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Open-ocean convection in the Japan (East) Sea

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Abstract: Based on the results of Marine Meteorological and Oceanographical Observations by Japan Meteorological Agency during 1966–1987, the phenomenon of open-ocean convection is found as a candidate for the formation of the Japan (East) Sea Proper Water (JSPW). The water types in the mixed regions denoting the deep convection are similar to those of the JSPW such as 0–1℃ in potential temperature, 34.0–34.1 ‰ in salinity and 68–80 cl/t in potential thermosteric anomaly from the sea surface to the deep layer. The static stabilities in the stations of the mixed regions are unstable or neutral. The phenomena of open-ocean convection are commonly observed in the area of the north of 40° N. This suggest that the deep water of JSPW is formed not in a limited area but probably in the overall region of the northern open ocean. The formation of the deep water may be mainly affected by the cooling of the sea surface because the temperature and salinity on the isoteric surface of about 76 cl/t in potential thermosteric anomaly are cold and low. The JSPW sunken from the surface layer on the mixed region spreads out under the Tsushima warm current area, following the isoteric surface of about 76 cl/t in potential thermosteric anomaly.

1. Introduction

The Japan (East) Sea is called a mini ocean because of the varieties of oceanological aspects due to the basins deeper than 2000 m depth and the connectors with other seas through narrow straits shallower than 150 m depth. These characteristics hinder the exchange of deep waters and contains a peculiar deep waters, the Japan (East) Sea Proper Water. Many authors explained that there must be exist the deep convection in the interior of the Japan (East) Sea (e.g., NITANI, 1972; GAMO *et al.*, 1986; SUDO, 1986).

The deep water is formed by two ways, the open-ocean and near-boundary convections. During the open-ocean convection, the homogeneous water column from the sea surface to a deep layer, so called chimney, and the cyclonic eddy had been observed in the Mediterranean (MEDOC group, 1970), Labrador (CLARKE and GASCARD, 1983), Greenland (JOHANNESSEN *et al.*, 1991) and Weddell Seas (GORDON, 1978).

MEDOC group (1970) suggested that the open-ocean convention takes three phases; namely, the preconditioning phase, the violent mixing phase, the sinking and spreading phase. The chimney is formed in the second phase and accompanied with cyclonic eddy and it also affects the sinking and spreading phase (GASCARD, 1991).

SENJYU and SUDO (1993, 1994) inferred the winter convection through the isopycnal analysis and water characteristics in the Japan (East) Sea. SEUNG and YOON (1995) showed the deep convection in the Japan (East) Sea. They explained that winter convection reaching down to about 1000 m depth takes place near Vladivostok, Russia. But the data for the distributions of temperature or salinity are not all occupied in every cruise, and the data was checked and chosen. Of course, it does not make a problem, but we want to know more about the deep convection in the Japan (East) Sea exactly.

Therefore, we set a question that 'Does an open-ocean convection really take place in the Japan (East) Sea ? ' The purpose of this study is to find out the evidence of open-ocean convection in the Japan (East) Sea.

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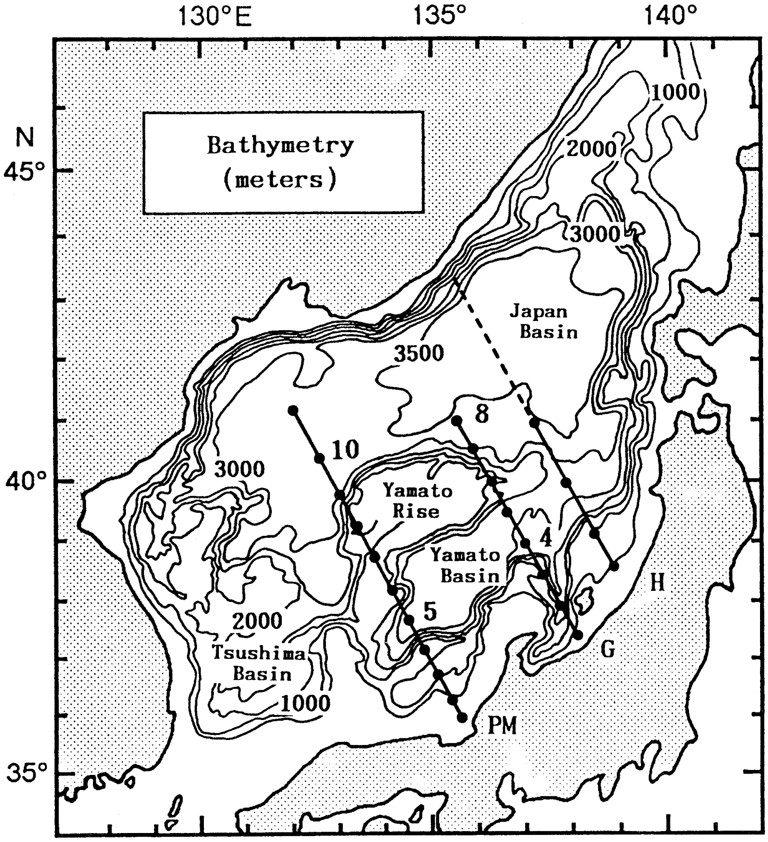


Fig. 1. Bathymetry and studied lines.

2. Data and Approach

The comprehensive observations for the Japan (East) Sea have been conducted by the Japan Meteorological Agency systematically and those data are available for studying the water characteristics to a deep layer in the Japan (East) Sea. So, the results of marine meteorological and oceanographical observations by Japan Meteorological Agency were used from 1966 to 1986 for about 22 years. But the observations were mostly occupied in the southeast part of the Japan (East) Sea. In the northwest part, the observations were scarce and there were also areas of no observations.

To see the water properties, the vertical distributions of potential temperature, salinity and potential thermosteric anomaly was presented for the lines shown in Fig. 1. These three lines, PM, G, H were selected for detailed analysis because these lines lie across the polar front to the northern part. In Fig. 1, the dotted line indicates that the observation was carried out during Coorperative Study of Kuroshio but is not conducted at present. The number of stations and the distances between the stations in lines of PM, G, H are somewhat different from year to year.

