The occurrence of winter convection at the open ocean polynya in the eastern part of the Okhotsk Sea indicated by the World Ocean Atlas 2005

Makoto Kashiwai

Faculty of Bio-Industry, Tokyo University of Agriculture, Abashiri, Japan
E-mail: m3kashiw@bioindustry.nodai.ad.jp

Introduction

The Okhotsk Sea is identified as the principal ventilation site of the intermediate density waters of the North Pacific (Talley, 1991). This ventilation process is driven by an overturn associated with brine concentration from sea ice formation at coastal polynyas on the northeastern shelf. Previous studies on the source of North Pacific Intermediate Water, or on the formation of Kuril Basin Intermediate Water, Okhotsk Sea Intermediate Water, Okhotsk Sea Mode Water or Dense Shelf Water (Watanabe and Wakatsuchi, 1998; Galdyshev *et al*., 2003; Itoh *et al*., 2003; Shcherbina *et al*., 2004a,b; Yamamoto *et al*., 2004) have made no reference to the ventilation or convection process at the open ocean polynya in the eastern part of the Okhotsk Sea. “Winter convection” usually means a deepening of the surface mixed layer by cooling and stirring by cold air temperatures and strong winds, and in the Okhotsk Sea, is reported to occur in the upper 100–150 m layer (Moroshkin, 1966) and is believed to not penetrate below the halocline or the temperature minimum layer (Gladyshev *et al*., 2003).

While turning attention to the interannual variation in the water adjacent to the Okhotsk Sea, the effect of oceanographic processes of the Okhotsk Sea appearing in the Oyashio Water, depicted by monitoring on the ‘A-line’ by HNFRI/FRA, is the increased magnitude and earlier initiation of spring blooms after the 1998 regime shift (Kasai *et al.*, 1997). This enhancement of primary productivity is associated with the increase in the density gradient of the water column within the euphotic layer (Kasai *et al.*, 1997) by increased temperature or decreased salinity in the surface layer (Kasai and Ono, 2007). The basis for these changes in oceanographic structure may include the interannual changes in the waters lying over the intermediate density ranges, *i.e.*, the water formed by winter convection. Thus, we need to pay attention to winter convection in the Okhotsk Sea.

In visualizing World Ocean Atlas 2005 (WOA05) data (Locarnini *et al.*, 2006a,b) using Ocean Data View (ODV; Schlitzer, 2006) to obtain a standard textbook picture of wintertime surface mixed layer convection, we found a pycnostad, *i.e.*, vertically dense homogeneous water extending down to *ca.* 500 m deep over the eastern part of the Okhotsk Sea in January. A pycnostad reaching this depth in the Okhotsk Sea has never been reported. Thus, this paper attempts to describe the pycnostad water, the history of its formation or deformation, its contribution in water mass formation processes in the Okhotsk Sea, and to indicate that pycnostad water is nothing more than the evidence of deep winter convection.

Pycnostad Water in the Eastern Part of the Okhotsk Sea

The WOA05 data indicate the existence of water having pycnostads in the eastern part of the Okhotsk Sea, in January (Fig. 1). This pycnostad water extends down to 300~500 m deep. As shown in Figure 2, this pycnostad water is not observed in December or February.

Pycnostad water in σ_0 sections

The left panel of Figure 3 is the January σ_0 section at 57.5°N, which runs on the northern shelf and at the northern end of TINRO Basin. The pycnostad reaching a depth of about 400 m exists on the bottom depression corresponding to the northern end of TINRO Basin. A low density surface layer of a few 10s of meters extends from the western (left) side of the section, but does not lie over the pycnostad water occupying the eastern (right) side of the section. The pycnostad water shows horizontal density variation ranging from 26.2 to 26.7 σ_0, which corresponds to that of the water just above the Okhotsk Sea Mode Water (26.7 to 27.0 σ_0; Gladychev *et al*., 2003). At the top of the pycnostad water, there is no surface mixed layer, *i.e.*, the surface 'sky-light' is open to the air and 'ventilation' is available.

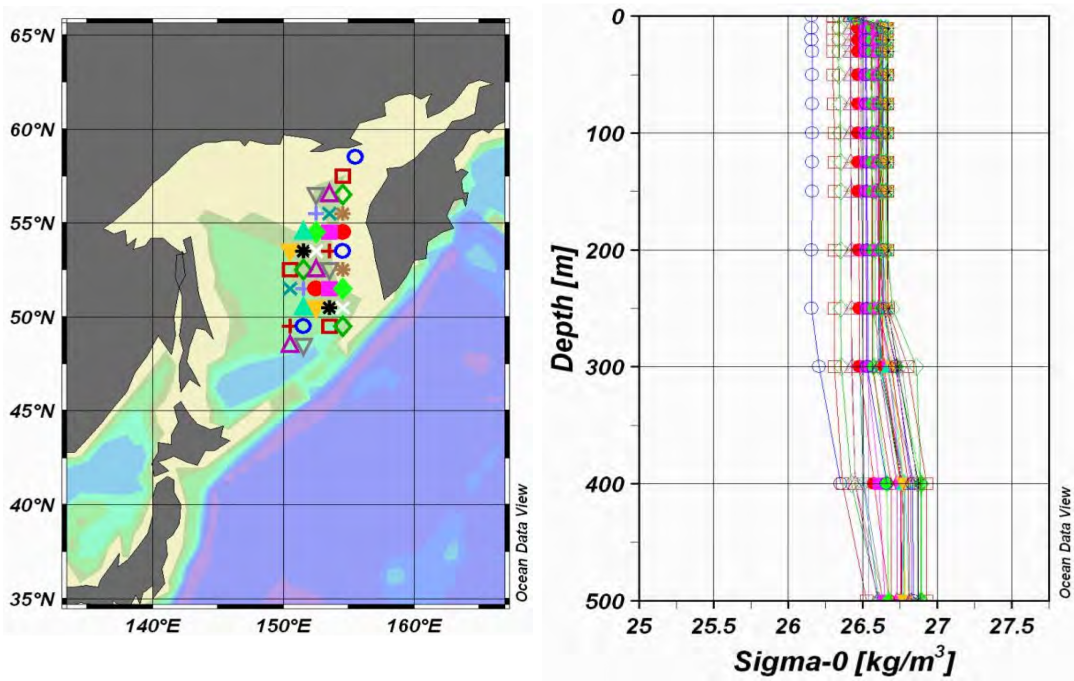


Fig. 1 January σ_0 profiles of the pycnostad water, and the location of the monitoring stations in the eastern part of the Okhotsk Sea.

