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Short Contribution

Thermohaline Front at the Mouth of Ise Bay

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The detailed structure of the thermohaline front at the mouth of Ise Bay during winter has been investigated by intensive field observation. The transport of suspended matter from Ise Bay to the Pacific Ocean through the thermohaline front has also been investigated using the data from a time-series sediment trap, a current meter and a nephelometer moored at the bay mouth station. The mixed coastal and offshore water at the surface of the thermohaline front sinks to a depth of about 200 m in the offshore area.

Keywords:
· Thermohaline front,
· material transport,
· density-driven current,
· sediment trap.

1. Introduction

It is well known that quasi-steady thermohaline fronts develop in the shelf sea area of the northwestern Pacific Ocean during winter (e.g. Yanagi, 1980; Lie, 1985; Yoshioka, 1988). Such a thermohaline front is generated in a transition zone between colder coastal water and warmer oceanic water. Due to cooling through the sea surface during winter, water of moderate salinity in the central region of the shelf sea becomes heavier and sinks there. The colder coastal water cannot become heavy enough to sink due to the inflow of fresh water from the land. Oceanic saline water cannot become heavy enough to sink due to mixing with warm water from the open sea. As a consequence there is little density difference between both sides of the thermohaline front because the salinity difference compensates the temperature difference. The thermohaline fronts exist at nearly the same position in Iyo-Nada and Kii Channel from late autumn to early spring, when the cooling through the sea surface is dominant (Yanagi and Koike, 1987; Yoshioka, 1988).

A remarkable thermohaline front was observed at the mouth of Ise Bay, Japan, during winter (Unoki, 1985; Sekine *et al*., 1992) but its detailed structure and its role in the material transport from Ise Bay to the Pacific Ocean have yet to be disclosed. We report here the detailed structure of a thermohaline front at the mouth of Ise Bay during winter. The role of such a thermohaline front in the transport of suspended matter from Ise Bay to the Pacific Ocean is also discussed, using data from a time-series sediment trap, a current meter and a nephelometer moored at the bay mouth station.

2. Observations

The field observation was carried out in Ise Bay (Fig. 1) by R.V. Tansei-Maru of the Ocean Research Institute, University of Tokyo, from 8 to 12 February 1995. The vertical profiles of water temperature, salinity, chlorophyll *a* (Chl.*a*) and dissolved oxygen (D.O.) from the head of Ise Bay (Stn. I-1) to the offshore region of Ise Bay (Stn. I-10) were observed on 8 and 9 February 1995. The vertical sections of water temperature, salinity, Chl.*a* and D.O. with high horizontal-scale resolution were observed across a thermohaline front (from Stn. IF-2 to Stn. IF-10) from 14:58 to 17:33 on 11 February 1995. Water temperature and salinity were observed by the CTD (Neil Brown Mark III) and Chl.*a* and D.O. were measured by the fluorometer (Turner Design) and by Winkler titration analysis, respectively, after water sampling using a Rosette Multi Sampler which was mounted on the CTD. All of the analyses were conducted on board with no delay after the sampling.

A time-series sediment trap (WHOI Mark V) with a nephelometer (Alec MTB-8M, 940 nm) and a current meter (Aanderaa RCM 4) were set at 118 m and 112 m (shown by a full star in Fig. 3) below the sea surface, respectively, and Knauer-type sediment traps were set at 97 m, 107 m, 128 m, 178 m and 228 m (shown by full triangles in Fig. 3) below the sea surface of Stn. I-9 (the depth was 271 m) above the shelf slope. Data on water temperature, salinity, current velocity and direction were obtained every 5 minutes and turbidity data every 10 minutes. The cup of the time-series sediment trap rotated at the slack water of Irago Strait which was predicted by the Hydrographic Department (see the full triangle in Fig. 1).

