FORMATION OF THE INTERMEDIATE WATERS OF THE JAPAN SEA

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Introduction

The Japan Sea concerns to the marginal seas of a Mediterranean type. Due to the shallow straits connecting the Japan Sea to the neighbor pools it in many respects can be considered isolated, mediterranean. Low temperature of water (less than 1 °C) and the high concentration of the dissolved oxygen (about 70% from saturation) intermediate and deep waters is explained by many authors of intensive vertical circulation and absence of water exchange with deep waters of the Pacific Ocean.

The active layer of the Japan Sea (top 200-300 m) is divided into two climatic areas, from which southern and southeastern parts are much warmer than northern and northwestern. Salinity at coast of Japan also is higher, than in northern part and at Primorye coast. The antagonism of warm and salty currents (Tsushima Current and East Korean Warm Current) with cold and fresh (Liman Current and North Korean Cold Current) forms cyclonic circulation and Subpolar Front with an abundance of mesoscale structures.

The detailed structural description of intermediate waters is given in works (Kim & Kim, 1999; Senjyu, 1999; Kim & Seung, 1999; Yoshikawa *et al.*, 1999). The authors discuss formation of a minimum and maximum salinity. Obviously, their formation is closely connected not only with general circulation of the Japan Sea, but also with vertical mixing.

Two basic mechanisms of renewing of intermediate and deep waters now are considered. One of them is downwelling of shelf waters along the continental slope of Primorye with subsequent advection (Vasil'ev & Makashin, 1991; Noh *et al.*, 1999). Other way is winter convection in northern and northwest part of the Japan Sea (Leonov, 1960; Panfilova, 1961; Fukuoka, 1965; Pokudov *et al.*, 1976; Fukuoka & Misumi, 1977; Kim & Chung, 1984; Senjyu & Sudo, 1994; Seung & Yoon, 1995; Wakatsuchi, 1996). The majority of the authors specify, that convection will penetrate deeper than 1000 m. By a discord of previous works the statements S.C. Riser *et al.* (1999) sound that "…which suggest that only isopycnal surfaces with σ_θ<27.25 (depths above about 150 m) or so were directly ventilated during the winter months of 1994-95". Luchin *et al.* (1997) came to more general conclusion that winter convection in the Japan Sea is not propagated deeper than 200-300 m. In such case there is a question on the mechanism and place of intermediate waters formation. In this respect Ryabov (1994) states most interesting idea. He believes that deep waters are formed in a frontal zone, in a place of meeting of cold and fresh waters with salty and warm ones. Here salty waters lose heat, are immersed and intermediate and deep waters are formed. The author considers, that the formation of intermediate waters, basically, occurs in area of the Korean plateau (38-39°N and 131-132°E), and also incidentally to the south of Peter the Great Bay. Important idea of Danchenkov and Aubrey (1999) stated that salinity of proper waters of western part of the sea is too low for deep water formation. The contribution of salty waters of Tsushima Current therefore is necessary. To the most probable area of formation of deep waters the authors suppose area of meander of Tsushima Current (between 43 and 45°N).

The mechanism of penetration of Tsushima water portions in deep levels here will be offered. This mechanism also provides explanation of disappearance of a minimum salinity of the intermediate water in local places.

Data

Basis of this paper are the CTD data and salinity measurements received in two international expeditions on R/V "Roger Revelle" and "Professor Khromov" in the period since June 24 till August 13, 1999. 203 oceanographic stations are rather in regular intervals distributed on water area limited in the south by the Korean Strait, and in north by a parallel 48°N. The observations cover a layer of waters from a surface to the bottom (maximal distance of a probe from seafloor did not exceed 4-10 meters at the stations). CTD data were collected using NBIS MKIIIB system equipped with a General Oceanics rosette sampler, with 24 10-liter Niskin Bottles. The onboard salinity measurements of samples were carried out using Guildline 8400A Autosal, which was calibrated before and after each station by means of WORMLEY standard seawater. At such procedure, onboard salinity measurements are accurate to approximately 0.001 practical salinity units (psu).

In addition, for demonstration of a general hydrological situation in the Japan Sea we involved in our consideration maps of long-term averaged temperature and salinity of mixed layer of waters for February. They are constructed using all data, available to the present time, of oceanographic observations (about 150 000 hydrological stations, carried out for the period from 1900 to 1998).

