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A Subsurface Low-salinity Thin Layar in the Kuroshio Region off Bungo-suido Passage

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Abstract

The CTD data obtained in the Kuroshio region off Bungo-suido Passage in autumn of 1981 revealed a thin-layered (ca 40 m width) and much lower salinity (ca 0.3 ppt difference) water embedded in the Subtropical Subsurface Water at ca 140 m depth. It is shown that the observed low-salinity thin layer can be attributed to the intrusion of low-salinity Seto Inland Sea Water to the subsurface layer of the Kuroshio region through the density frontal zone at Bungo-suido Passage.

1. Introduction

It is a well known fact that the interleaving thermohaline fine structures will appear around some oceanic frontal zones, *e.g.*, ODAMAKI and KUNISHI (1977) in the East China Sea, COACHMAN and CHARNELL (1979) in the Bristol Bay, TOOLE (1981a, b) near the Antarctic Polar Front and in the Equatorial Pacific Ocean. In the region south off Shikoku, a front always exists between the coastal cold water of low-salinity and the Kuroshio of warm and saline water (cf. KAKANO *et al.*, 1981). Therefore, it may be conjectured that the similar interleaving themohaline fine structures must be found in this region. However, they have not been clarified yet in this region, since any results of CTD observation have not been presented. Concerning the fine structures in this region, only NAGATA (1979) analysed the results of many BT (bathythermograph) observations and showed that the occurrence frequency of shallow temperature inversion is ca 20%.

The authors had an occasion to carry out a CTD observation in the region southwest off Shikoku in autumn of 1981. In this observation, a subsurface low-salinity thin layer is found, which shows a saline fine structure.

In this paper, analysing this CTD data and nearly simultaneous serial observation data at Bungo-suido Passage, west off Shikoku, the origin of the subsurface low-salinity water is examined precisely.

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2. Observation

Stn. K (32°−10′.0N, 132°−24′.1E) in Fig. 1 represents the location of our CTD observation carried out on Nov. 21 in 1981 on board the training ship Kagoshima-maru of Faculty of Fisheries, Kagoshima University. According to the Prompt Report of Oceanographical Surveys carried out during the period from Nov. 18 to Dec. 3 of 1981, published by Maritime Safety Agency, the Stn. K located exactly in the Kuroshio current.

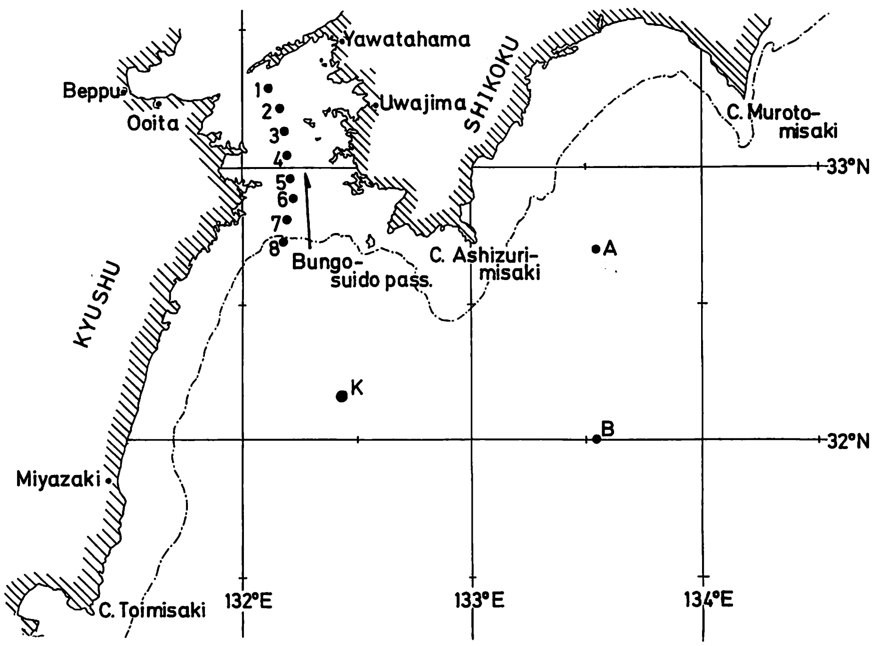

Fig. 1. Map showing the locations of hydrographic observation stations.