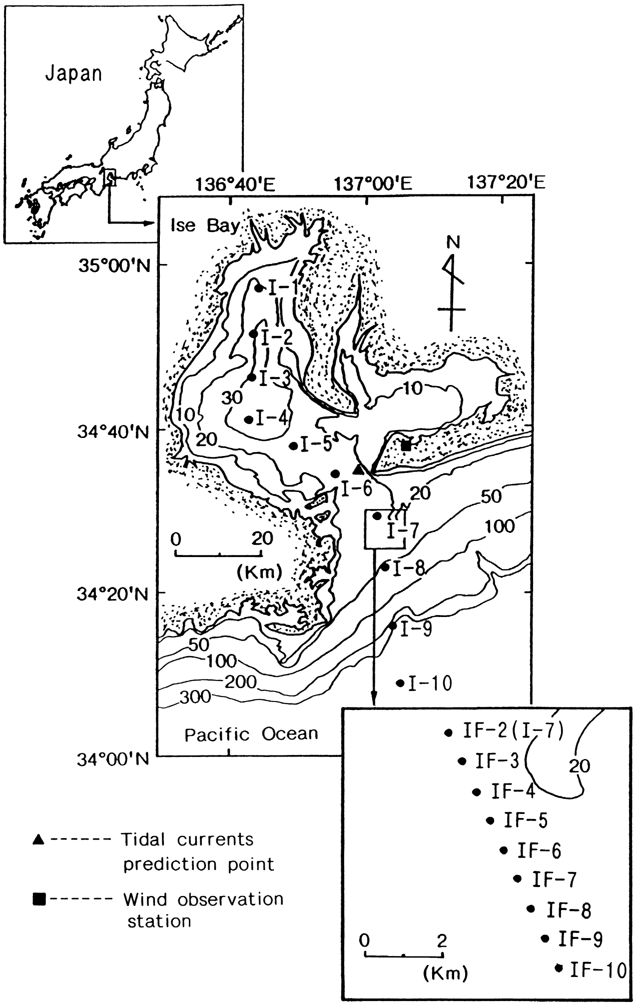

Fig. 1. Observation stations in Ise Bay. Contour numbers show the depth in meters.

3. Results

Figure 2 is a NOAA 12 infrared image, collected at 8:00 JMT on 11 February 1995, which shows the position of the thermohaline front at the mouth of Ise Bay. The thermohaline front, represented by the discontinuity line between cooler coastal water (shown in a gray color) and warmer offshore water (shown in blue and green), runs across the mouth of Ise Bay.

The vertical distributions of water temperature, salinity, density (sigma-t), Chl.*a* and D.O. from the head to the offshore region of Ise Bay are shown in Fig. 3. No data on water temperature, salinity and D.O. were obtained at Stn. I-10 due to instrument malfunction. The water temperature is low in Ise Bay and high out of the bay, and an abrupt change of water temperature from 10°C to 14°C occurs at the mouth of the bay near Stn. I-7. This abrupt change of water temperature corresponds to the thermohaline front at the mouth of Ise Bay. A weak salinity stratification exists in Ise Bay due to the large river discharge from the head of the bay (about 200 m^3s^{-1} in this season) and a such structure affects the density distribution in the bay. The concentration of Chl.*a* is high in Ise Bay and low out of the bay, and an abrupt change occurs at the thermohaline front. It is noteworthy that the coastal water with high Chl.*a* and high D.O. in Ise Bay seems to sink at the thermohaline front and reaches to a depth of 200 m at Stn. I-9. D.O. is supersaturated in the surface layer of Ise Bay, which suggests high activity of photosynthesis by phytoplankton, and is undersaturated out of the bay. The vertical flux of sinking particles is high below 175 m and this corresponds to the vertical Chl.*a* distribution at Stn. I-9 mentioned above.

