold-water tongue extending southeast from Kinkazan. This same feature can be seen in the distribution of the mean temperature in the upper 200 m in June 1957 (Fig. 4b). Therefore, the general structure at the time of our observations seems to have been similar to that of June 1957.

Approximately four miles served as the space interval between the pre-

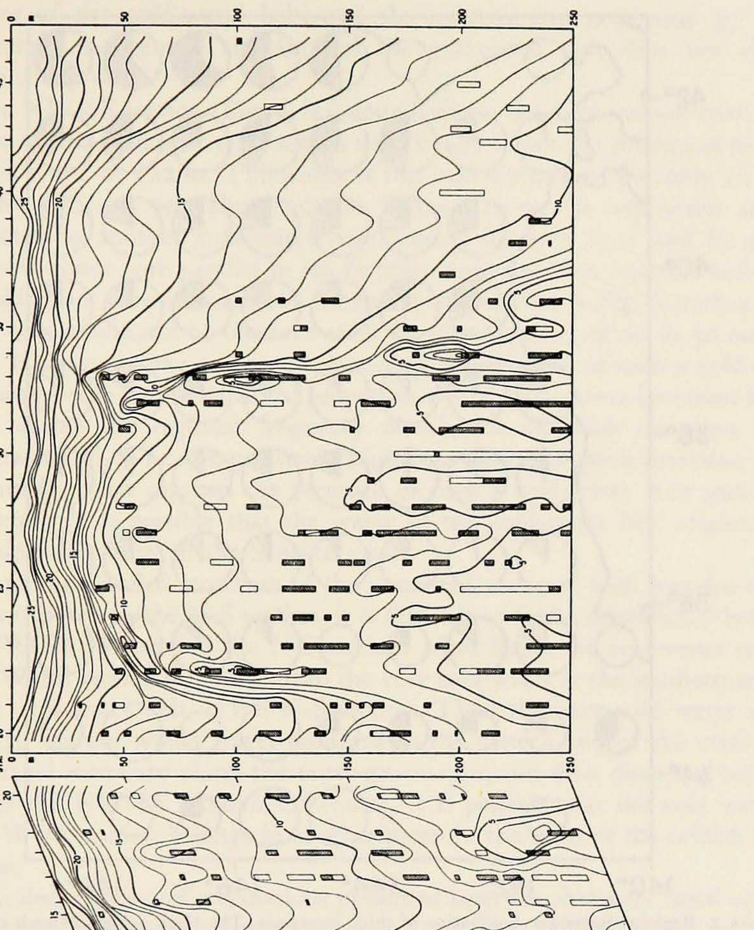

Figure 6. Temperature (Celsius) cross section derived from the preliminary observations on August 4–5, 1967. The interval between the stations was about 4 miles. Shaded and unshaded parallelograms show the positions of the temperature inversion layers and isothermal layers, respectively. The N–S section (right) corresponds to the detailed cross section in Fig. 2.