Data were obtained by a Neil Brown Instrument System Inc., Mark III CTD/DO and they were recorded directly on a computer compatible magnetic tape. In order to check the CTD data, water samples and temperatures were collected at several depths, using General Oceanics Inc., Rosset Multi-bottled Water Sampler. Processing of CTD data was made on a NOVA-01 computer system on board. In Figs. 2a, 2b and 2c are shown the obtained vertical profiles of salinity, water temperature and density (σ_t), respectively.

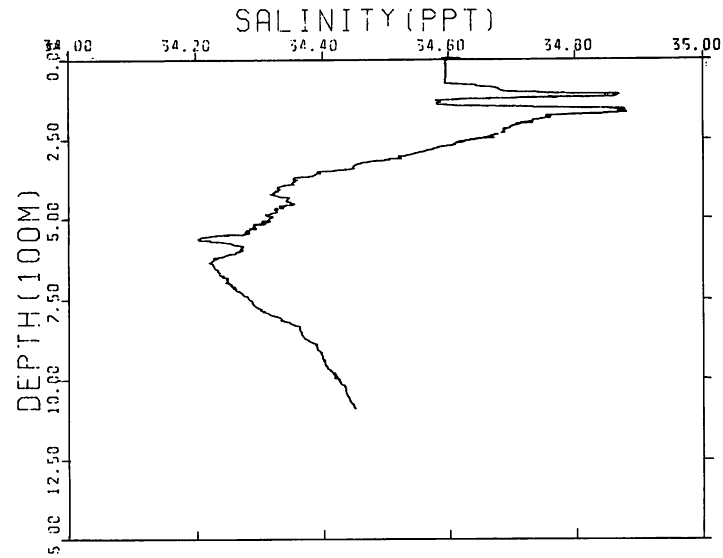

Fig. 2(a). Vertical profile of salinity at Stn. K on Nov. 21, 1981.

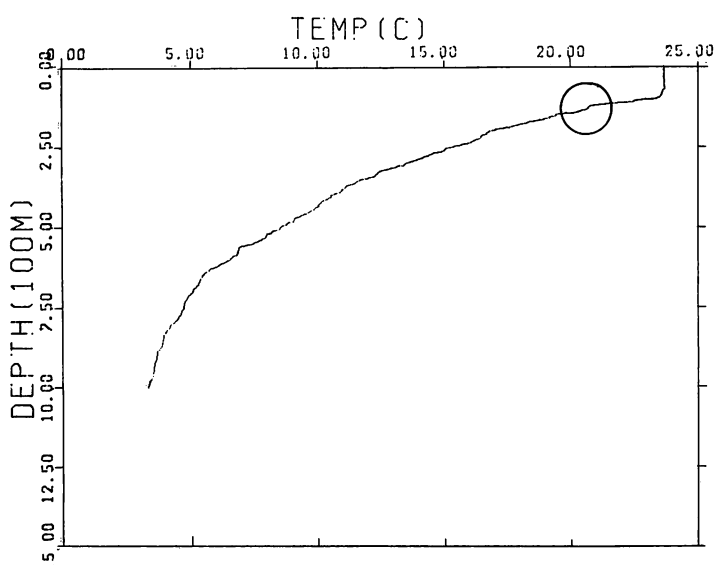

Fig. 2(b). Vertical profile of water temperature at Stn. K on Nov. 21, 1981.