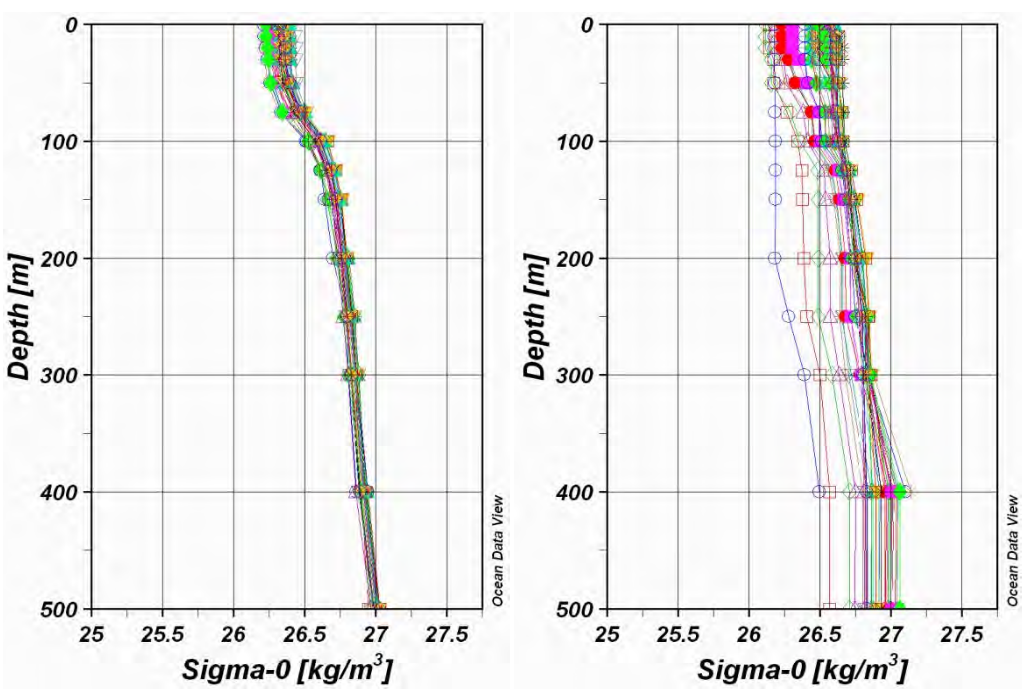


Fig. 2 December (left) and February (right) σ_0 profiles of the stations shown in the map of Figure 1.

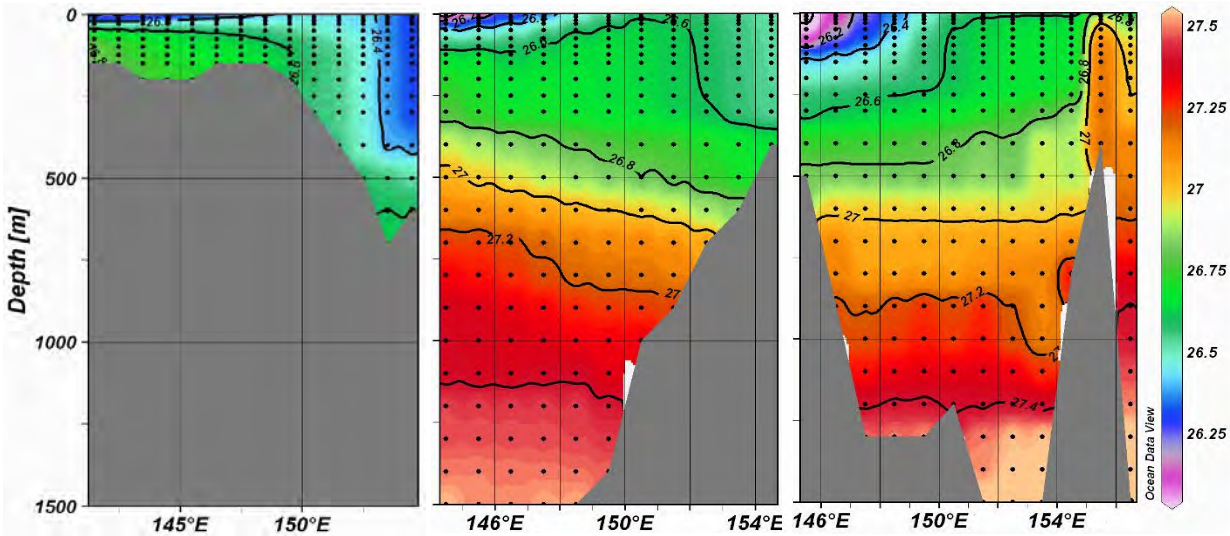


Fig. 3 January distribution of σ_0 (kg m^{-3}) for sections 57.5ºN (left), 53.5ºN (middle) and 49.5ºN (right).

The middle panel of Figure 3 is the 53.5ºN section, which passes through the northern part of Deryugin Basin (deeper than 1500 m in the Central Basin and east off the northern part of Sakhalin Island). In this section, the σ_0 range of the pycnostad water becomes a little denser to 26.5~26.6. The bottom of the pycnostad water extends westward along 350 m depth.

The right panel of Figure 3 is the 49.5ºN section, extending from the north of Cape Terpeniya to Onekotan Island, north of Kruzenshtern Strait. In this section, a higher density water mass of well mixed Kuril Islands Water appears in the eastern part of the section, connects with the pycnostad water interfaced by a sharp density front. This suggests that the tidal mixing and tidal exchange at/through the Kuril Straits have an important roll in the formation of the pycnostad water. The pycnostad water becomes denser to 26.6~26.7σ_0. The detailed structure (doming or depression) of the pycnostad water shown by shape of the isopycnals (*e.g.*, σ_0 = 26.6) can be interpreted as a result of either dynamic balance or local vertical mixing or convection. Thus, we must suspend interpretation here, based on a specific assumption.

As seen from Figure 3, the core density of the pycnostad water becomes less dense towards the north. On top of the dense homogeneous water, there is a very thin surface mixed layer with a pycnocline of moderate density gradient. The vertical gradient of σ_0 in the pycnostad water is as low as an order of 1 kg·m^{-3}·km^{-1} or less. The east–west difference in density structure in the upper layer (<500 m) suggests a geostrophic balance with strong currents, including the East Sakhalin Current, driven by a strong northerly winter monsoon.

The evidence of pycnostad water identified in the density sections can be summarized as follows:

- The T/S vertical profile compensating each other tends to be isopycnic;
- A horizontal density gradient exists;
- Depth reaches 300~400 m;
- The horizontal extent north–south is 1000 km and east–west is 300 km;
- It is observed only in January.

The most important questions to be addressed are "What is the nature of this pycnostad?" and "Is it merely a deepening of the surface mixed layer or the result of simple tidal mixing?" In view of its appearance only in January and disappearance in February, this pycnostad water may not be a simple deepening of the surface mixed layer or the result of tidal mixing.

T/S sections of pycnostad water

Figures 4, 5, and 6 represent the temperature and salinity sections corresponding to Figure 3. The temperature and salinity of the pycnostad water are not vertically homogeneous, but compensate each other so that the density becomes vertically homogeneous, as is clearly shown in the T/S diagram of pycnostad water for January (Fig. 11).

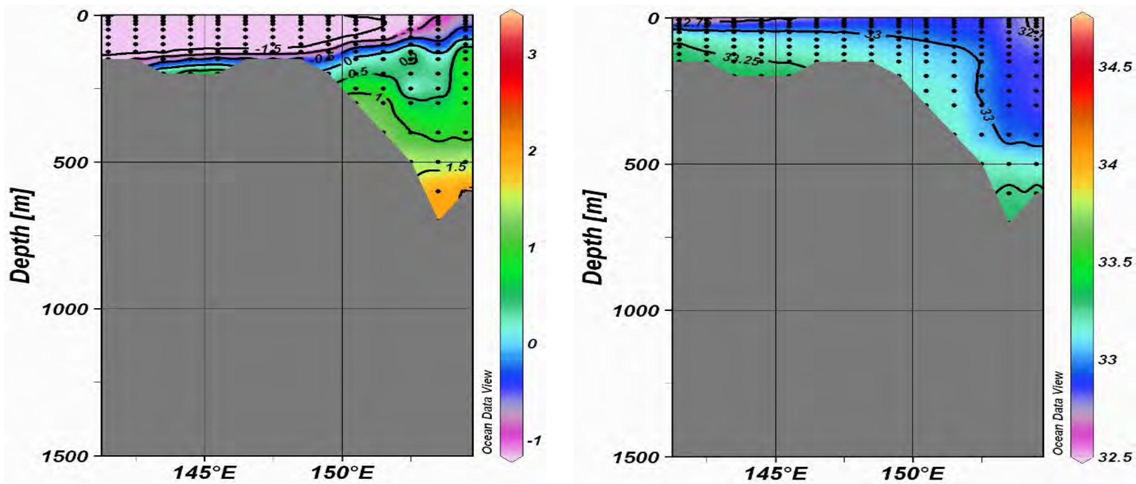


Fig. 4 57.5°N section in January for (left) temperature (ºC) and (right) salinity (psu).