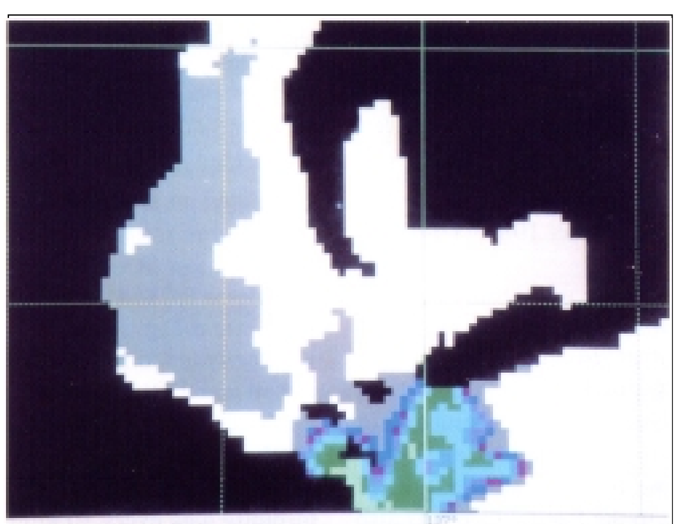

Fig. 2. NOAA 12 infrared image collected 8:00 JMT on 11 February 1995. Grey color denotes the lower water temperature, blue and green higher water temperatures and white the cloud.