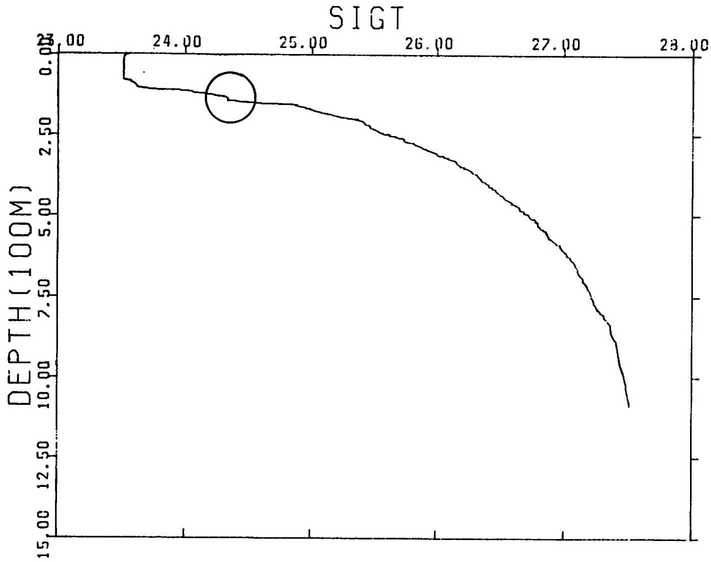

Fig. 2(c). Vertical profile of density (σ_t) at Stn. K on Nov. 21, 1981.

3. Subsurface Low-salinity thin layer

Figs. 2a, 2b and 2c show apparently that the surface mixed layer reaches to a depth of ca 100 m and that the pycnocline exists beneath the surface mixed layer. In the pycnocline, the value of salinity increases to a maximum of ca 34.9 ppt at ca 120 m depth. Below this level, it decreases rapidly to have a minimum value of ca 34.6 ppt at ca 140 m, and afterwards it increases rapidly again to have another maximum value of ca 34.9 ppt at 160 m. Thus, a thin layer of ca 40 m width of much lower salinity of ca 0.3 ppt difference exists centering at the depth of ca 140 m. On the other hand, the water temperature and density have not any singularity around the depth where the low-salinity water is observed. It must be noticed that the values of salinity, temperature and density are nearly constant within the central part of the thin layer and their vertical gradients are very small except in the uppermost and lowermost 10 m in the layer.

It is appropriate to examine here the water type of the thin layer stated above, comparing with the coastal and the Kuroshio water in this region. For this purpose, the serial observation data obtained by the R/V Shoyoo of Maritime Safety Agency on Dec. 4 in 1981, only two weeks after our CTD observation, at Stns. A and B shown in Fig. 1, are available. According to the GEK data obtained simultaneously, Stn. A is located in the onshore edge of the Kuroshio current and Stn. B in the offshore region far from the Kuroshio axis. In Fig. 3, TS-diagram (temperature-salinity relation) of Stn. K is made from the CTD data at every 10 m and those of Stns. A and B the hydrocast data at standard depths.

Inspecting Fig. 3, it is obvious that the salinity of Stn. B has the maximum value of ca 34.9 ppt

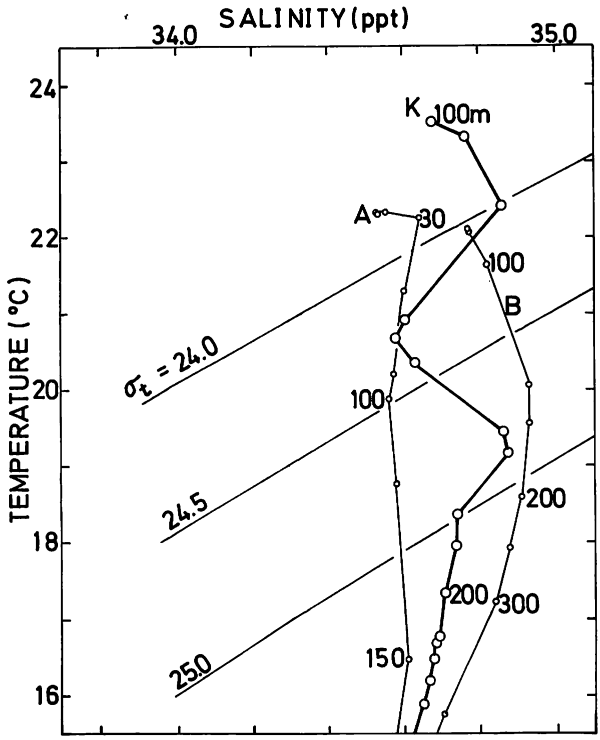

Fig. 3. TS-diagrams at Stns. A, B and K.
TS-diagram at Stn. K is made from the CTD data at every 10 m and those at Stns. A and B the hydrocast data at standard depths.