Potential thermosteric anomaly (Δ_θ) was used instead of sigma-theta (σ_θ). The Japan (East) Sea Proper Water is very homogeneous in temperature and salinity. So, potential thermosteric anomaly is more convenient to distinguish the density difference than sigma-theta because it does not need to express the decimal point in density. With the potential thermosteric anomaly, the static stability was calculated in some hydrographic stations following POND and PICKARD (1983) as

$$E = \frac{1}{\alpha} \frac{\partial \Delta_\theta}{\partial z}$$

where α is the specific volume, Δ_θ the poten-

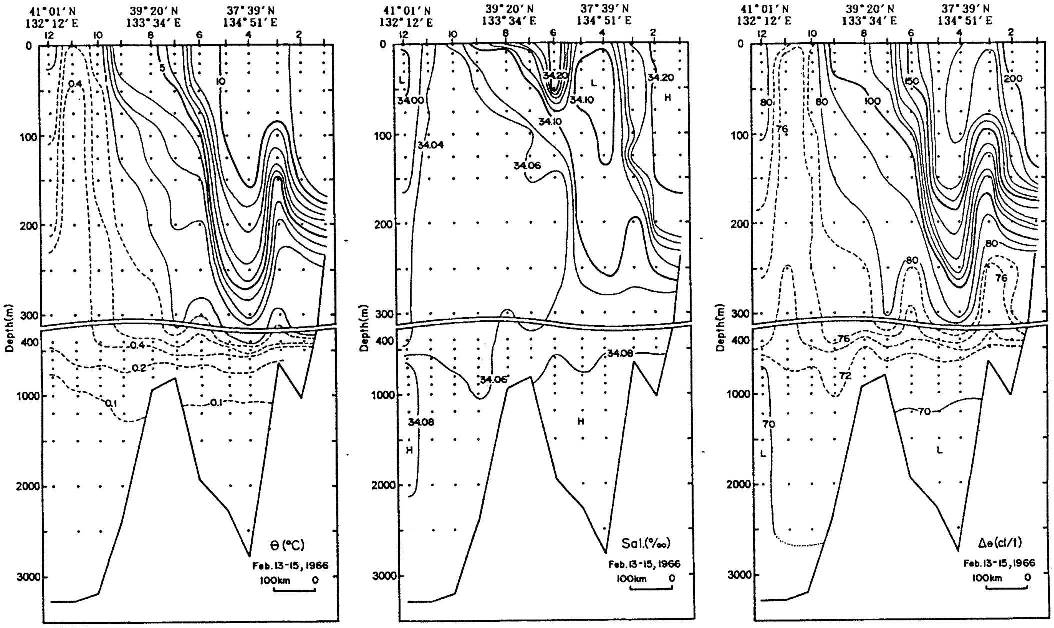


Fig. 2. Vertical distributions of potential temperature (right), salinity (middle) and potential thermosteric anomaly (left) for line PM in 1966.

tial thermosteric anomaly and z the depth interval. Also, horizontal distributions of potential temperature, salinity were presented for the isosteric surface which is denoted the characteristics of the Japan (East) Sea Proper Water. The proper value of the potential thermosteric anomaly on the isoteric surface was chosen from the T-S plots during winter from 1996 to 1987.

3. Results

3-1 Occurrence of Open-ocean Convection

Fig. 2 shows the vertical distributions of potential temperature, salinity and potential thermosteric anomaly in line PM on Febuary, 1966. The potential temperature and potential thermosteric anomaly of station 11 are lower than those of stations 10 and 12. In station 11, from the sea surface to about 400 m depth, it can be seen the nearly homogenous water column with below 1℃ in potential temperature, about 34.02–34.06 ‰ in salinity and below 80 cl/t in potential thermosteric anomaly. Salinity becomes low from the south (34.20 ‰) to the north (34.00 ‰) of station 11.

Fig. 3 is the vertical distributions of potential temperature, salinity and potential thermosteric anomaly for line H in 1966. In station 26, it shows the homogeneous water column whose characteristics of water properties denotes the Japan (East) Sea Proper Water. It is noteworthy that 72 cl / t in potential thermosteric anomaly is distributed from the sea surface to about 500 m depth in station 26.

Fig. 4 is the same one as the previous figures except for line G in 1986. In station G8, we can see the outcropping of isothermal line, isohaline and isostere, which denote the characteristics of the Japan (East) Sea Proper Water below 1℃ in potential temperature, 34.08 ‰ in salinity and 76 cl/t in potential thermosteric anomaly. Although we could not show the complete shape of homogeneous water column embedded in more stratified waters due to the limit of the measurement to the north, it also may be shown the homogeneous water column if the observation was performed to the northern part.

The vertical distributions of potential temperature and potential thermosteric anomaly are illustrated in Fig. 5, which shows the homogeneous water column and outcropping. The homogeneous water column appeared in station 21 on February in 1967. In station 39 in

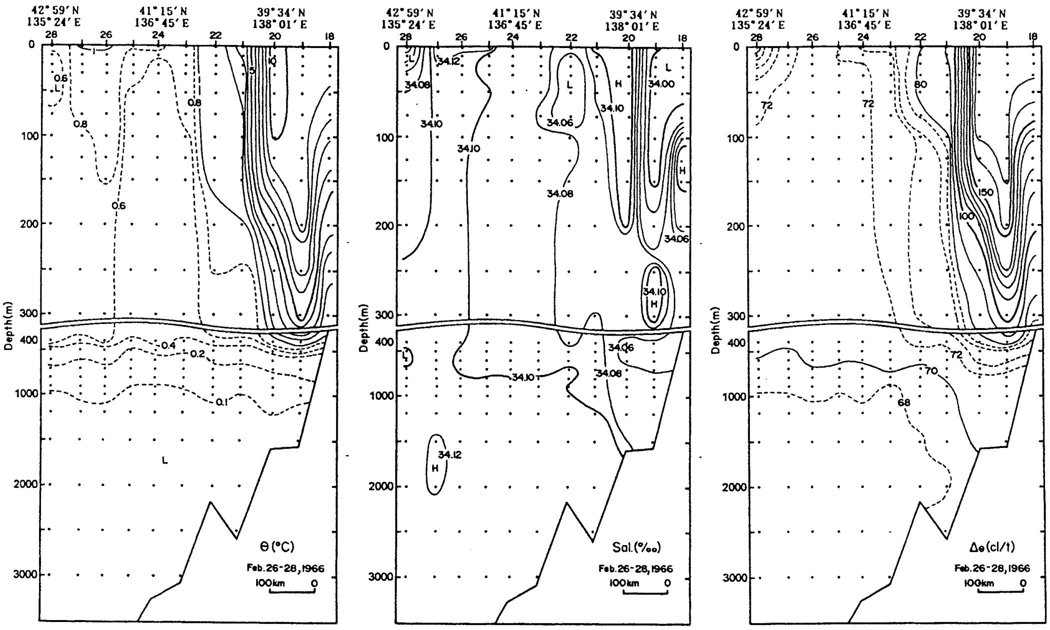


Fig. 3. Vertical distributions of potential temperature (right), salinity (middle) and potential thermosteric anomaly (left) for line H in 1966.