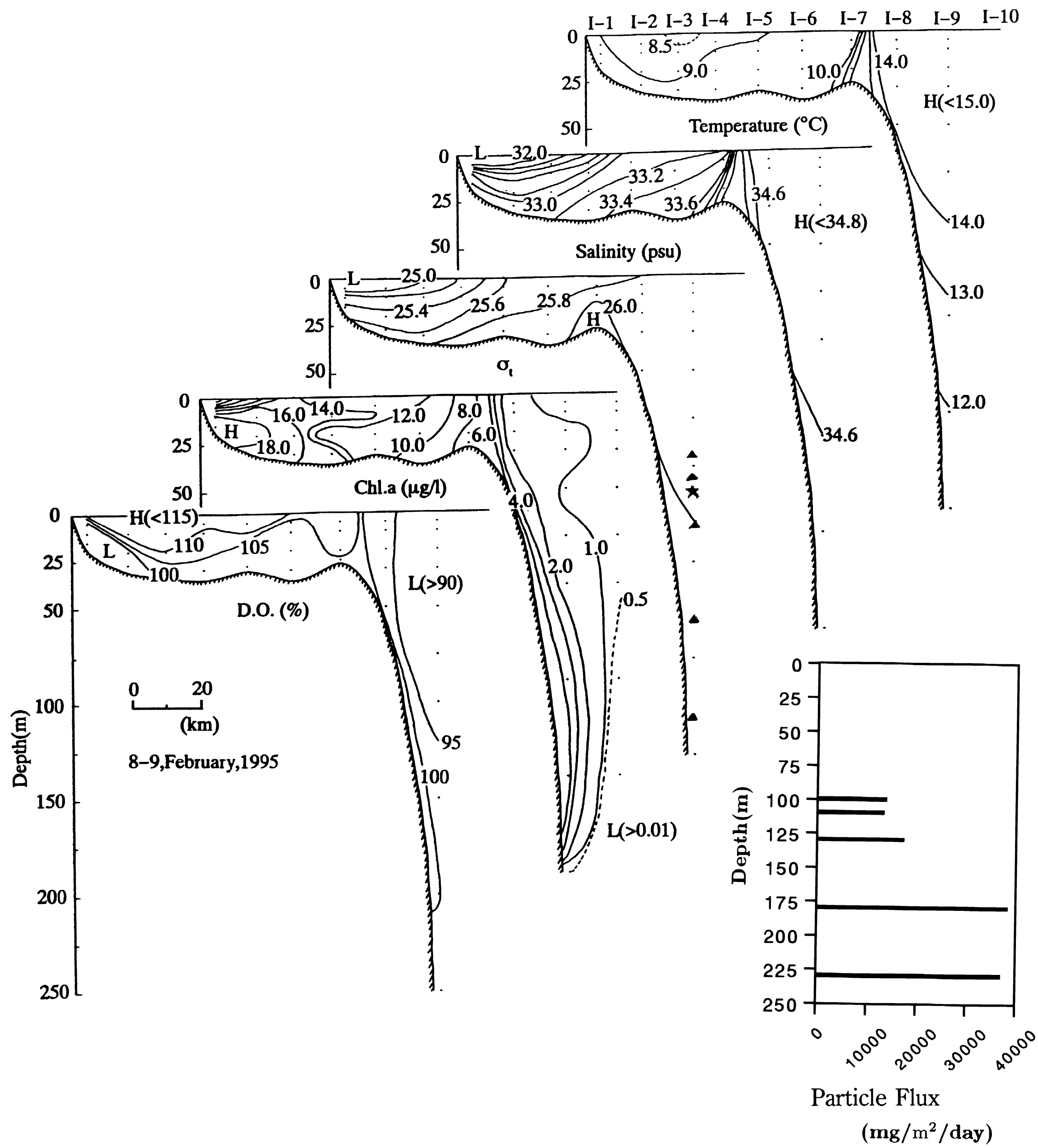

Fig. 3. Vertical distributions of water temperature, salinity, sigma-t, Chl.*a* and D.O. from the head of Ise Bay (Stn. I-1) out of Ise Bay (Stn. I-10) and vertical flux of sinking particles at Stn. I-9. Full triangles in the density section show the positions of Knauer-type sediment traps and full star that of time-series sediment trap.

Figure 4 shows the vertical distributions of water temperature, salinity, density, Chl.*a* and D.O. at high horizontal-scale resolution across the thermohaline front, which is located at Stn. IF-5. Cold and fresh water exists on the nearshore side of the thermohaline front, and warm and saline water lies on the offshore side, but there is little density difference between both sides and the heaviest water exists just below the thermohaline front. The maximum horizontal gradients of water temperature and salinity are 2.5°C/100 m and 0.6 psu/100 m, respectively, across the thermohaline front. The cold-fresh coastal water and the warm-saline offshore water seem to converge in the surface layer at the thermohaline front and the mixed water diverges like a skirt in the bottom layer below the thermohaline front. The concentration of Chl.*a* is high in the nearshore water and low in the offshore water. D.O. is supersaturated in the coastal water and mixed water, and is undersaturated in the offshore water.