The Characteristic of Intermediate Waters

CTD data and onboard salinity measurements have been used for plotting of vertical profiles. The typical profiles are shown in Fig. 1. As it is visible from Figure, intermediate water is above very homogeneous proper water of the Japan Sea. According to our data proper water of the Japan Sea has salinity in narrow range, 34.065-34.069 psu. Intermediate water is not so homogeneous as proper water. There are maximum and minimum of salinity in intermediate water as a rule. The inhomogeneous reaches depth of 700-1000 m. Such point of view on intermediate water closely corresponds to Yoshikawa *et al.* (1999). We plotted maps of salinity and depth for core of salinity minimum of intermediate water. They are presented on Fig. 2a, b. Here we note that not at all stations the salinity minimum has been found out. Areas unspecified on salinity minimum were masked on Fig. 2.

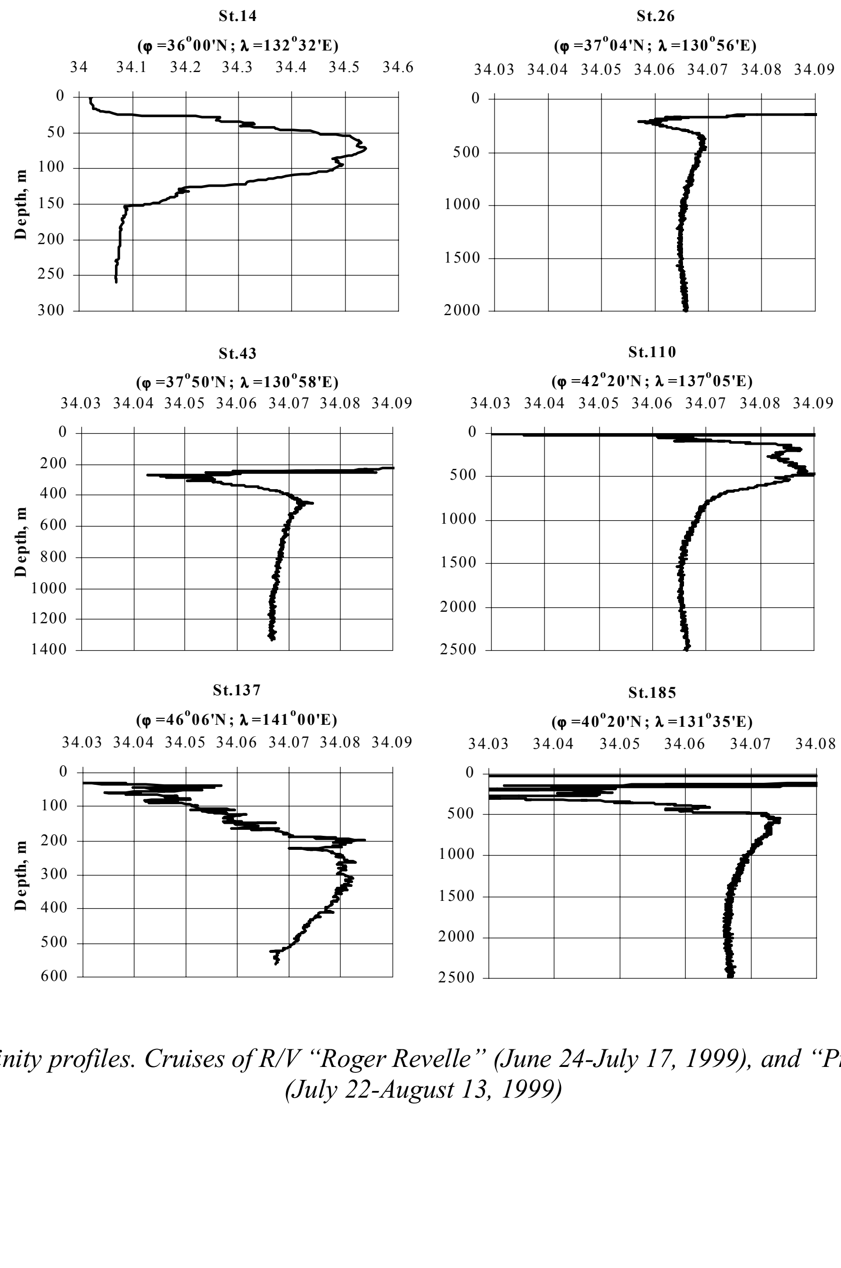

Fig. 1. Typical salinity profiles. Cruises of R/V "Roger Revelle" (June 24-July 17, 1999), and "Professor Khromov" (July 22-August 13, 1999)