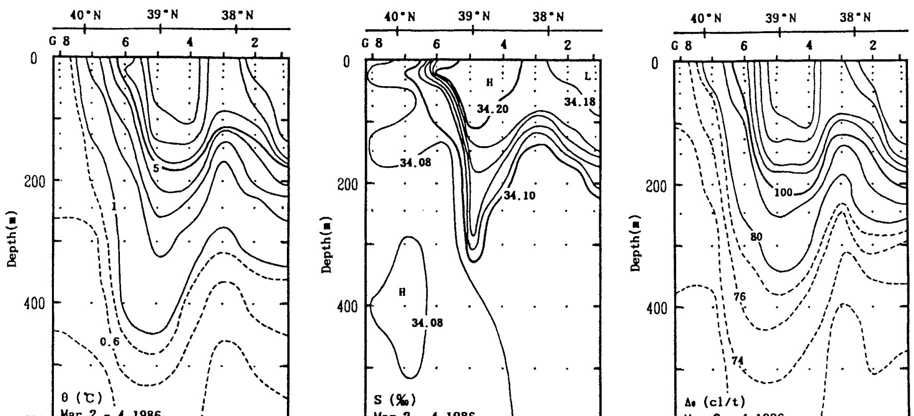


Fig. 4. Vertical distributions of potential temperature (right), salinity (middle) and potential thermosteric anomaly (left) for line G in 1986.

1969 and stations from 35 to 38 in 1970, the potential thermosteric anomalies are lower than 74 cl/t, in particular, from the sea surface to below 600 m depth.

In order to see the trace of the cyclonic eddy in the stations of homogeneous water columns and outcroppings, we plotted the dynamic depth anomaly on 1966A, 1966B, 1967A, 1967B in Fig. 6 because the complete shape of homogeneous water column were shown in these lines. Arrows denote the centre of the homogeneous water column. The values of dynamic depth anomalies in the centre of the homogeneous water columns are lower than those of the others. We can deduce the existence of the cyclonic–eddy vaguely.

Fig. 7 shows the positions of homogeneous water column and outcropping during last 22 years. Solid circles denote the homogeneous water column and open circles the outcrop-

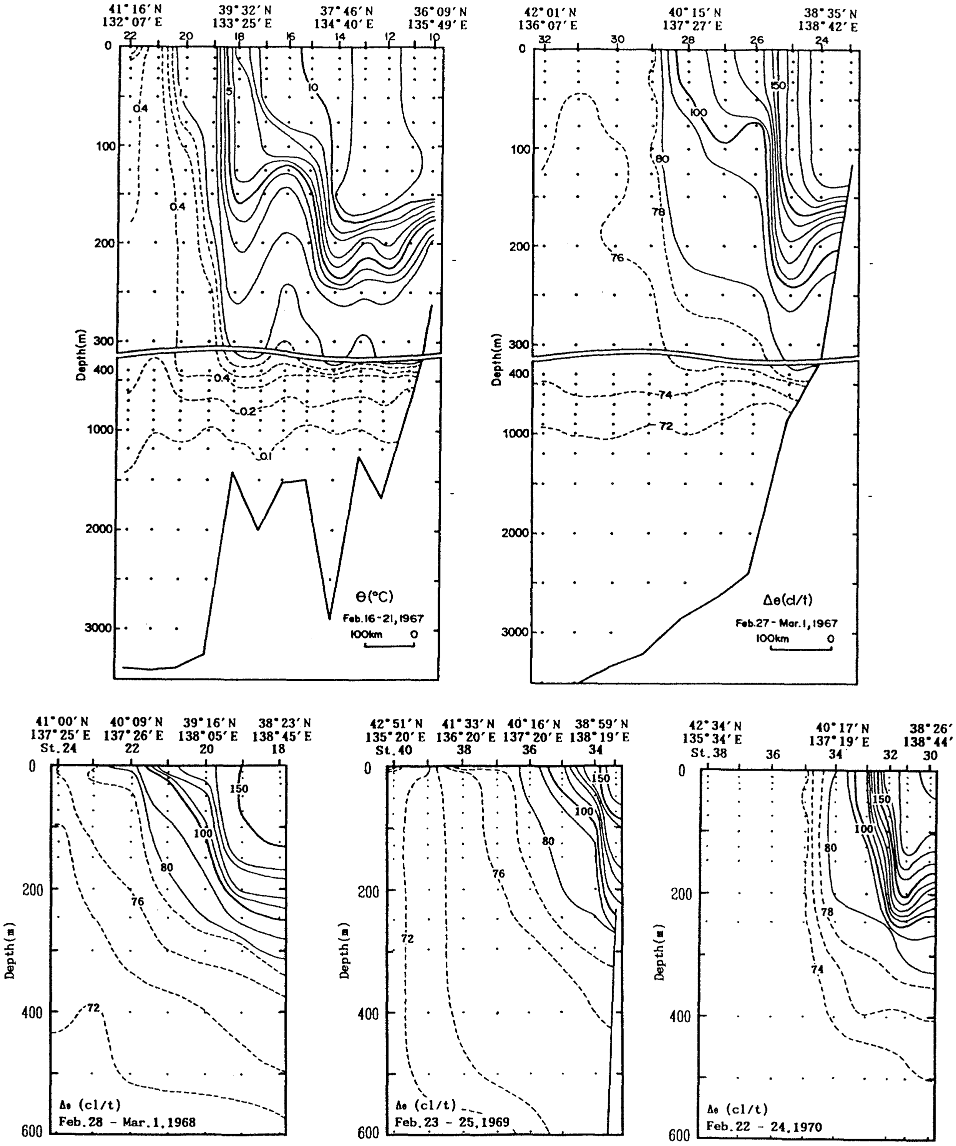


Fig. 5. Vertical distributions of potential temperature for line PM in 1967, potential thermosteric anomaly for line H in 1967, 1968, 1969, 1970, 1972 and 1974 and for line PM in 1975 and 1981, respectively.

ping. The homogeneous water column and outcropping occurs here and there in the northern part. We know that these are not all. If the data covered the northern part, it would be able to find out the phenomenon of open-ocean convection in the area.