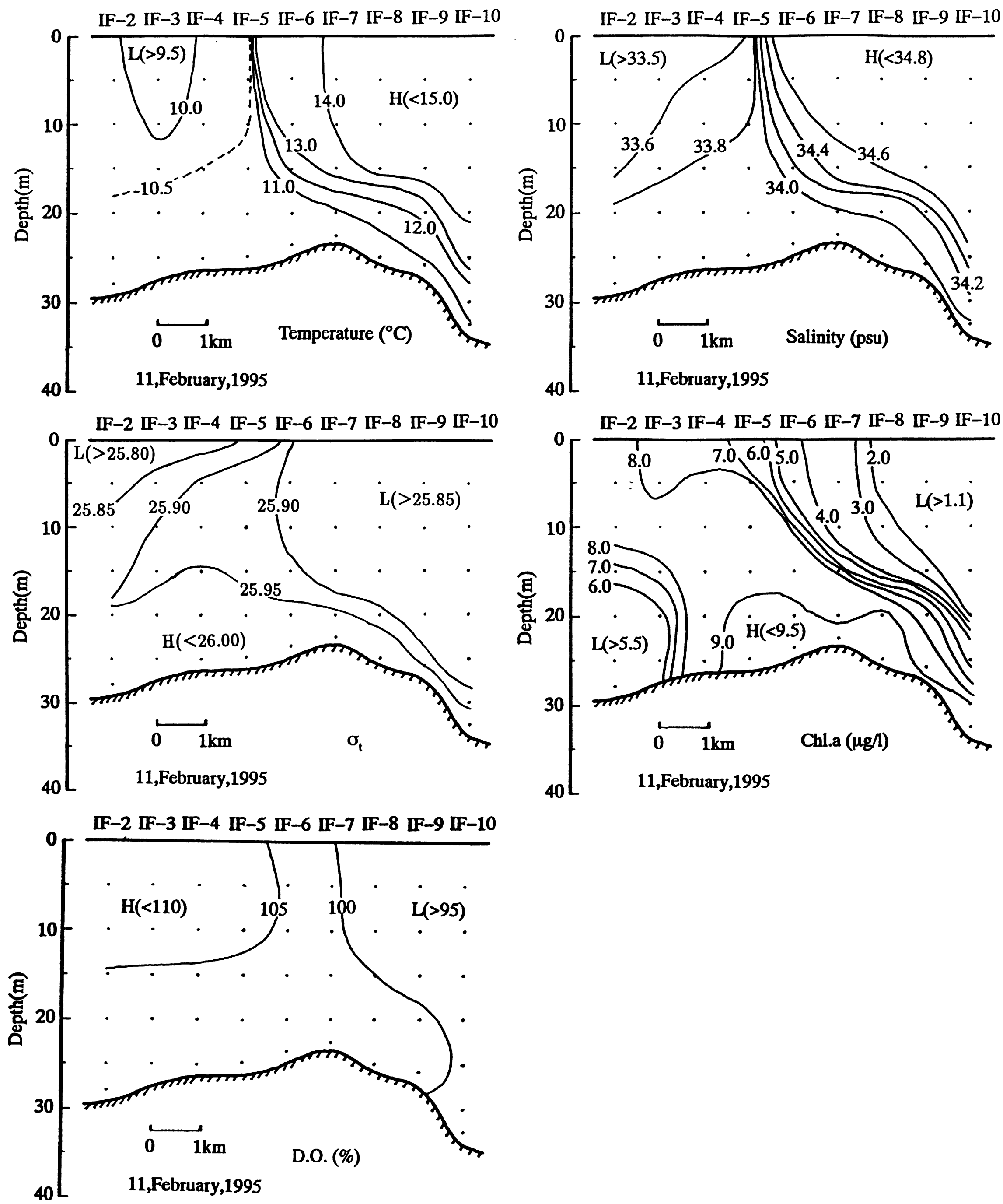

Fig. 4. Vertical distributions of water temperature, salinity, density (sigma-t), Chl.*a* and D.O. across the thermohaline front at the mouth of Ise Bay.

The results from the deployment of the time-series sediment trap at a depth of 118 m at Stn. I-9 are shown in Fig. 5. The vertical flux of sinking particles in the odd-numbered cups is obtained at flood tidal current and that in the even-numbered cups at ebb tidal current, but the tidal signal is not dominant in the current record shown in Fig. 5. The vertical fluxes of sinking particles at cups numbered from 2 to 9, when the northward current prevails, are larger than those at cups numbered from 10 to 11, when the southward current prevails. When the southward current begins around 3 A.M. on 11 February, water temperature suddenly increases and the density decreases. Temporal variation in salinity is very low during this observation period and the turbidity variation does not well correspond to that of particle flux.