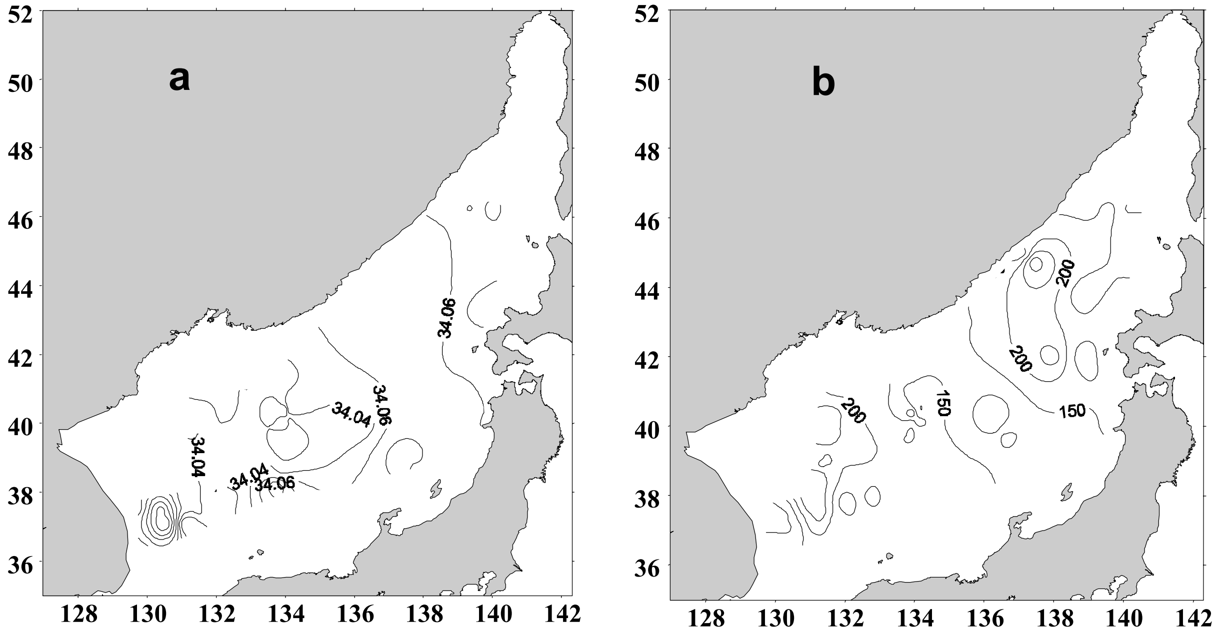

Fig. 2. Salinity (a) and depths (b) of the salinity minimum core of intermediate water of the Japan Sea. Cruises of R/V "Roger Revelle" (June 24-July 17, 1999), and "Professor Khromov" (July 22-August 13, 1999)

We assumed that waters with salinity exceeding 34.07 psu received salt from waters of Tsushima Current. Using results of onboard measurements of salinity, we have established the maximal depths of penetration of waters with salinity exceeding 34.07 psu and have plotted a map for this surface (Fig. 3). At construction of a Fig. 3 we have neglected alone horizons, on which salinity exceeded 34.07 psu, while the neighboring horizons had salinity less than 34.07 psu. Such stations there was 9, for example, an 119 St. (34.07 on depth 1490 db), 144 St. (34.083 on depth 1948 db), 196 St. (34.074 on depth 1234 db).

Before discussion of the mechanism of formation of intermediate waters, let us to consider potential stability of column water of the Japan Sea.