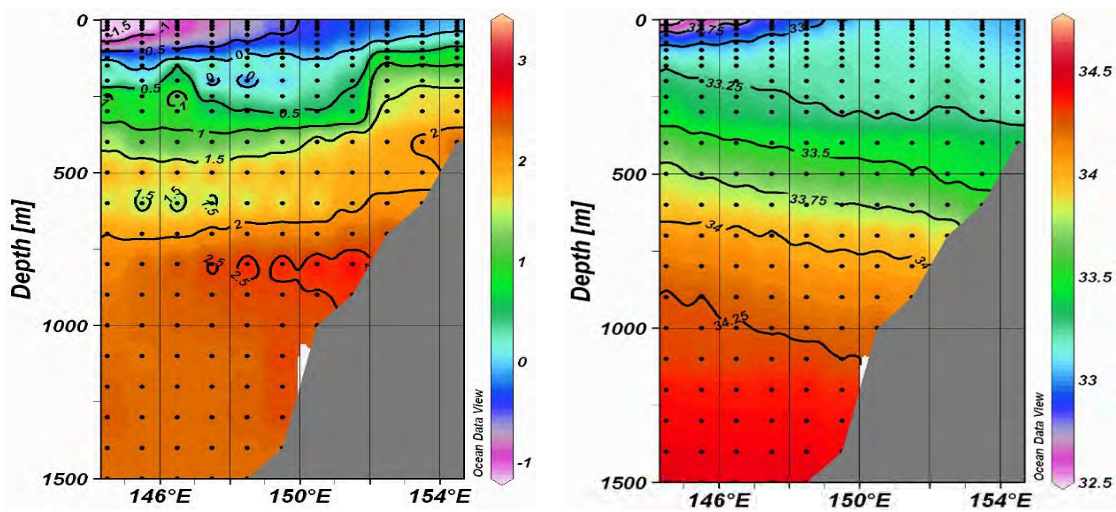


Fig. 5 53.5°N section in January for (left) temperature (ºC) and (right) salinity (psu).

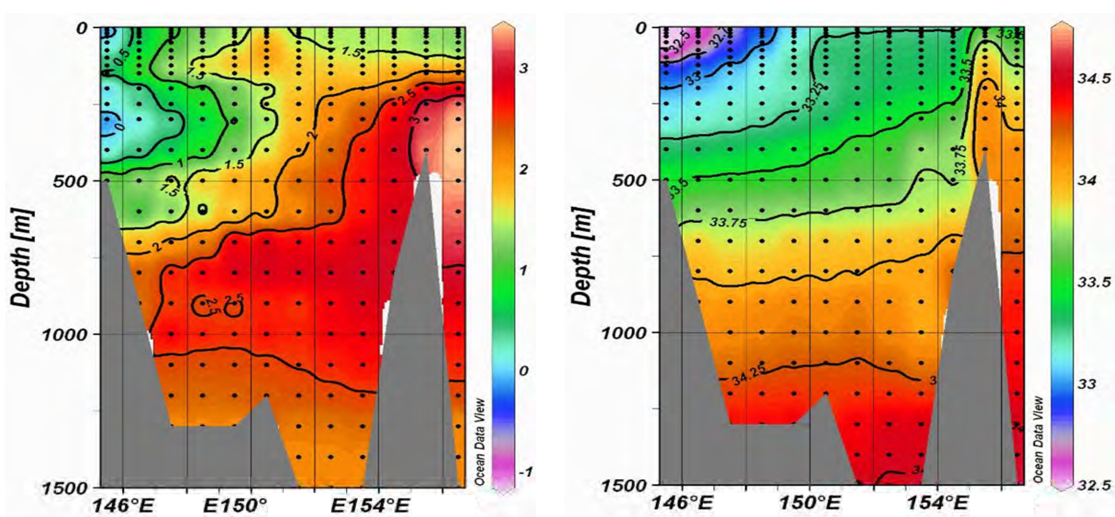


Fig. 6 49.5°N section in January for (left) temperature (ºC) and (right) salinity (psu).

The important observations from the above temperature and salinity sections are as follows:

1) Warmer water extending from the North Pacific is dominant only in the middle layer of the southern part of Central Basin (Fig. 6, left). The surface of pycnostad water is covered by water colder and less saline compared to the water occupying the Kuril Straits. This means that the open ocean polynya observed in the eastern half of the Central Basin is not caused by the inflow of warm North Pacific Water.
2) Comparing with density sections, the effect of salinity dominates in determining density structure.
3) The major source of saline water is the inflow of North Pacific Water through the Kuril Straits.
4) The cold and low salinity water is distributed along the western side of the Central Basin, *i.e.*, along the coast of Sakhalin Island, but does not extend eastward beyond 150ºE.

The open ocean polynya and pycnostad water in the eastern part of the Okhotsk Sea had long been considered to be formed by the inflow of warm North Pacific Water, but this assumption is not supported by the temperature and salinity sections of Figures 4–6. Another possible explanation is that the polynya in the eastern part of the Okhotsk Sea can be formed and maintained, not by heat advection from the Pacific Ocean, but by mechanical processes, such as wind and/or currents. Thus, the pycnostad water could be formed by the result of local processes, *e.g.*, upwelling or vertical mixing or convection.

These two explanations bring quite different points of view on the watermass formation and modification process in the Okhotsk Sea. In order to answer the question "What will happen when sea ice of the Okhotsk Sea disappears due to global warming?", the cause and results of the open ocean polynya and pycnostad water in the eastern part of Okhotsk Sea will be very important.

Formation and Deformation of Pycnostad Water

Time evolution from December to January/ January to February

To look for evidence on possible formation mechanisms of the pycnostad water, the difference in time between December and January for the cross-sections of temperature, salinity and σ_0 in each section is shown in Figures 7, 8, 9. The T/S diagrams for December and January are shown in Figures 10 and 11, respectively.

The remarkable changes occurring from December to January are:

1) The density decrease of almost the entire water column of the Central Basin, except for the upper 100 m. The degree of decrease is more intense in the northern part;
2) The density increase of the surface mixed layer shallower than about 100 m in the middle and eastern portions of the sections;
3) The increase of salinity in the middle layer of the central section and decrease of temperature in the middle layer of the southern section. These changes may be the result of freezing.

These changes in temperature and salinity are shown in the general pattern of the T/S profiles between December and January (Figs. 10–11). The December T/S profile (Fig. 10) conserves characteristics similar to those of the Okhotsk Sea in summer time, *i.e.*, a fresh and warm surface layer, temperature minimum layer and deep temperature maximum.

The temperature minimum layer disappears from January T/S profiles (Fig. 11), while those of the surface/middle layer align parallel to isopycnals instead. The positions where the surface or intermediate layer T/S profiles are aligning correspond almost to the position of the temperature minimum layer in December (26.4~26.7σ_0), except at the shallow stations on the shelf. The aligned T/S profiles of the pycnostad water are the result of a salinity increase and temperature decrease in the surface water, and a salinity decrease and temperature increase or decrease in the water just below temperature minimum layer in December. This change means that the distribution of T/S plots becomes more compact. In other words, the uniformity of the water mass increases. The deep temperature maximum moves to a lower salinity and higher temperature position in January. Thus, we can see that the pycnostad water is formed by a density increase in the surface mixed layer of thickness *ca.*100 m, and by a density decrease in the rest of the water column.