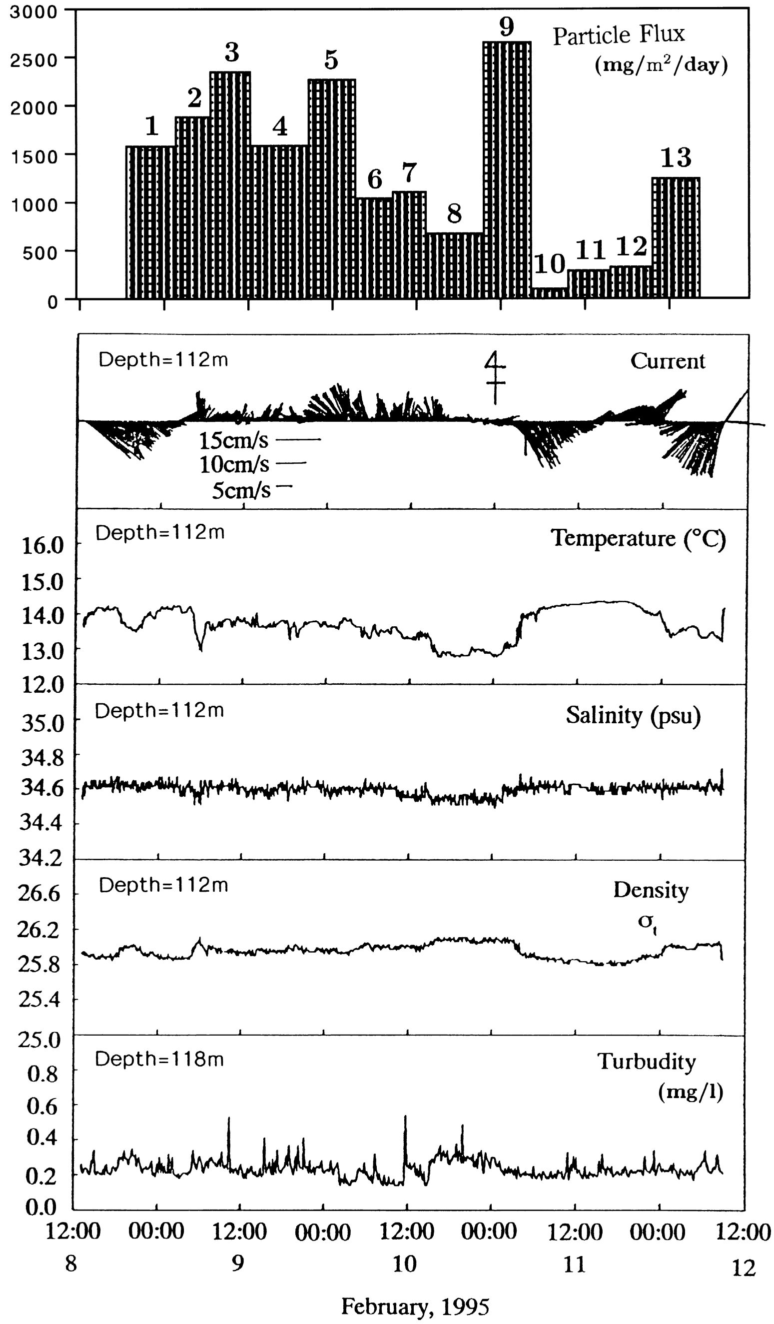

Fig. 5. Results of deployments of time-series sediment trap, current meter and nephelometer 112–118 m below the sea surface at Stn. I-9.

4. Discussion

The T-S diagram of observed water temperature and salinity at Stns. IF-2 to IF-10 and I-9 is shown in Fig. 6. The offshore surface water having high water temperature and high salinity (Stns. IF-6, 7, 8, 9 and 10), and the nearshore surface water having low water temperature and low salinity (Stns. IF-2, 3, 4 and 5) mix at the thermohaline front, and form the heaviest bottom water shown by triangles in Fig. 6 just below the thermohaline front. The nature of this heavy bottom water is nearly the same as that of the water 200 m below the sea surface of Stn. I-9; however, the water 200 m below the sea surface of Stn. I-9 is not generated by vertical mixing of the waters 150 m and 250 m below the sea surface of Stn. I-9 from Fig. 6. This implies that the bottom heavy water at the thermohaline front sinks and intrudes to 200 m depth in the offshore region, as suggested in the Chl.*a* and

D.O. sections shown in Fig. 3.

The bottom heavy water at the thermohaline front in the Kii Channel (Yoshioka, 1988) and that at the mouth of Tokyo Bay (Yanagi *et al*., 1989) sink to about 80 m depth in the offshore region. The bottom water at the thermohaline front of Ise Bay is heavier than the bottom waters in the Kii Channel and at the mouth of Tokyo Bay and sinks to about 200 m depth. This difference may be due to the salinity stratification remaining throughout the winter only in Ise Bay due to large river discharge, as shown in Fig. 3, although salinity in the nearshore region is nearly homogeneous during winter in the Kii Channel (Yoshioka, 1988) and Tokyo Bay (Yanagi *et al*., 1989) due to a small river discharge. The sinking water from the surface layer at the thermohaline front of Ise Bay may become heavy at the bottom due to mixing with the surrounding saline water existing below the thermohaline front, as shown in Figs. 3 and 4.