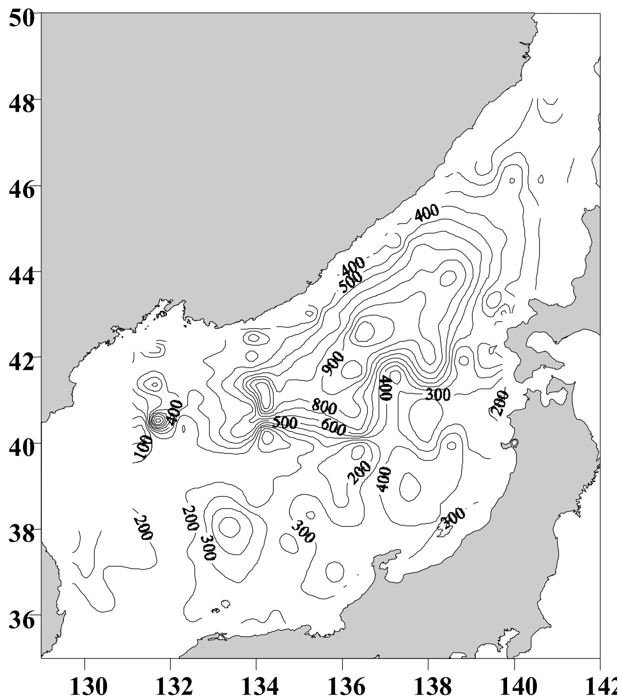

Fig. 3. Penetration depth of salinity exceed 34.07. Cruises of R/V "Roger Revelle" (June 24-July 17, 1999), and "Professor Khromov" (July 22-August 13, 1999)

Potential Stability

At study of mixing processes, potential stability of water column is most valuable parameter (Fine *et al.* 1978; Rogachev *et al.*, 1996; Fofonoff, 1998). The thermodynamic equations for account of this magnitude are given by Fofonoff (1961). They include expression for static stability

$$EH = 0.5 \cdot g^2 \cdot \left[\frac{d\rho}{dP} - \left(\frac{\partial \rho}{\partial P} \right)_\theta \right]. \quad (1)$$

Contributions caused by different compressibility of two elements of water at different temperature and salinity are taken into account by the equation

$$EC = 0.5 \cdot P \cdot \left(\frac{g}{V}\right)^2 \left\{ \frac{\partial}{\partial T}\left(\frac{\partial V}{\partial P}\right)_\theta \left[\left(\frac{dT}{dP}\right) - \left(\frac{\partial T}{\partial P}\right)_\theta\right] + \frac{\partial}{\partial S}\left(\frac{\partial V}{\partial P}\right)_\theta \left(\frac{dS}{dP}\right) \right\} \tag{2}$$

Volume contraction effect at mixing of two elements of sea water with different salinity and temperature (cabbeling) are taken into account by the expression

$$EM = -0.5 \cdot P \cdot \left(\frac{g}{V}\right)^2 \left\{ \frac{\partial^2 V}{\partial T^2} \left[\left(\frac{dT}{dP}\right) - \left(\frac{\partial T}{\partial P}\right)_\theta\right]^2 + 2 \cdot \frac{\partial^2 V}{\partial T \partial S} \left[\left(\frac{dT}{dP}\right) - \left(\frac{\partial T}{\partial P}\right)_\theta\right] \left(\frac{dS}{dP}\right) + \frac{\partial^2 V}{\partial S^2} \left(\frac{dS}{dP}\right)^2 \right\}. \tag{3}$$

A non-linear terms of enthalpy of sea water contribute additional effect which was taken into account by the equation

$$EL = 0.5 \cdot \frac{P}{C_P} \cdot \left(\frac{g}{V}\right)^2 \frac{\partial V}{\partial T} \left\{ \frac{\partial C_P}{\partial T} \left[\left(\frac{dT}{dP}\right) - \left(\frac{\partial T}{\partial P}\right)_\theta\right]^2 + 2 \cdot \frac{\partial C_P}{\partial S} \left[\left(\frac{dT}{dP}\right) - \left(\frac{\partial T}{\partial P}\right)_\theta\right] \left(\frac{dS}{dP}\right) + \frac{\partial^2 L}{\partial S^2} \left(\frac{dS}{dP}\right)^2 \right\} \tag{4}$$

Factor 0.5 gives energetic effect on unit of mass element. In these equations the standard designations were used: g – gravity;

P – pressure;
ρ – density;
V – specific volume;
T – absolute temperature;
S – salinity;
C_p – specific heat;
L – relative specific enthalpy of sea water;
θ – designation adiabatic process.

The sum of all components represents potential stability of mass element in seawater column

$$E_T = EH + EC + EM + EL \tag{5}$$

At calculations of E_T the equation of state of sea water (Fofonoff, 1985) was used.