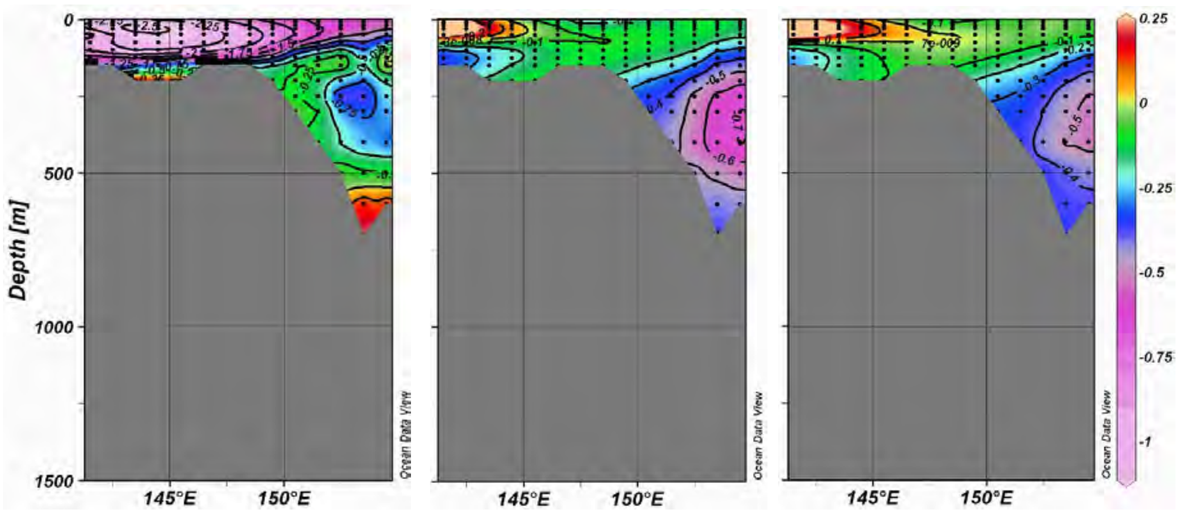


Fig. 7 The differences in (left) temperature, (middle) salinity and (right) σ_0 between December and January for the 57.5°N section.

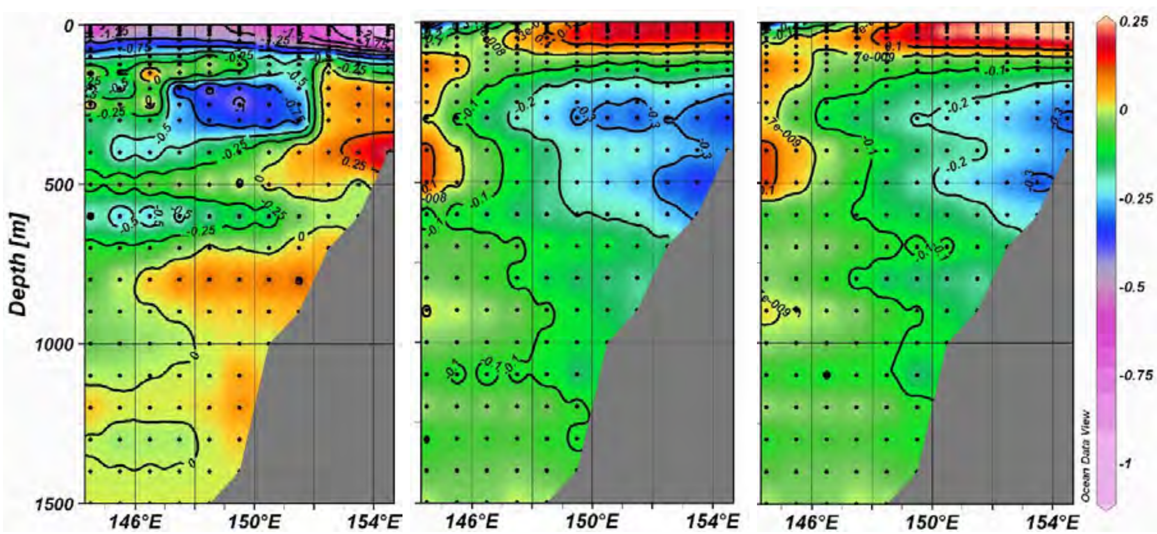


Fig. 8 The same as in Figure 7 but for the 53.5°N section.

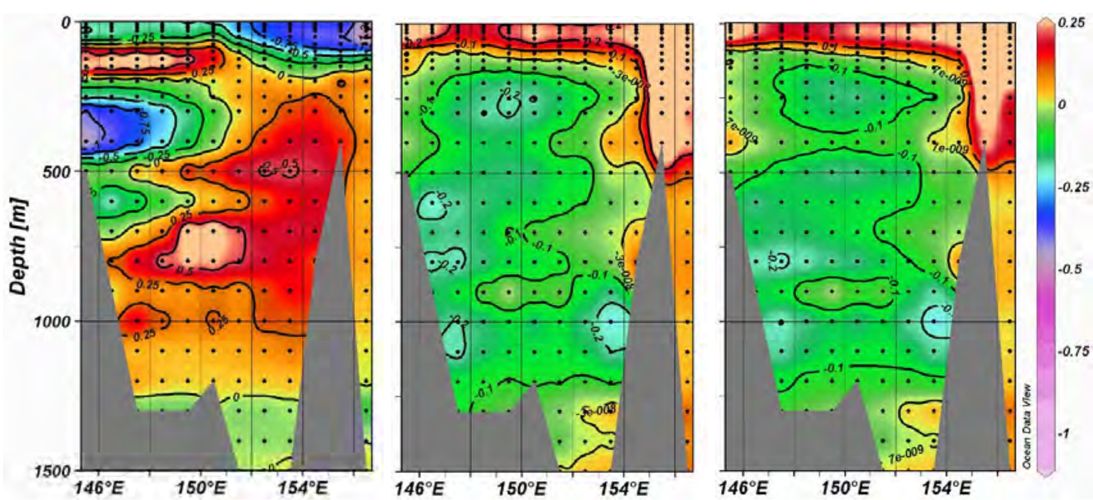


Fig. 9 The same as in Figure 7 but for the 49.5°N section.

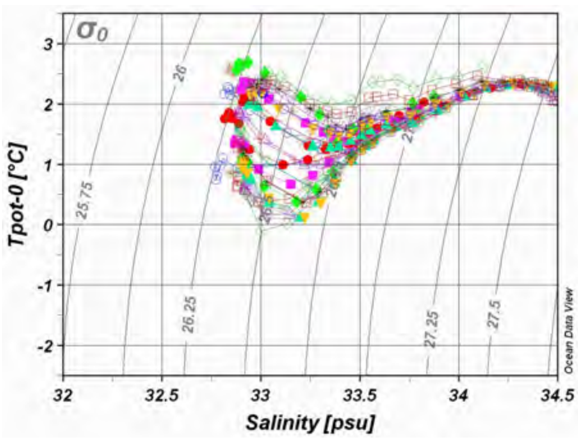


Fig. 10 T/S diagram of the pycnostad region in December.

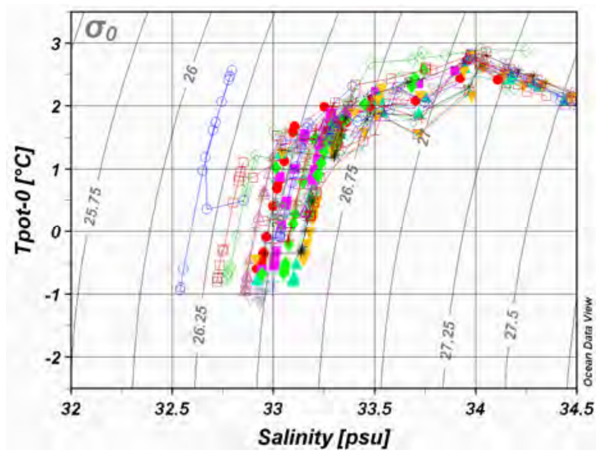


Fig. 11 T/S diagram of the pycnostad region in January.