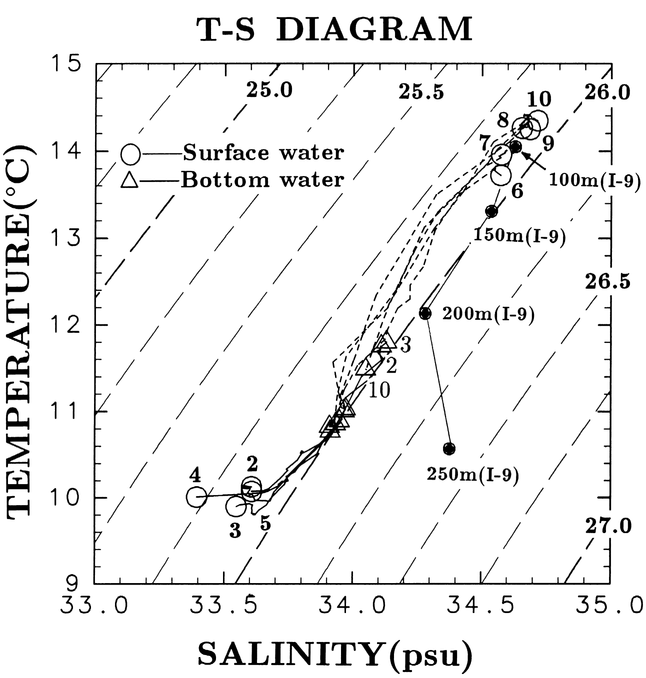

Fig. 6. T-S diagram of observed water temperature and salinity at Stns. IF-2–IF-10 and Stn. I-9.

The temporal variation in hourly wind vector at the Irago peninsula (see full square in Fig. 1), which was observed by the Japan Meteorological Agency during our observation period is shown in Fig. 7. A strong southeastward wind with a speed of about 10 m s^{-1} blew on 6, 7 and 10, 11 February and the southeastward current occurred 112 m below the sea surface at Stn. I-9 on 8 and 11 February, as shown in Fig. 5, about a day after such a strong southeastward wind blew. When the wind was weak, a weak northward flow appeared 112 m below the sea surface at Stn. I-9. After the beginning of southeastward flow at about 3:00 on 11 February, water temperature increased, density decreased and the vertical flux of sinking particles decreased, as shown in Fig. 5. On the other hand, after the northeastward current stopped at about 0:00 on 12 February, water temperature decreased, density increased and the vertical flux of sinking particles increased at the depth of about 110 m of Stn. I-9.

These facts suggest that the current and water characteristics at the depth of about 110 m of Stn. I-9 were affected by the wind blowing and that the intrusion of mixed water at the thermohaline front to the depth of about 200 m was not steady but rather an intermittent phenomenon. The strong southeastward wind may be related to the development of gravitational circulation in Ise Bay, and may result in the supply of saline offshore water to the bottom layer of the thermohaline front and the formation of a heavy bottom water mass below the thermohaline front. On the other hand, during the weak wind, the gravitational circulation in Ise Bay may not be not developed, the heavy water mass may not be formed at the bottom of thermohaline front and the deep intrusion of mixed water to the depth of 200 m may not occur. Both observations at the mouth of Ise Bay shown in Figs. 3 and 4 were carried out on 8 and 11 March, respectively, just after the strong southeastward wind blew.

It remains for us to conduct consecutive field observations around the thermohaline front at the mouth of Ise Bay and three-dimensional numerical experiments to give a quantitative clarification of the relation among the wind

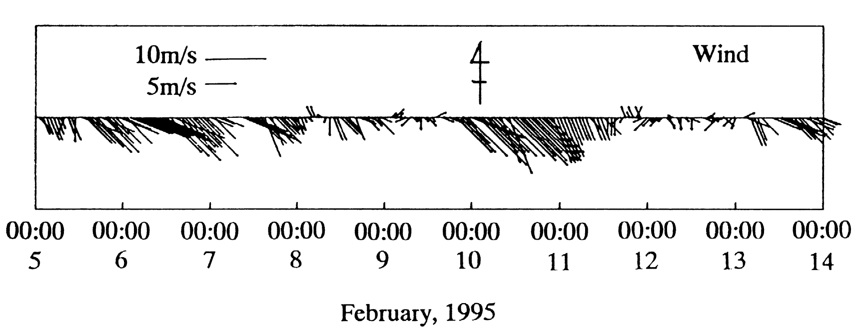

Fig. 7. Temporal variation in hourly wind vector at the Irago peninsula (observation station is shown by full square in Fig. 1).

blowing, the development of gravitational circulation, the formation of heavy water mass at the bottom of thermohaline front, and the intrusion of mixed water to the depth of about 200 m out of the mouth of Ise Bay in the near future.

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