at a depth of ca 150 m which represents the high salinity Subtropical Subsurface Water. Therefore, the low-salinity water around 140 m depth of Stn. K can be regarded to have been embedded in the Subtropical Subsurface Water.

The low-salinity water at Stn. A, located in the onshore edge of the Kuroshio, can be attributed to the Seto Inland Sea Water flowing out through the Kii-suido Passage and/or the Bungo-suido Passage. The water at Stn. K seems to be a mixture of two water of Stns. A and B in the depth deeper than 180 m. The water type of the low-salinity water at 140 m depth of Stn. K coincides with that of the water at ca 65 m depth of Stn. A. However, it should not be said that the low-salinity water at Stn. K originates from the coastal water of Stn. A, because the location of Stn. A is in the downstream region of the Kuroshio current with regard to Stn. K.

4. Oceanographical condition at the Bungo-suido Passage

The coastal water of Seto Inland Sea seems to be the source of the observed low-salinity water because any large river discharge can not be found in the east coast of Kyushu nor the south coast of Shikoku. Kii-suido Passage, one of the two passeges connecting the Seto Inland Sea and the Pacific Ocean, is rather far from the observation point. Therefore, it can be conjectured that the observed low-salinity layer can be attributed to the intrusion of low-salinity water of the Seto Inland Sea to the observation region through the Bungo-suido Passage, another passage connecting the Seto Inland Sea and the Pacific Ocean, near the observation point.

In order to clarify the source of the thin-layered low-salinity water at Stn. K, are analysed the oceanographical data in the Bungo-suido passage obtained by the R/V Kuroshio-maru of Ooita Prefectual Fisheries Experiment Station on Nov. 9 and 10, ten days before our CTD observation. Stns. 1～8 in Fig. 1 represent the locations where the serial observations were carried out.

The distributions of water temperture, salinity and σ_t in the vertical section along the passage are shown in Figs. 4a, 4b and 4c, respectively. The water temperature is nearly uniform in the region from Stn. 1 to Stn. 4 in contrast with the rather complicated distribution in the region from Stn. 5 to Stn. 8. A thermal front exists between Stns. 6 and 7,*i.g.*, the water temperature at Stns. 7 and 8 is ca 2 °C higher than those in the region from Stn. 1 to Stn. 6.

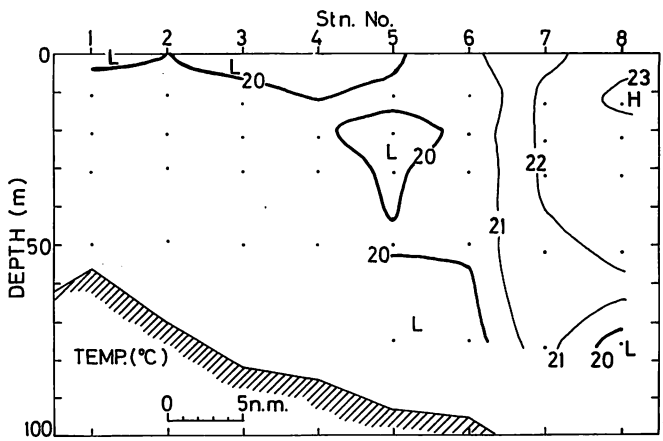

Fig. 4(a). Distribution of water temperature in the vertical section along the Bungo-suido Passage on Nov. 9 and 10, 1981.