In Fig. 4 three types of a profile of potential stability are shown. The profile *4a* is typical for deep part of the Japan Basin. A profile *4b* is typical for waters close to coast of Primorye. A profile *4c* is typical for waters of Yamato Basin. One can note two main features of potential stability of waters of the Japan/East Sea. First, water deeper than 300 m has potential stability very close to zero. In words, it has neutral buoyancy due to homogeneity in temperature and salinity. Secondly, there are layers with negative stability. They correspond to transitive area between warm/salty and cold/fresh waters. Due to close density of these layers and volume contraction effect (eqn (3)) there is a negative stability. Or else, due to cabbeling there is source of energy, which may enhance mixing. We have plotted maps of potential stability on horizontal levels 50 m and 250 m, accordingly (Fig. 5a and 5b). As it is visible from Figure 5, there are areas with negative magnitudes of potential stability. That is area where energy releases under vertical mixing.

Discussion

It follows from results of multiyear oceanographic observations, that in the autumn-winter period mixed layer reaches the maximal development in February (Luchin and Man'ko, 1999). At this time on a most part of the sea its development is not propagated deeper than 50-100 m. Only in a deep-water part of the sea, between latitudes 40.5-42°N and longitude 131-138°E, mixed layer reaches depth 150-200 m. From long-term observation the maps of distribution of surface temperature and salinity for February are plotted (Fig. 6). From Fig. 6 two important conclusions follow. First, salinity in coastal areas of northern and northwest part of the sea (33.8-33.9 PSU) is insufficient for an explanation of formation of intermediate and deep waters only by the continental slope processes. Secondly, this mixed layer can serve a source for formation of an intermediate layer with low salinity. We believe that salinity-minimum layer is formed due to advection of the mixed layer (fresh and cold waters) on the south and southeast, and warm and salty waters (Tsushima waters) on north and northwest. As Tsushima waters are less dense (Tishchenko *et al.*, 2000, Fig. 8), they cover cold and fresh, forming an intermediate minimum of salinity. This structure is very important for processes of vertical mixing. Because in transitive area, between two types of waters the area of potential instability ($E_T<0$) is formed. It is an energy source for mixing. That fact that in Fig. 5a and 5b are areas with negative potential stability (filled contours) specifies that these layers as a whole do not mix up. But in transitive area, between a minimum salinity and upper portion of proper waters the process of mixing should go, as there is an energy source (cabbeling). An opportunity of mixing between minimum salinity layer and upper portion of proper waters is specified in work (Senjyu, 1999). In that case, when two layers (warm/salty above on cold/fresh) have close density and are thin enough, they become unstable due to an exchange of a heat among themselves. The internal heat exchange results in counter vertical movement and mixing. The mixing of these layers will give more dense water than average of two layers as result of effect of volume contraction at mixing (eqn (3)). Therefore mixing elements will penetrate into deeper layers. As deeper 300 m the sea has neutral buoyancy, the parcels of mixing can penetrate deep enough. The Fig. 7 to some extent demonstrates this process. Above there are two layers, which density is close to each other. In the field of transition between them the potential stability is negative, *i.e.* there is energy source for enhance mixing. It is obvious, that the mixing of two layers will give salinity about 34.07, which is higher