Fig. 8 represents the static stabilities of stations for the homogeneous water column and outcropping. The static stabilities are generally unstable or neutral in the surface layer. Below 200 m depth, the static stabilities are neutral in all stations. With this figure, we know that the deep convection will be take place in these stations.

3-2 Spreading Features

In order to choose the proper value of the isosteric surface and to see the distributions of

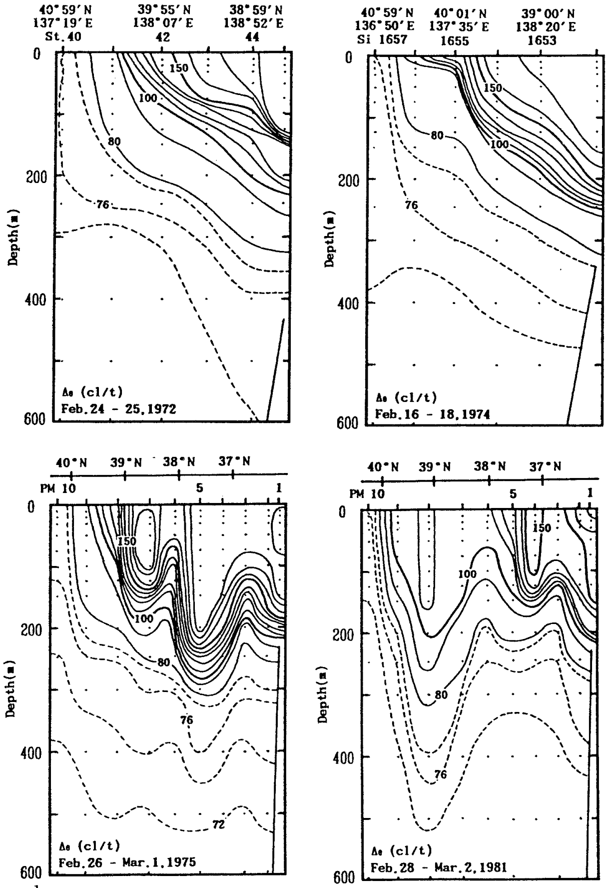


Fig. 5. Continued

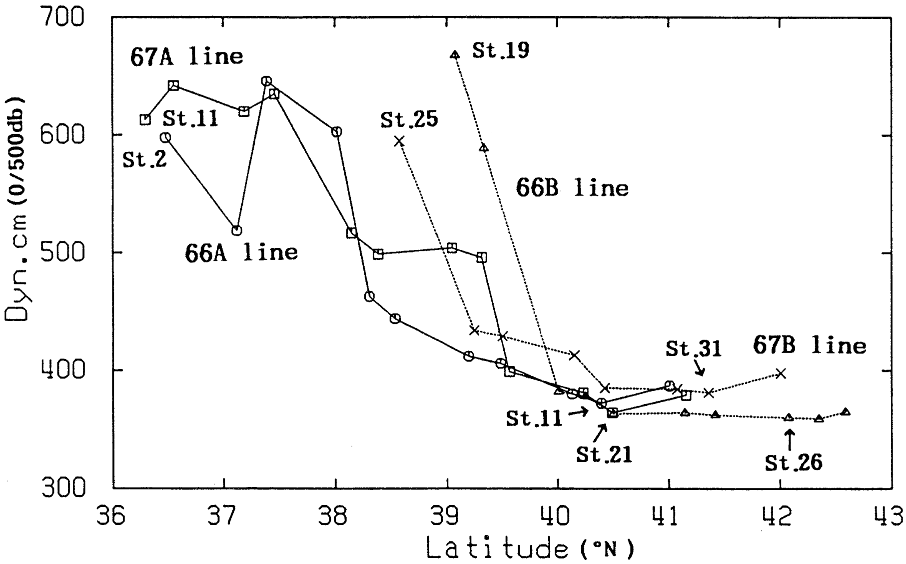


Fig. 6. Dynamic depth anomaly at the sea surface based on the 500 db of the 1966A, 1966B, 1967A and 1967B. A and B denote the line PM and H, respectively. Arrows indicate the stations showing chimney-type.

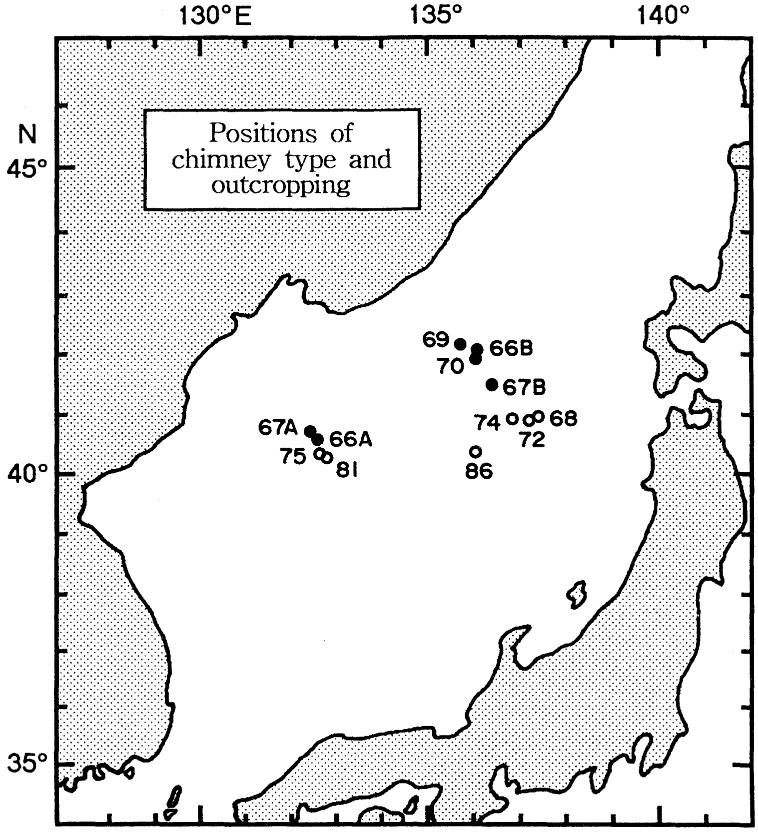


Fig. 7. Positions of chimney-type (solid circles) and outcroppings (open circles) in winter during 1966–1987.