The density increases of the surface layer in the eastern and central portion of sections are caused by an increase of salinity and decrease of temperature. These changes in T/S could be the result of vertical mixing with the lower layer. However, as shown in Figure 9, the increase of surface mixed layer salinity is most outstanding at the Kuril Straits, where salinity increases over whole water column. The tidal mixing at the Kuril Straits could transport higher salinity water from the deep layer, or from East Kamchatka Current Water. If the West Kamchatka Current, forming the northward flow of counter-clockwise circulation as the eastern side of the Okhotsk Sea circulation dominates, this saline water could be transported north along the western shelf slope of the Kamchatka coast. However, the existence of a sharp front, bounding the tidal mixing zone around the Kuril Islands, makes the explanation by simple advection of a water mass through it difficult, and needs to be explained using transport by tidal currents, *i.e.*, tidal exchange.

The decrease in density in the lower layer of the sections corresponds to the decrease in salinity and partly to the increase in temperature, though the contribution of the latter is not remarkable. However, what is notable is the decrease in salinity of the lower layer in the northern section as shown in the middle panel of Figure 7, and the increase in temperature of middle layer in the southern section as shown in the left panel of Figure 9.

As the changes in temperature and/or salinity from December to January are different in the layers, explaining the mechanisms of changes by isopycnal mixing will be not easy. Possible mechanisms of decreasing density by a decrease in salinity in the lower layer of the northern section can be vertical mixing, convection by surface cooling, and strengthening of the cyclonic gyre. Among these, the only mechanism that can generate a pycnostad with compensating T/S distribution is the sinking of the water parcel by a density increase to the depth with same density, *i.e.*, cooling convection.

In the February T/S diagram (Fig. 12), for the same water for Figures 10 and 11, the vertically dense homogeneous water is not so developed as in January. However, through careful examination of Figure 12, we will find the following features; (1) the pycnostad waters starting from the surface still exist in the lower salinity stations, *i.e.*, in the stations on the shelf; (2) the middle layer pycnostad waters can be indentified in the intermediate density layer (σ_θ = 26.8 ~ 27.1). The possible mechanism forming intermediate pycnostad layer can be diapycnal mixing by tidal currents and bottom topography. This is an important and interesting phenomenon, but in order to focus of this paper on the formation mechanism of the pycnostad layer starting from the surface, here it is sufficient to just point out this phenomenon.

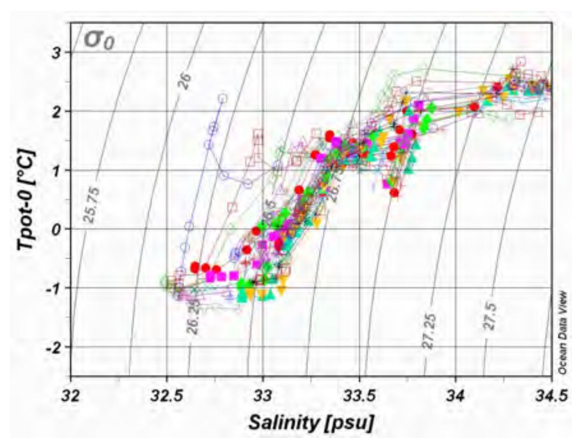


Fig. 12 T/S diagram of pycnostad region in February.

Changes in volume of water for density ranks

The changes in the volume of water for each density rank are clearly shown by comparing the occurrence of σ_0 ranks in each section between January and February (Fig. 13). As the occurrences are counted for data of standard depths, having different spacing from surface to depth, the counts of occurrence are not equally comparable between different σ_0 ranks.

The formation of pycnostad water is clearly shown as dominant peaks in the January histogram (Fig. 13, upper panel) at σ_0 of 26.2~26.7, which corresponds to the density range of the water just above the Okhotsk Sea Mode Water in the Okhotsk Sea, and to the density range of Oyashio Water just above the temperature minimum layer or around the salinity minimum layer. This formation can still be observed among the histogram peaks in February when the pycnostad water is already deformed. However, the volume of water having higher σ of 26.75~27.1 increases between January and February. At the same time, the volume of water having a lower density increases in the northern section. Thus, winter is the season when the water masses of surface, intermediate and deeper layers are formed through typical mechanisms, including that which forms pycnostad water.

Is it Deep Convection?

The most plausible formation process of this pycnostad water, having a signature of aligned T/S profiles, is 'deep convection', because this signature is quite similar and unique to that of deep convection sites, such as the Gulf of Lions, south of France (Schott *et al*., 1996) and/or the Labrador Sea (Lilly *et al*., 1999). The T/S profiles for these deep convection sites produced from WOA05 data also indicate the existence of a pycnostad exhibiting T/S profiles aligning along the isopycnals (Fig. 14).

The semblance of the T/S profiles may not be enough to identify winter convection as the process responsible for the formation of the pycnostad. Thus, we must first present an overview of past studies in order to understand the specific requirements of winter deep convection; then those requirements may be examined for the case of eastern part of Okhotsk Sea.

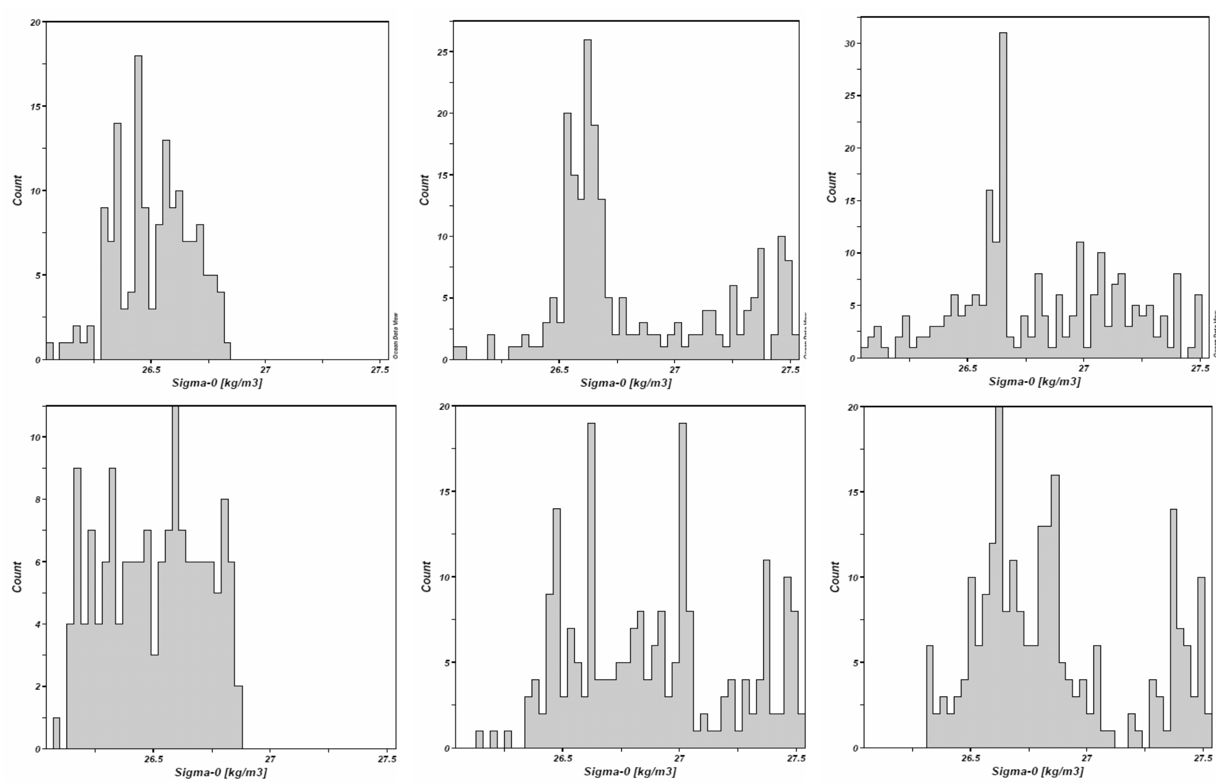
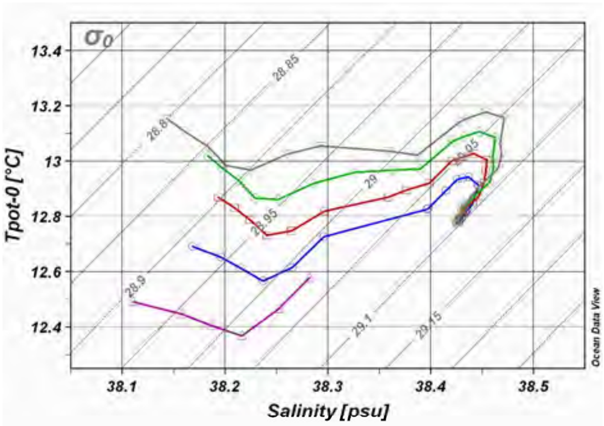