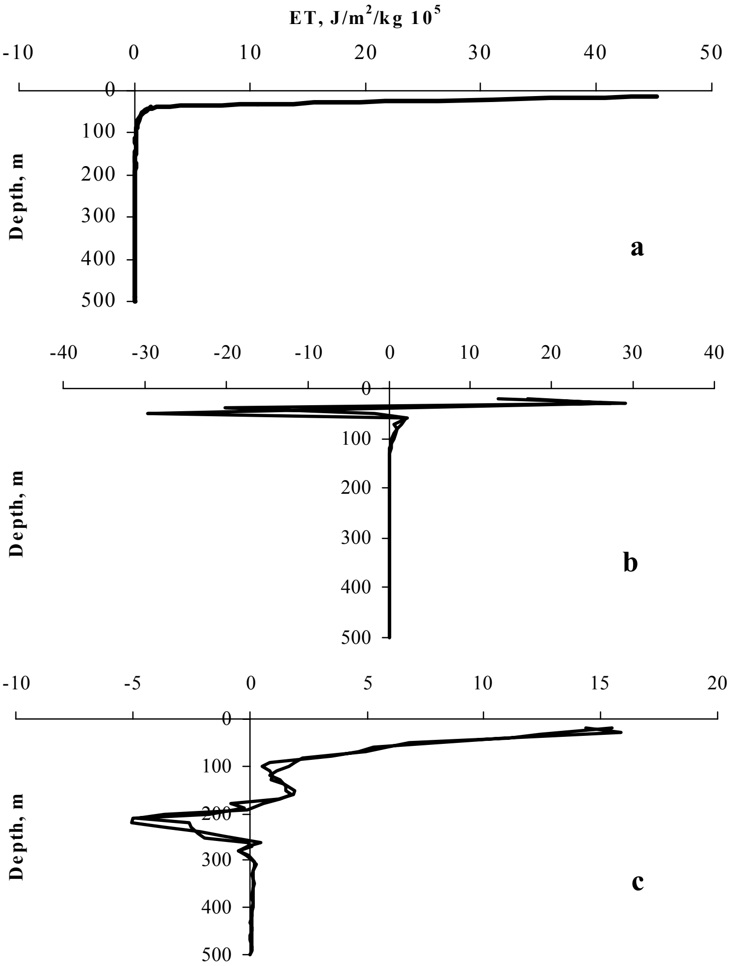

Fig. 4. Examples of the three kinds of the potential stability profiles. Station 144 (φ=44°41.9′N, λ=137°30.4′E) -(a); Station 200 (φ=42°22.3′N, λ=131°35.3′E)-(b); Station 46 (φ=38°0.5′N, λ=133°15′E)-(c). Cruises of R/V "Roger Revelle" (June 24–July 17, 1999), and "Professor Khromov" (July 22–August 13, 1999)

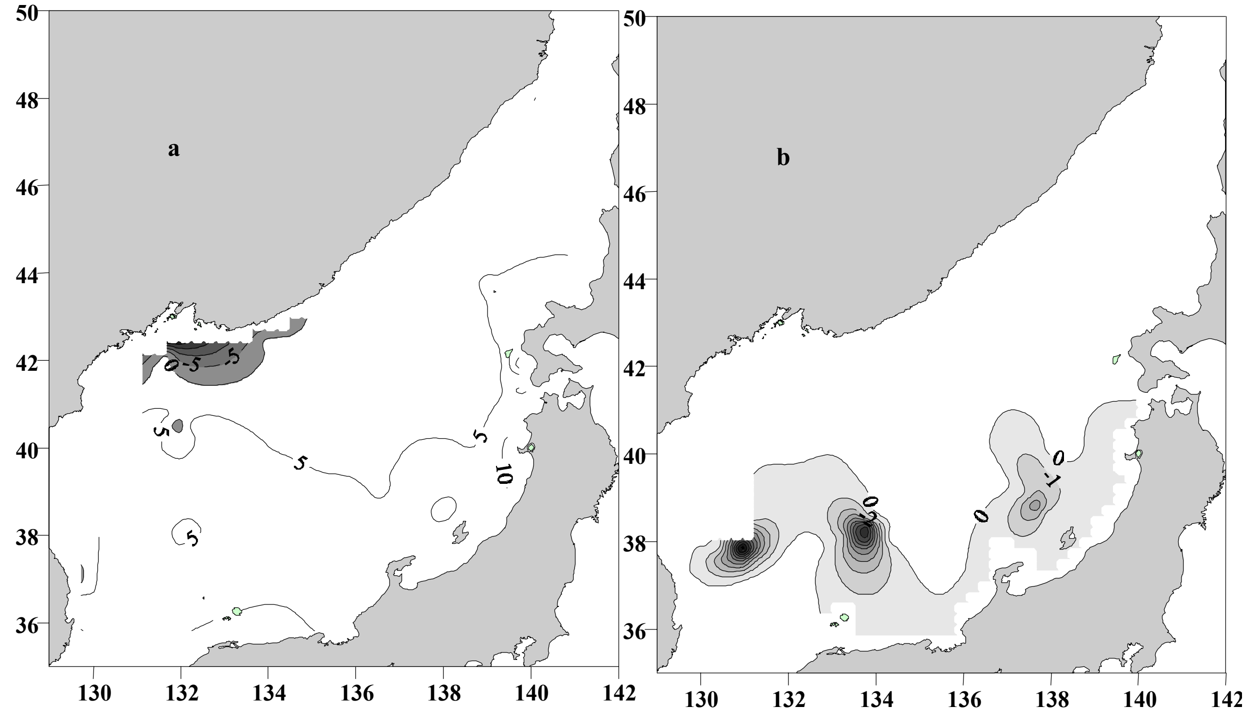

Fig. 5. Potential stability ($J/m^2/kg \cdot 10^5$) for 50 m (a) and 250 m (b) of the Japan Sea, in summer 1999