the water properties on the isosteric surface, we plotted T–S diagrams in winter during last 22 years in Fig. 9. All water types of the Japan (East) Sea Proper Water are plotted between about 70 cl/t to about 80 cl/t in potential thermosteric anomaly. To see the horizontal distributions of the water properties on the isosteric surface, the value of 76 cl/t in potential thermosteric anomaly is the most proper. So we drew the horizontal distributions of depth, potential temperature and salinity on the isosteric surface of 76 cl/t. Although it can not be scrutinized the flowing path following the isosteric surface, the shape of spreading may be shown in those figures.

Fig. 10 shows the depth where potential thermosteric anomly equals to 76 cl/t. The isosteric surface of 76 cl/t come in contact with the sea surface in 1996, 1967, 1969, 1970, 1981 and 1986. In the case of 1966, 1967 and 1969, the isosteric surface contacted with the sea surface looks like an eddy shape. The isoteric surface of 76 cl/t becomes deep to the south below 400 m depth.

Fig. 11 and Fig. 12 show the potential temperature and salinity where potential thermosteric anomaly equals to 76 cl/t. Hatched area denote the surface below 76 cl/t in those figures. The potential temperature is below about 0.4–0.8℃ in the north. It becomes high to the south about 0.8–1.0℃. On the sea surface the salinity of the northern part is lower than those of the southern part.

Fig. 13 shows some aspects of spreading. The upper denote the positions of stations and vertical distribution of potential thermosteric anomaly in the case of 1967. The lower denotes the T–S relation according to the sea surface and the depth. Crosses denote the T–S relation of the sea surface from the station 13 of the

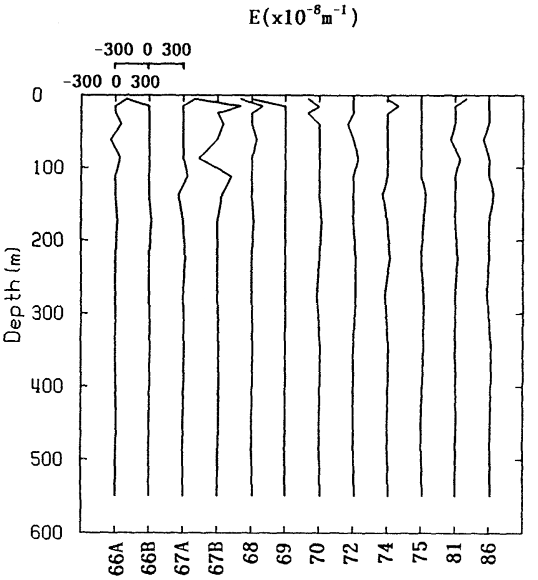


Fig. 8. Static stabilities of the stations in chimney-type and outcroppings. Numerals denote the year, A and B the line PM and H, respectively.

south to the station 21 of the north, circles the T-S relation with the depth in the station 13. If the water formed by the open-ocean convection in the northern part spreads out under the Tsushima Warm Current area following the isosteric surface, the water types between the sea surface of the northern part and the deep layer one of the southern part will agree with each other. In this diagram, both the water type of the sea surface of the station 21 and the water type of about 600 m depth of the station 13 agree well with each other.

4. Discussion

MEDOC group (1970) explained the violent mixing phase that narrow region of deeply penetrative convection occurs in the centre of the gyre. The central mixed region in the second phase is so narrow that the horizontal scale is merely about a few tens of kilometers (MEDOC group, 1970 ; GASCARD, 1991).

The homogeneous water column from the sea surface to a deep layer indicates the well mixed water (c.f., Fig. 2) and may be regarded as the deep water formation (Fig. 8, Fig. 13). When the cooled surface water sinks it is replaced by warmer water from the sides. As

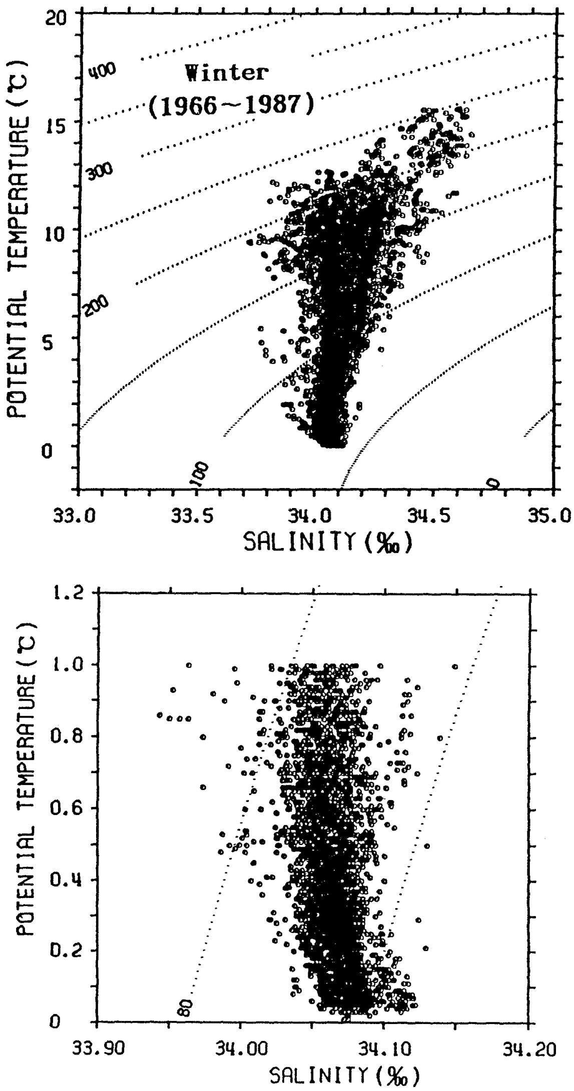


Fig. 9. T-S diagrams (upper) and the enlarged T-S plot for the Japan Sea Proper Water (lower) in winter during 1966–1987.

cooling continues the entire water column is gradually mixed with new water masses from the surface (SANDVEN *et al.*, 1991).