Fig. 13 Comparison between the occurrence of σ_0 ranks in January (upper panel) and February (lower panel); left: 57.5°N section; middle: 53.5°N section; right: 49.5°N section.



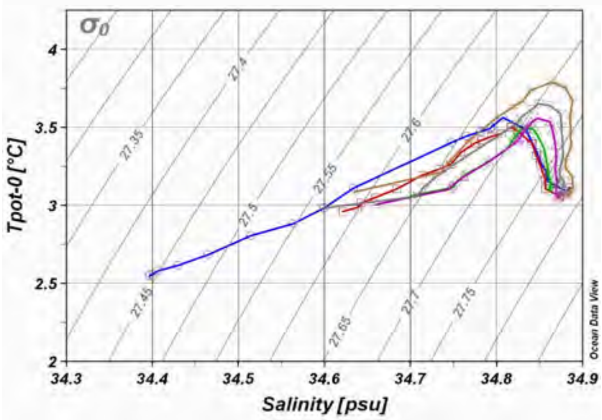


Fig. 14 T/S diagrams in February for (top) Gulf of Lions and (bottom) Labrador Sea.

The development of convective overturn is well illustrated not only through intensive field studies by Schott *et al*. (1996) and Lilly *et al*. (1999), but also through a series of laboratory tank experiments by Maxworthy and Narimousa (1994) and through a series of plume-resolving numerical model experiments by Send and Marshall (1995).

Deep convection in the Gulf of Lions and the Labrador Sea

Based on extensive observations, the development of deep convection in the Gulf of Lions (Send and Marshall, 1995; Schott *et al*., 1996) can be outlined as follows:

1) The situation leading to deep convection is based on a permanently present cyclonic circulation.
2) This cyclonic circulation leads to a doming of the isopycnals with shallowest mixed layer depths.
3) Cold and dry offshore winds blow from the land over the isopycnal dome: the Mistral out of the Rhone Valley and the Tramontane from the Pyrenees.
4) With continued cooling during the early phase of winter, the upper layer continues to be cooler, deeper, and saltier by entraining warm and saline water from below.
5) The stability against the weakly stratified sublayer is reduced enough for deep convection to set in.
6) The downwelling velocities (exceeding 10 cm s^{-1}) of dense water plumes ‘raining down’ from surface mixed layer are compensated by upwelling velocities in between the ‘convection plumes’ and thus the integral effects of a patch of convection plumes are mainly to act in mixing the water column vertically and do not act as the mechanism of net vertical mass transfer.
7) These convective plumes comprise a convection region called the ‘Convection Chimney’ of 50~100 km scale.
8) A ‘rim current’ is generated around the edge of the convection regime, in thermal wind balance with the density gradient between the interior of the regime and the exterior.
9) The rim current develops meanders and instability eddies. These eddies break up the convection chimney into ‘cones’. The heavy water in the cones propagates and slumps down to its neutrally buoyant level, adding extra volume to the deep water.
10) Under weakened forcing, a thin stratified surface layer of warmer water moves in by lateral advection and forms capping over convection water.
11) Immediately following the end of convection, the convection region is a mixture of cold/fresh and warm/salty water, which soon settles down into a more isopycnally homogeneous and vertically stratified state through the sorting and mixing of lateral fine structure.

The Labrador Sea is one of the deepest convection sites in the world ocean. Air temperatures at nearby Iqaluit can average colder than –30ºC during winter months, when northerly and northwesterly winds can average 6 m s^{-1}. The regional ocean circulation is dominated by a cyclonic circulation, the western extremity of the cyclonic subpolar gyre of the North Atlantic. The sea off the continental shelf is held ice free by an inflow of warm, saline waters from the subtropics. This collision of cold air and ice-free ocean leads to large upward heat flux, reaching 700 W m^{-2} or more, with monthly averages in the range 200~300 W m^{-2}. Combined wind and buoyancy forcing uplifts isopycnals in the central Labrador Sea, reduces the stratification and makes the central waters susceptible to repeated deep convection.

Another important characteristic of winter convection is an essentially instable oceanographic structure, with increasing instability by negative buoyancy flux at the sea surface, sustained by dynamic balance, with increasing cyclonic circulation spun up by increasing wind stress. Thus, winter convection is a transitory phenomenon only observable during a strong and cold wind event. When driving forces of convection weaken or stop, the pycnostad water, forming a ‘convection chimney’, will collapse down into the oceanographic structure with density stratification in hydrostatic balance.

The process of winter deep convection forces us to revise the ordinary concept of ‘ventilation’ with an outcropping of isopycnals at the surface. With the exception of deep convection events, there remains a firm stratification with capping by the surface mixed layer. We cannot expect to capture the evidence of winter deep convection by making usual bimonthly or monthly ship observations, as winter deep convection can occur during monitoring breaks.

During deep winter convection, cyclonic circulation and its enhancement by strong, cold, dry winter winds blowing off the surface capping layer, and source of the salinity supply, can be common preconditioning and driving factors for the winter convection, as summarized in Table 1. Thus, in order to identify the mechanism of pycnostad water formation in the eastern part of the Okhotsk Sea to be winter convection, the occurrences of these factors will be examined in the next section, and compared to the Gulf of Lions and Labrador Sea.

Comparison of the Gulf of Lions and Labrador Sea, and with the Okhotsk Sea

We must note that the winter convection in the Gulf of Lions and the Labrador Sea is facilitated by the existence of higher salinity and higher temperature subsurface water, and with temperature maximum and salinity maximum or halostad, these are characteristics of tropical or subtropical waters. On the other hand, in the Okhotsk Sea the density stratification is mainly comprised from salinity stratification. Another difference is in the temperature of convection water, with potential temperature ranging from 12.8~12.95ºC in the Gulf of Lions (Schott *et al*., 1996) and 2.7~2.9ºC in the Labrador Sea (Lilly *et al*., 1999) compared to –1.0~2.0ºC in the Okhotsk Sea.