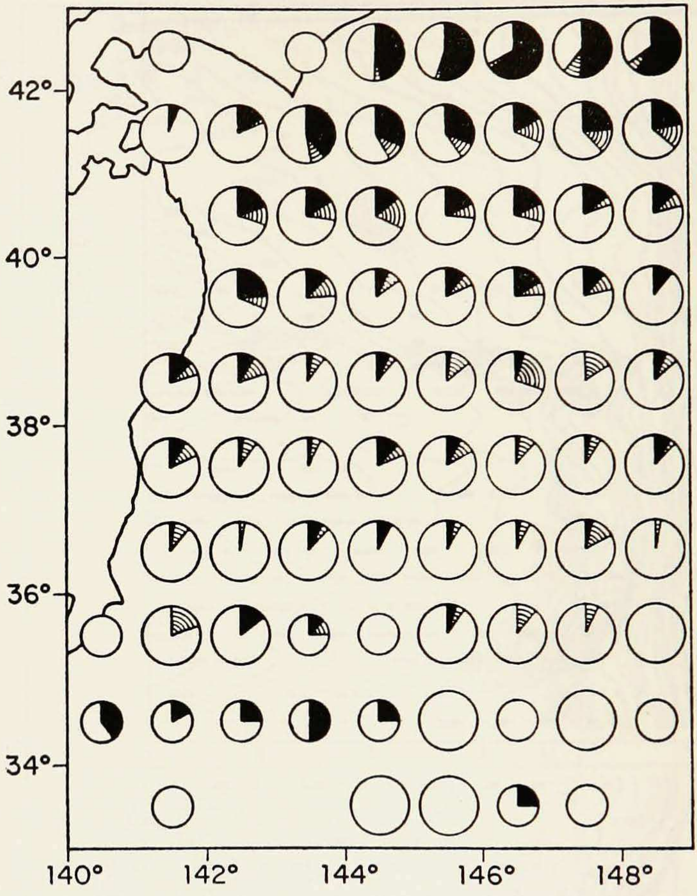

Figure 7. Regional frequency distribution of thick inversions. The black portion of each circle indicates the ratio of the number of BT traces containing inversions thicker than 50 m to the number of BT traces containing inversions. The hatched portion indicates the ratio of the number of traces in which the lower ends of the deepest inversion layers could not be defined; the limitation of the observational range made it impossible to determine whether the maximum inversion thickness was larger than 50 m. The small circle shows that the number of analyzed BT traces containing inversions was less than 10 in that subregion. From Nagata 1968.

liminary stations. Although these stations were not spaced closely enough to show the configurations of the temperature inversion layers, the stations were closer than those occupied during the multiple-ship current survey in 1957. The positions of the 1967 observations are shown in Fig. 5, and the temperature cross section is shown in Fig. 6. The N-S section (Fig. 6, right frame) corresponds to the cross section in Fig. 2; Fig. 6 also shows the double structure of the Kuroshio front, the very cold water at both margins of the cold-water belt, and the noninversion area near 37°15'N. Apparently the general structure of the cold-water belt does not change within a day or so.

The NW-SE section (Fig. 6, left frame) shows the very narrow cold-water core at depths shallower than 200 m near St. 10, where the minimum temperature is 1.5°C at 122 m. The width of this cold-water core was only 12 miles and the thickness was about 100 m. Below 200 m, the cold-water core is connected to another cold-water core located between St. 7 and St. 9. No such cold-water core parallel to the Sanriku coast has been reported before. If the cold-water core is usually as narrow as that shown in Fig. 6, such a cold-water core would not be observed with the usual spacing of 20 to 30 nautical miles. However, some evidence concerning the presence of such a cold-water core can be seen in the statistical properties of the temperature inversion layers. Fig. 7 shows the regional frequency distribution of thick inversion layers (Nagata 1968). The comparatively high occurrence of thick inversion along the Sanriku coast suggests the presence of such a cold-water core parallel to that coast. It is possible that the water in the cold-water belt originates in the cold-water core off the Sanriku coast.

As to the detailed structure of the very cold water at both margins of the cold-water belt in the N-S section, it is difficult to find a relationship between the NW-SE section and the N-S section. Most likely the cold-water core in the NW-SE section is connected to the very cold water at the southern margin of the cold-water belt in the N-S section. Then the very cold water at the southern margin would travel eastward to the eastern end of the cold-water belt, travel westward along the northern margin, and then disappear before it reaches the NW-SE section. Of course, it is possible that the cold water in the NW-SE section belongs to another patch in the train of the coldest water patches.

The deductions and speculations presented here are obviously based on very limited and inadequate observations, but I hope that this study will serve as a stimulus in providing the more elaborate detailed observations that are needed to determine in greater detail the structure of the cold-water belt.

Acknowledgments. I wish to express my thanks to C. S. Cox, R. B. Montgomery, F. C. Fuglister, Mizuki Tsuchiya, Keiichi Hasunuma, and B. A. Taft for their helpful discussions and suggestions. I also thank Nobuo Suginohara, Toshimitsu Kaiho, Masaaki Shishido, and Hideki Nagashima and the crew of the Tansei-maru for their help in making the observations, and Miss Tamiko Osada for her help in the data analysis. This work was partially supported by the U.S. Office of Naval Research under contract with the University of California, Nonr 2216 (23).

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