Surface temperature inversion exists in the whole region, suggesting that the atmospheric cooling efffect is dominant in the observation period of November. Since the heat accumulation of water column is proportional to its total depth, the water temperature of shallow sea such as the Seto Inland sea and Stns. 1～4 decreased more rapidly than those of deep sea such as Stns. 7 and 8 during the period when the heat is losing from the surface.

The vertical mixing due to atmospheric forcing reaches down to several ten meters from the surface, while that due to tidal current reaches up to several ten meters from the bottom, as suggested by COACHMAN and CHARNELL (1979). Therefore, the vertical mixing will be intense in the whole depth at shallow sea in contrast with at deep sea where the vertical mixing is limited separately near the surface and the bottom. Thus, the differences of vertical mixing effects between shallow and deep seas may be a plausible reason to explain the thermal structure in Fig. 4a.

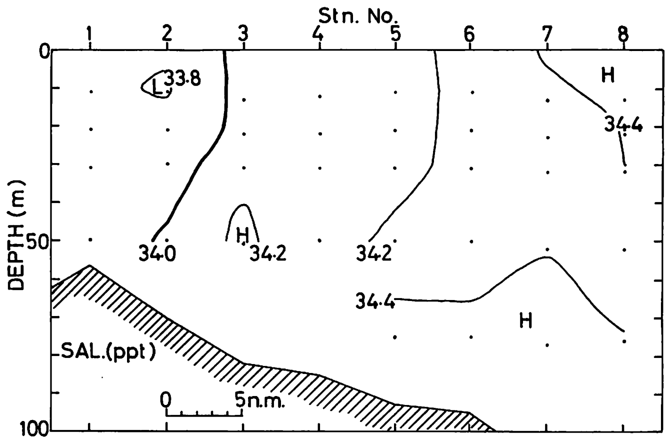

Fig. 4(b). Distribution of salinity in the vertical section along the Bungo-suido Passage on Nov. 9 and 10, 1981.

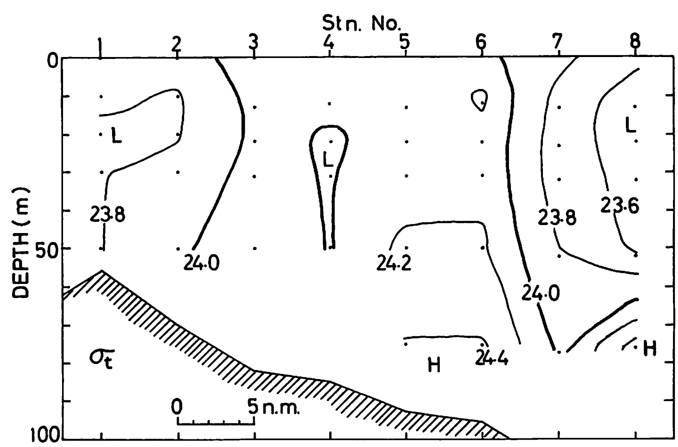

Fig. 4(c). Distribution of density (σ_t) in the vertical section along the Bungo-suido Passage on Nov. 9 and 10, 1981.

In Fig. 4b, is found another aspect that the salinity is nearly unifrom from the surface to bottom and it gradually increases from Stn.1 toward Stn.8, which represents a typical feature of the well-mixed estuary. Furthermore, it is found from Fig. 4c that the water density is rather large in the central region of the passage, which may be called a density front. This density front can be attributed to the superposition of the distributions of water temperature and salinity described above, *i.e.*, the density increases from Stn.1 toward Stn.6 due to increment of salinity with uniform water temperature, while it decreases from Stn.6 toward Stn.8 due to increment of water temperature with nearly uniform salinity.

This density front at the Bungo-suido Passage play an important role in the generation of subsurface thin-layered saline structure at Stn.K, which will be shown in the next section.