Surface cooling will bend the head of T/S profiles downward to be aligned to isopycnals. Further cooling will shift them to the right (direction of salinity increase), as vertical mixing associated with convection produces mixed water of less saline and cold water surface water, and saline and warmer intermediate water. Colder air with stronger winds will deepen the convection depth. In the case of the Gulf of Lions or the Labrador Sea, this procedure can take place in a temperature domain far higher than the freezing point while in case of the Okhotsk Sea, as water temperature is ranging near zero, and density is determined mainly by salinity, freezing

Table 1 Comparison of factors preconditioning and driving winter convection in the Gulf of Lions, Labrador Sea and Okhotsk Sea.

Factors preconditioning and driving winter convection	Winter convection sites		
	Gulf of Lions	Labrador Sea	Okhotsk Sea
Cyclonic circulation	Yes	Yes	Yes
Strong wind	Yes (Mistral)	Yes	Yes
Coldness	Yes	Yes	Yes
Open water	Open water	Open water	Open ocean polynya
Salinity supply	Warmer and saltier (13ºC, 38.47 psu) Levantine Intermediate Water	Warm and high salinity (4ºC, 34.95 psu), Irminger Water	Sea ice formation (North Pacific Water?)

can be easily reached. Therefore, for the winter convection to occur in the Okhotsk Sea, we need to consider the possible contribution of sea ice formation.

Another characteristic of the convection region in the Okhotsk Sea is that it is connected to the pycnostad waters in the Kuril Straits and to shallow water on the shelf, where strong tidal mixing dominates. Therefore, we also need to examine the effects of tidal mixing.

Factors preconditioning and driving winter convection in the eastern part of the Okhotsk Sea

Cyclonic circulation and strong winds

As currents over the Okhotsk Sea are difficult to measure in winter, a map of general circulation is produced only for the warm season, as shown in Figure 15. In this figure, the general cyclonic circulation around the Okhotsk Sea can be recognized, traced by the major currents.

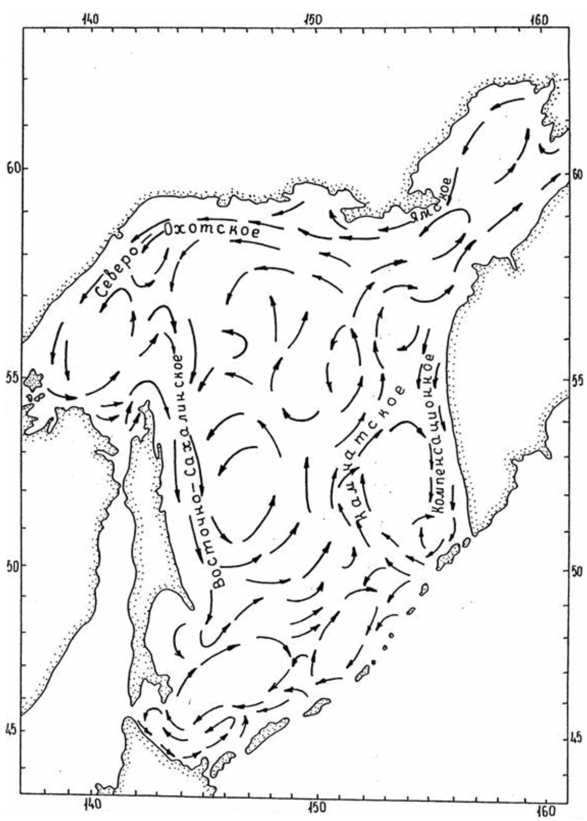


Fig. 15 General surface circulation of the Okhotsk Sea (Luchin, 1998). Clockwise from top right: the Yamskoe Current, the (West) Kamchatka Current and its northern countercurrent branch, the East Sakhalin Current, and the Northern Okhotsk Current.

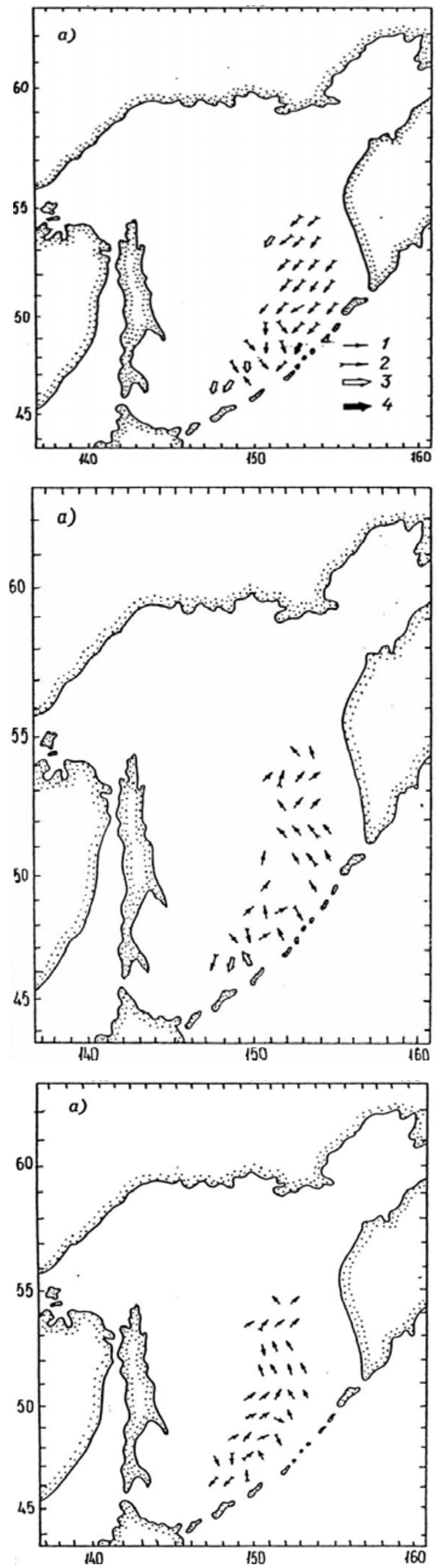


Fig. 16 February currents in the Okhotsk Sea calculated from density distribution and surface wind stress: (top) surface; (middle) 5m; (bottom) 100 m. (Luchin, 1998).

Figure 16 shows the surface, 5 and 100 m current vectors in the open water of the Okhotsk Sea in February (Fig. 16). The surface current vectors are directed southwest, indicating Ekman transport caused by strong northern winter monsoons. However, the current vectors for the 5 and 100 m layers are directed northward. Figure 17 displays the monthly mean transport of the East Sakhalin Current at 53ºN (Mizuta *et al.*, 2003). Therefore, the observed currents in winter are a strong northward current (the West Kamchatka Current) in the eastern part and a strong southward current (the East Sakhalin Current) in the western part of the Okhotsk Sea, indicating the development of a cyclonic circulation by strong winter monsoons. The transport of the East Sakhalin Current has a sharp peak in January–February, indicating that the driving wind is strongest at this time of year (Fig. 17).

Coldness and ice cover

A comparison of net heat flux between four marginal subarctic seas (Wang *et al*., 2007; Fig. 18) shows that the net heat flux from the sea surface greater than 200 $W{\cdot}m^{-2}$ occurs in the Okhotsk Sea during winter (December and January), and is the greatest among the four marginal subarctic seas.