The homogeneous water columns embedded in more stratified waters and outcroppings occurred here and there of the area in the north of 40° N (Fig. 7). This suggests that the deep water of the Japan (East) Sea Proper Water is formed not in a limited area but probably in the overall region of the northern open ocean.

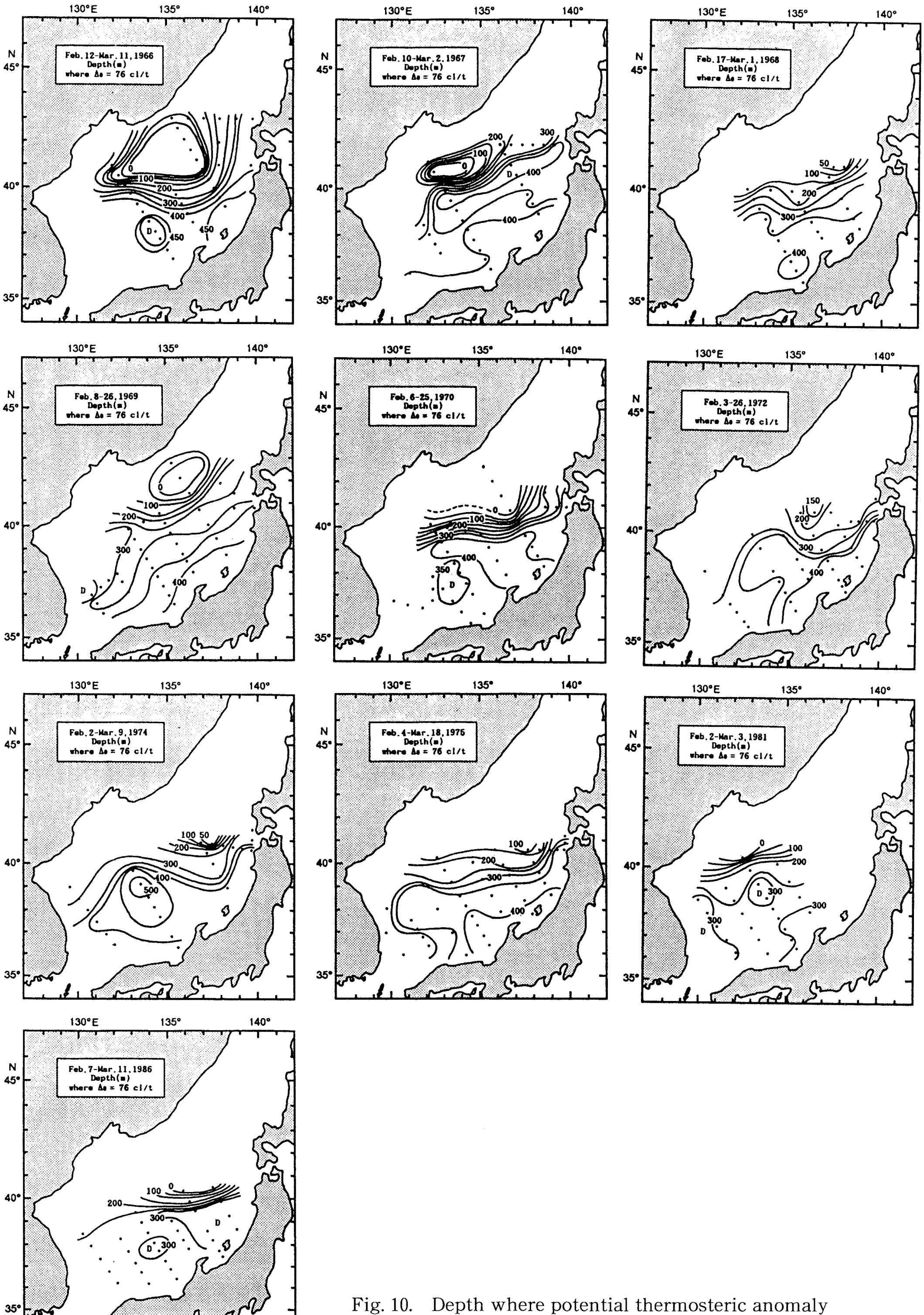


Fig. 10. Depth where potential thermosteric anomaly equals to 76 cl/t.