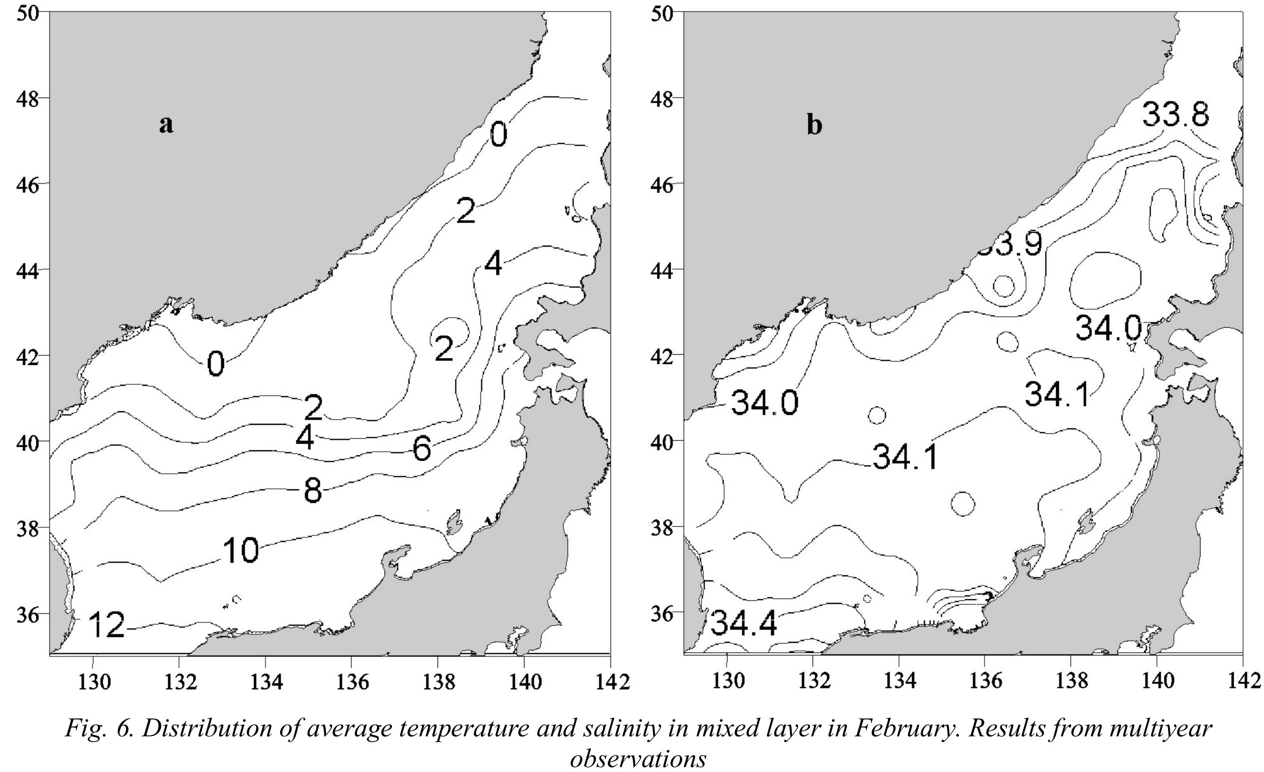

Fig. 6. Distribution of average temperature and salinity in mixed layer in February. Results from multiyear observations

than underlying layers. This element will continue to penetrate into deeper layers, loosing heat because it is warmer than surrounding water. We believe, that the layer with salinity 34.07 psu on depth 300-400 m is result of the previous mixing, and again formed two-layer structure is standing on line in turn on mixing. By the offered mechanism we explain penetration of Tsushima water in to deep horizons. As follows from Fig. 3, this process basically goes to the north of polar front. Especially it actively goes to the west from Tsugari Strait and forms area of diapycnal mixing (Tishchenko *et al.*, 2000). By this process it is possible to explain inconstant display of an intermediate layer of minimum salinity as well.