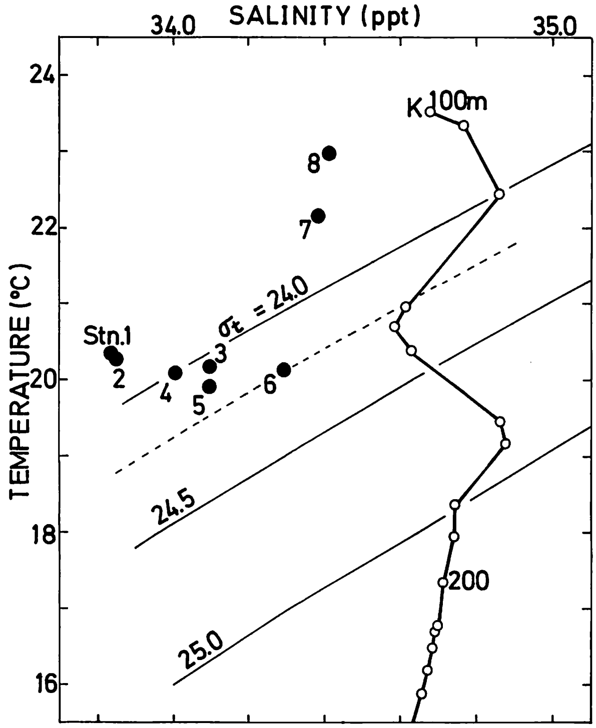

Fig. 5. Water types of Stns. 1~8 and TS-diagram at Stn. K.
Each water type is determined from the mean values of temperature and salinity averaging the values at 10, 20 and 30 m depths on each station.

5. Intrusion of low-salinity water

In Fig. 5 are shown the water types of Stns. 1~8 together with the TS-diagram of Stn. K. Each water type is determined from the mean values of temperature and salinity averaging the values at 10, 20 and 30 m depths on each station. It is apparent in this figure that the value of σ_t at Stn. 6, the maximum in the Bungo-suido Passage, approximately coincides with that of the subsurface low-salinity water at Stn. K. This fact suggests that the low-salinity water at the density front in the Bungo-suido Passge intrudes to the subsurface at Stn. K along the isopycnal surface and generates there the saline structure described above. This conjunction seems to be supported by the monthly mean water temperarure distribution at 100 m depth in November of 1981 which is shown in Fig. 6. This figure is redrawn from the Ten-day Marine Report of Japan Meteorological Agency. The colder water at the Bungo-suido Passage seems to intrude to Stn. K through the coastal region off Kyushu as indicated by an arrow in Fig. 6.

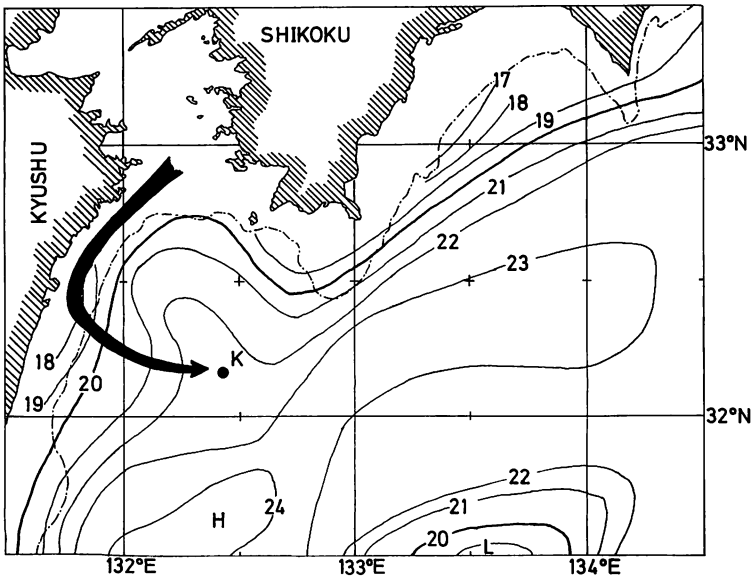

Fig. 6. Monthly mean water temperature distribution at 100 m depth in Nov. of 1981 redrawn from the Ten-Day Marine Report No. 1268. The arrow indicates the conjectured path of the intrusive low-salinity water from the Bungo-suido Passage to Stn. K.