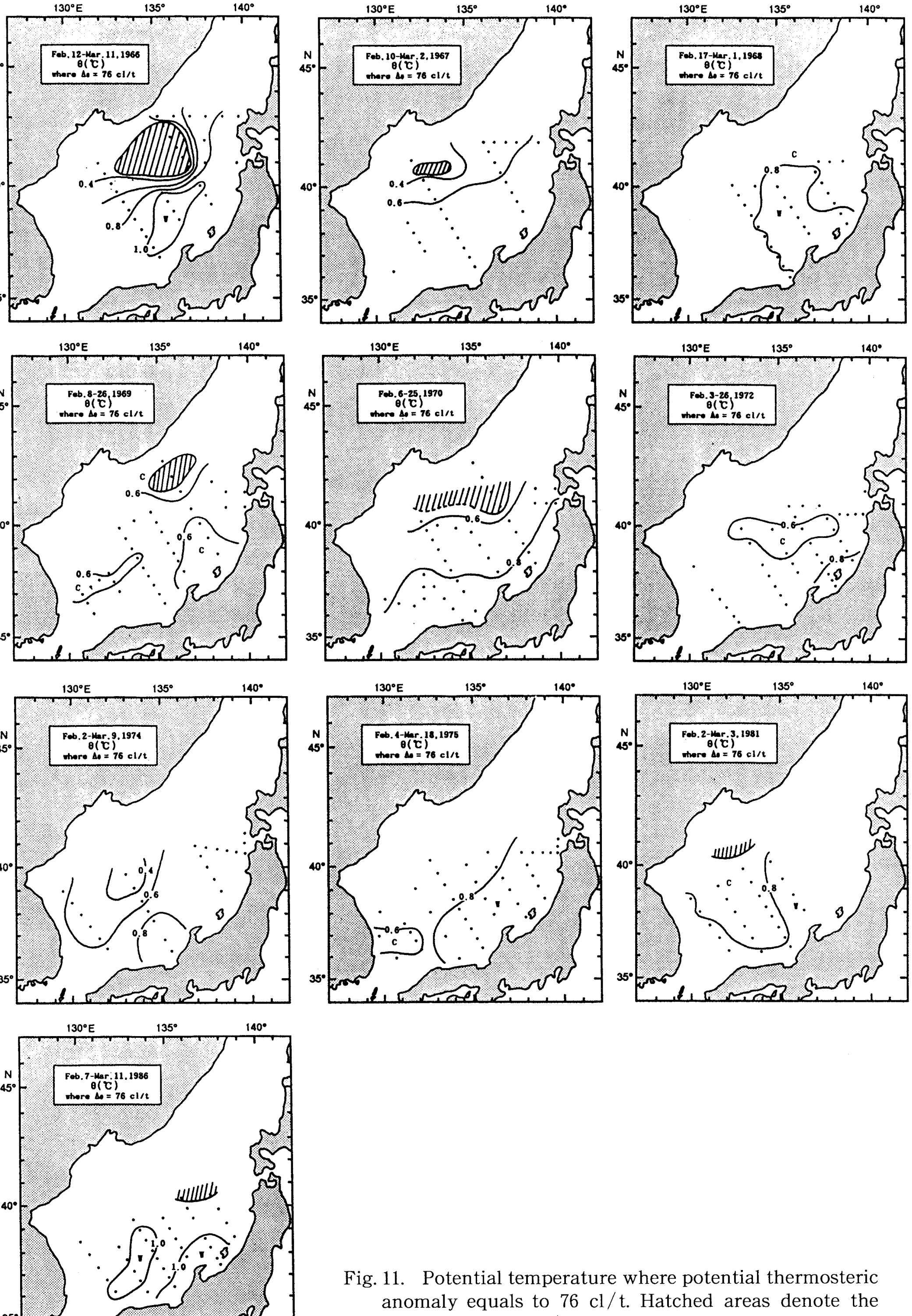
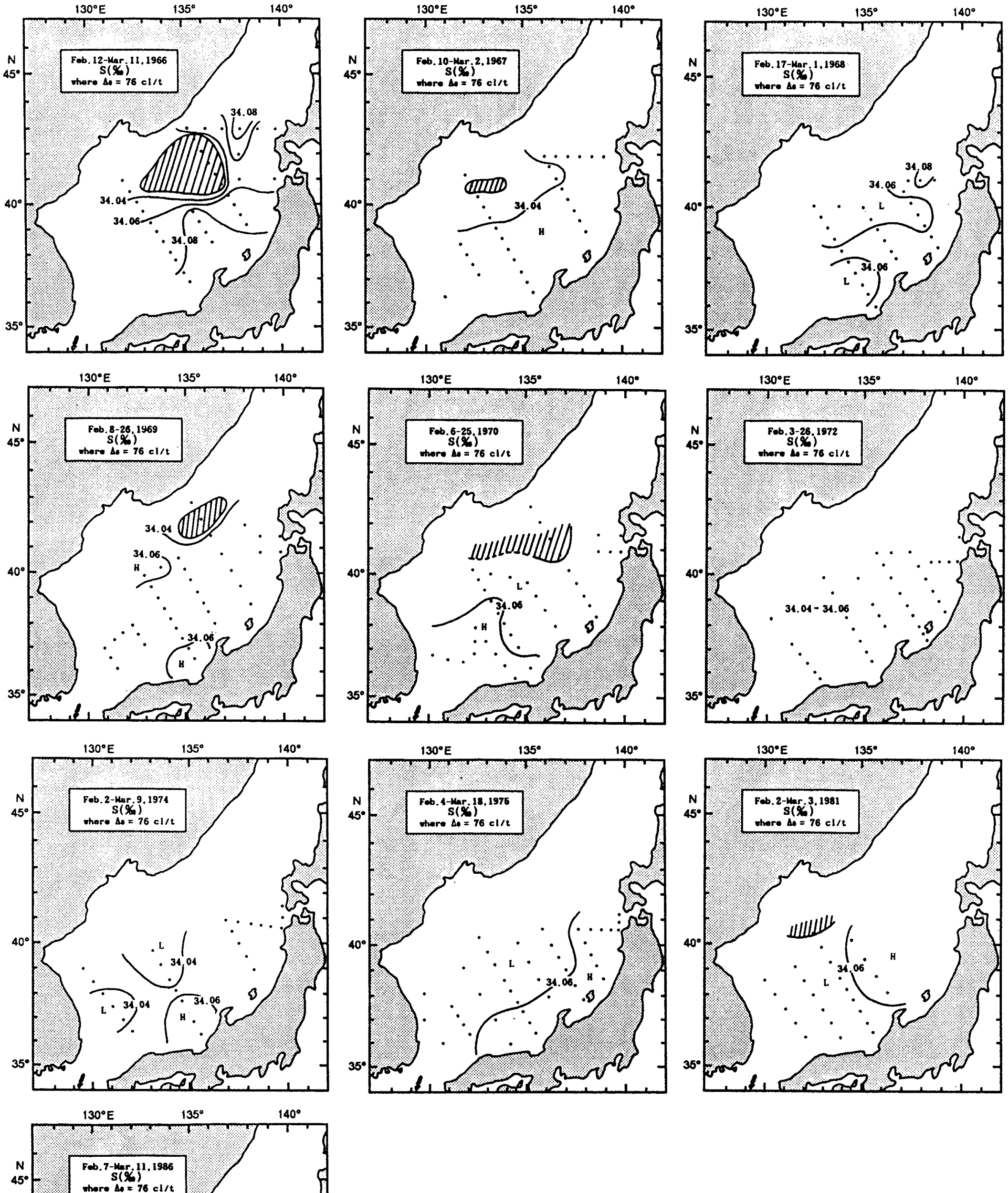


Fig. 11. Potential temperature where potential thermosteric anomaly equals to 76 cl/t. Hatched areas denote the surface below 76 cl/t.