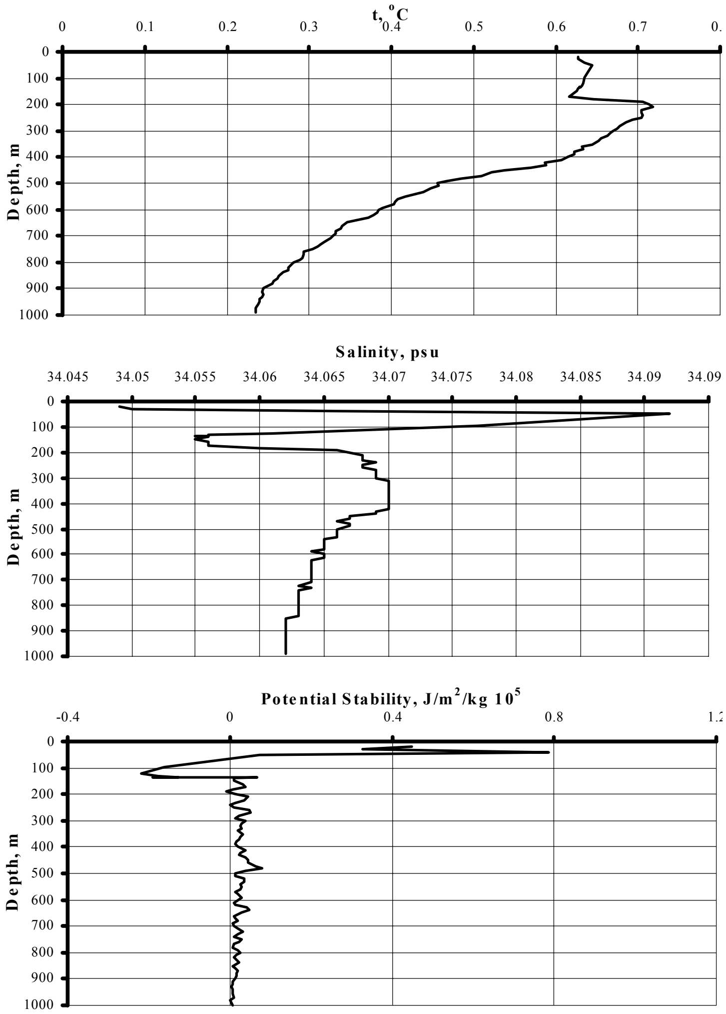

Fig. 7. Temperature, salinity and potential stability profiles of St.34 (φ=41°50′N, λ=132°42′E). Cruise of R/V "Professor Khromov" (February 22– March 23, 2000)

As it was already noted above, there is a divergence of opinion on depth of penetration of winter time convection. Partly it is explained to that really there are local places in the Japan/East Sea, where there is a vertical mixing from a surface up to 600 m (Talley *et al.*, 2000) or more deeper than 800 m (Riser & Danchenkov, 2000). Two explanations of the reason of existence of such local places are possible. One explanation consists in existence of places with the special meteorological conditions, which could result in local cooling and, accordingly, to deep convection. It is necessary to search another explanation, apparently, in the general circulation of currents of the top layer of the sea, which would result in continuous formation of thin two-layer structure. This structure makes more dense water that at the end gives vertical mixing.

Thus, the offered mechanism is capable to explain the basic features of formation and display of intermediate water of the Japan Sea.

Our consideration of formation of intermediate water of the Japan Sea can be summarized as follows.

- Upper portion of the Pacific water (Tsushima water) and mixed layer (cold/fresh water) formed in winter time between 40-43°N result in salinity minimum of intermediate water due to their isopycnal movement and mixing.
- Heat exchange between two waters (warm/saline and the cold/fresh) results in their contrary moving which gives mixing. Salinity minimum will disappear.
- Mixing forms more dense water due to volume contraction (cabbeling).
- Loosing heat dense parcels spread into deep layers which have a neutral buoyancy and portions of Tsushima water penetrate into deep layers.

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