The water temperature, salinity and σ_t at Stn. 6 shown in Fig. 5 are 20.1°C, 34.3 ppt and 24.2, respectively. The water temperature and salinity of the Subtropical Subsurface Water with the same value of σ_t as that at Stn. 6 are ca 21.5°C and 34.9 ppt, respectively. Therefore, if the water at Stn. 6 intruded to Stn. K without any mixing or diffusion, not only the salinity anomaly but also the temperature inversion must exist at Stn. K. However, any temperature inversion is not found at Stn. K as described in Sec. 3. This result can be attributed to the fact that the diffusion coefficients of heat and salinity are not equal to each other, *i.e.*,the heat dissipates more rapidly than the salinity and only the salinity anomaly has been retained at Stn. K although the temperature inversion has been already broken down during the intrusion .

6. Concluding remarks

Is investigated in this paper, the origin of the subsurface thin-layered low-salinity water revealed by the CTD observation carried out on Nov. 21 of 1981 at Stn. K in the Kuroshio region off Bungo-suido Passage. From the analysis of oceanographical data in the Bungo-suido Passage, the following facts are found. The water temperature is uniform in the north region, while the salinity increases gradually from north to south. Owing to these distributions of water temperature and salinity, a density front exists in the central region of the passage. The numerical value of density at the front is nearly equal to that of the subsurface thin-layered low-salinity water observed at Stn. K. This result suggests that the low-salinity thin layer at Stn. K is induced by the intrusion of low salinity water from the density front in the Bungo-suido Passage along the isopycnal surface towards the observation point.

Finally it must be mentioned that the relation between the intrusion of coastal water and the path of the Kuroshio current remains to be discussed in this paper. Furthermore, it is not determined in this paper whether the observed thin-layered low-salinity water has a tongue-like distribution or an isolated core distribution, because there is no available CTD data except only one CTD observation at Stn. K. In order to clarify the distribution of intrusive low-salinity water and its time change, another extensive CTD observation is desired to be made in the region south off Bungo-suido Passage.

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References

COACHMAN, L.K. and R.L. CHARNELL (1979): On Lateral Water Mass Interaction-A Case Study, Bristol Bay, Alaska. *J. Phys. Oceanogr.*, **9**, 278–297.

NAGATA, Y. (1979): Shallow Temperature Inversion in the Pacific Ocean near Japan. *J.Oceanogr. Soc. Japan*, **35**, 141–150.

ODAMAKI, M. and H. KUNISHI (1979): On the Oceanographical Structure in the Boundary Region between Water Masses (An Observation in the East China Sea during KH-74-3 Hakuho-Maru Cruise). *Umi to Sora*, **52**, 83–90 (in Japanese with English Abstract).

TAKANO, I., S. IMAWAKI and H. KUNISHI (1981): Surface Temperature-Salinity front in the Kuroshio South of Japan. *La mer*, **19**, 171–178.

TOOLE, J.M. (1981a): Intrusion Characteristics in the Antactic Polar Front. *J. Phys. Oceanogr.*, **11**, 780–793.

TOOLE, J.M. (1981b): Anomalous Characteristics of Equatorial Thermohaline Finestructure. *J. Phys. Oceanogr.*, **11**, 871–876.

Data sources

Prompt Data Report of Fishing Ground Survey at Bungo-suido Passage, Ooita Prefectual Fhisheries Experiment Station, Ooita. Nov. of 1981.

Prompt Data Report of Hydrographic Observation (South of Honshu), Hydrographic Department, Maritime Safety Agency, Tokyo. No. 4 of 1981.

Prompt Report of the Sea Condition, Hydrographic Department, Maritime Safety Agency, Tokyo. No. 23 of 1981.

Ten-Day Marine Report, Japan Meteorological Agency, Tokyo. No. 1268 (1981).