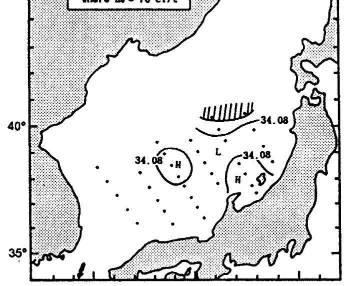
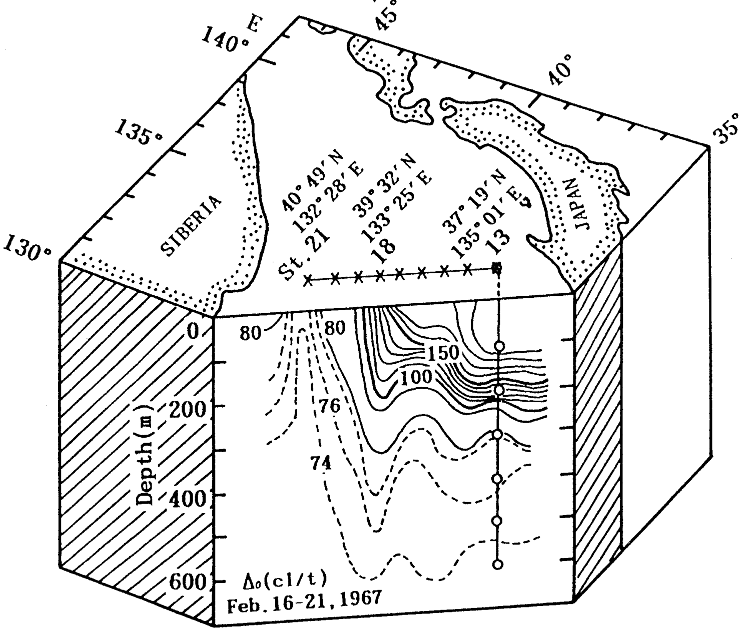


Fig. 12. Salinity where potential thermosteric anomaly equals to 76 cl/t. Hatched areas denote the surface below 76 cl/t.



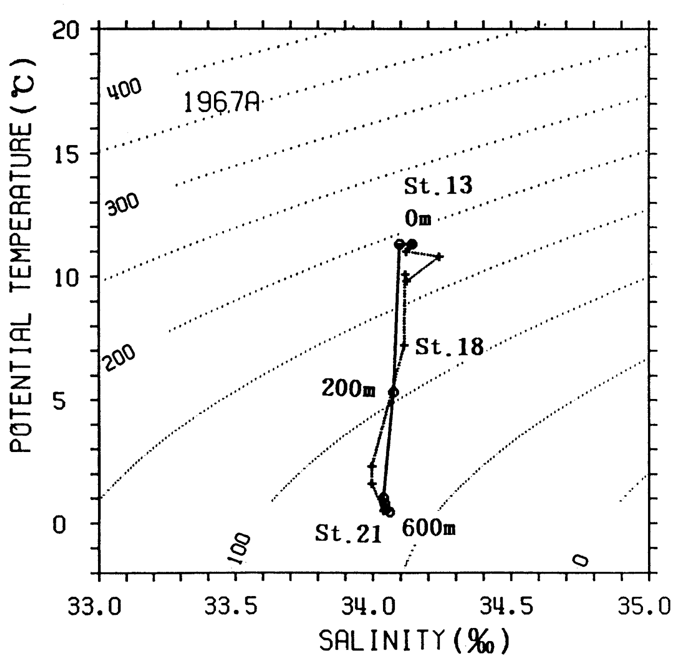


Fig. 13. Station map and vertical distribution of potential thermosteric anomaly (upper) and vertical T-S relations in the station 13 and horizontal T-S relations from the station 13 to the station 21 on the sea surface (lower) for line PM in 1967.

VASILEV and MAKASHIN (1992) reproduced the ventilation of the Japan Sea waters in winter with their quasi-stationary friction model and explained that bottom waters are periodically replenished by shelf waters, sinking down along the continental slope of Primorye. So, both open-ocean and near-boundary convections can be taken place in the Japan (East) Sea. Deep Waters are formed by the open-ocean convection and bottom waters may be formed by the near-boundary convection. The near-boundary convection probably occurs in the Siberian coast (NITANI, 1972; GAMO *et al.*, 1986; SUDO, 1986; VASILEV and MAKASHIN, 1992).

The horizontal scales of mixed regions at the sea surface are about 80 km (Fig. 2) and 300–400 km (Fig. 3) with the value of 76 cl/t in isostere. The horizontal view of mixed regions seems to be an eddy shape (c.f., Fig. 10). UDA (1934) pointed out that there is (are) one or two large-scale cyclonic gyre (gyres) and the Japan (East) Sea Proper Water exists directly under the surface layer in the northern Japan (East) Sea. GAMO and HORIBE (1983) and GAMO *et al.* (1986) stated that cold and oxygen-rich surface water is supplied to the deep water frequently and rapidly. Therefore, in the Japan (East) Sea it may be suggest with care that the primitive formation and the beginning aspect of central mixed region in the open ocean are somewhat different from other oceans in its scales, etc.

KILLWORTH (1979) explained that baroclinic instability of the mean flow is capable of producing cyclonic and anticyclonic eddies with horizontal length scales of the same width as the observed chimneys. At the centre of the cyclonic eddies, the vertical stratification is greatly reduced in the top 300 m, thus acting as an efficient preselection mechanism at the onset of winter cooling. According to GASCARD (1991), these chimneys appear at the places where overall stratification can be destabilized and destroyed from the interior rather than from the surface. And a much more efficient way for mixing water over great depth is when a subsurface layer is injected from below into the surface layer by a baroclinic instability process. As mentioned above, the Japan (East) Sea has peculiar characteristics with one or two gyre (gyres) and very thin surface layer in the northern part. So, the open-ocean convection in the Japan (East) Sea may occur in scales larger than those of other oceans.

Not only a study but also an observation on the configuration of chimney is required for the Japan (East) Sea in near future.

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