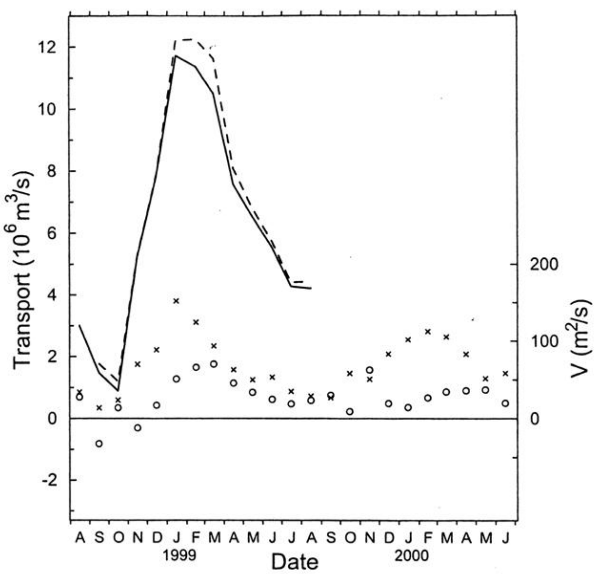


Fig. 17 Time series of the monthly mean transport (10^6 m^3s^{-1}) and vertically integrated velocity obtained from the data of four moorings M1 to M4 on the cross section at 53ºN on the east shelf slope of the Sakhalin Island. Solid and dashed lines denote the transport with and without the extrapolation outside of the mooring sites, respectively. Positive value indicates southward transport. Crosses and open circles indicate vertically integrated velocity at mooring sites M2 and M4, respectively (Mizuta *et al*., 2003).

Ice cover over the Okhotsk Sea exhibits large interannual variation, with a maximum of 150 × 10^4 km^2, minimum of 80 × 10^4 km^2, and average of 115 × 10^4 km^2. The period of annual maximum extent is February~March. Even in this period the open ocean polynya exists in the eastern part of the Okhotsk Sea, except when almost the whole Okhotsk Sea is covered by sea ice at the time of historical sea ice extent.

Ice potential analysis

For winter convection to reach a specific depth penetrating shallow stratification of surface capping, the density of the surface water must become equal to the density of water at that specific depth, through an increase of density by a decrease of temperature through cooling, and/or by an increase of salinity through the entrainment of saltier water laterally or vertically, as shown in the cases of the Gulf of Lions and the Labrador Sea. However, in the case of the subarctic Pacific, as density stratification is mainly determined by salinity stratification, simple cooling cannot cause density inversion and automatically deepen the cooling convection as in the subtropical waters or waters under the influence of subtropical water. Therefore, salinity increase through brine concentration during ice formation is an important driving factor for winter convection to reach deeper depths.

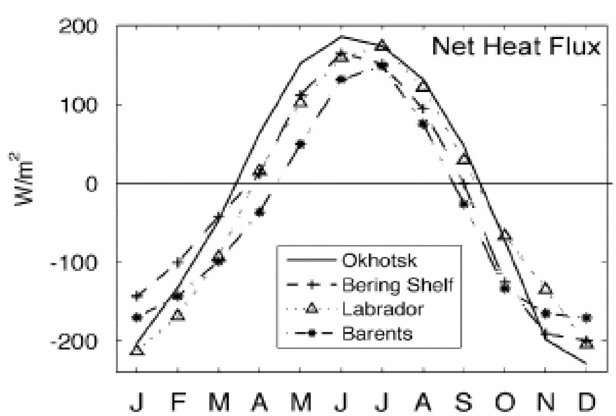


Fig. 18 Comparison of annual cycle of net heat flux among four marginal seas around the North Pacific (Wang *et al*., 2007).

Zubov (1945) coined the term ‘ice potential’, the amount of heat to be transferred from the water surface to air, necessary for convection to reach a specific depth ‘without ice formation’ in an effort to answer the questions “When will sea ice be formed?” and “How much heat is needed to be transferred from the water column to air before sea ice can form?” Terms needed to compute the ice potential include thickness of ice to be formed for convection to reach a specific depth, and the heat necessary to be transferred from sea. Thus, the ice potential calculation can be a useful diagnostic tool to determine winter convection in the first order approximation.

For calculation, the density of seawater is assumed equal to 1.00; density of sea ice is assumed equal to 0.90; salinity of sea ice is assumed 0; and latent heat of sea ice is equal to 335 $kJ \cdot kg^{-1}$ (= 80 $cal \cdot g^{-1}$). Results for the January ice potential at 52.5ºN, following the method of Zubov (1945) introduced by Tabata (1977), are shown in Tables 2 and 3. Table 2 shows the thickness of ice to be formed in order for convection to reach different depths for various stations. At the stations east of 149.5ºE, ice does not need to be formed by cooling for convection to reach as far down as 300 m. For stations in the western part of the section, ice some 10s of centimeters thick need to be formed by cooling in order for convection to reach beyond 100 m depth.

Table 2 Ice potential as depth of convection and ice thickness for January at 52.5°N in the Okhotsk Sea. The ranks of ice thickness are indicated by colour of cells: red: 0–10 cm; orange: 10–20 cm; yellow: 20–40 cm; green: 40–60 cm; light blue: 60–80 cm; blue: 80–100 cm; purple: 100–140 cm.

Ice Potential / Ice Thickness (cm) / 52.5°N January / Okhotsk Sea												
Depth	**144.5E**	**145.5E**	**146.5E**	**147.5E**	**148.5E**	**149.5E**	**150.5E**	**151.5E**	**152.5E**	**153.5E**	**154.5E**	**155.5E**
0 (m)												
10												
20	11	7	5	3	3	3	4	0	0	0	0	8
30	27	20	14	10	3	3	4	3	2	2	2	8
50	32	26	14	10	7	6	4	3	3	2	2	8
75	38	27	20	14	10	8	4	3	3	3	4	9
100	50	35	27	20	15	13	4	4	4	5	7	22
125	83	74	38	31	28	22	6	7	8	9	10	45
150	98	83	69	56	43	25	8	9	10	12	10	45
200	151	131	110	86	59	23	8	9	11	12	10	
250		148	120	91	54	21	7	9	12	14	10	
300		178	143	104	58	13	8	13	19	22	19	
400		336	168	127	81	38	27	28	37	55	91	
500		559	477	414	185	151	143	150	152	216		
600		632	544	475	409	354	321	312	289	376		
700		1335	1242	1161	1093	1034	543	506	483			
800		1348	1256	1187	1121	1062	1003	971	945			
900		1702	1585	1518	1453	1400	1354	1345				
1000		1874	1796	1739	1676	1627	1592	1602				
1100		1882	1986	1957	1921	1892	1869					
1200		1965	1995	2037	2058	2045	2035					
1300		2176	2261	2414	2417	2340						
1400		2426	2545	2743	2674							
1500		2628	2668									

Table 3 Ice potential as depth of convection and necessary heat transfer for January at 52.5°N in the Okhotsk Sea. The ranks of necessary heat transfer are indicated by colour of cells: red: 0–500 MJ m^{-2}; orange: 500–1000 MJ m^{-2}; yellow: 1000–1500 MJ m^{-2}; green 1500–2000 MJ m^{-2}; light blue: 2000–2500 MJ m^{-2}; blue: 2500–3000 MJ m^{-2}; purple: 3000–3500 MJ m^{-2}.

Ice Potential / SumQ (MJ m^2) / 52.5°N January / Okhotsk Sea												
Depth	**144.5E**	**145.5E**	**146.5E**	**147.5E**	**148.5E**	**149.5E**	**150.5E**	**151.5E**	**152.5E**	**153.5E**	**154.5E**	**155.5E**
0[m]												
10												
20	44	71	77	81	85	90	95	86	87	89	94	123
30	111	158	166	171	163	173	181	182	182	185	191	219
50	152	228	230	243	254	263	267	269	271	275	285	313
75	235	341	376	399	418	435	439	446	452	464	494	509
100	375	517	569	604	633	666	657	678	697	727	788	805
125	627	816	792	838	880	927	891	928	965	1015	1096	1178
150	900	1061	1110	1134	1159	1177	1134	1188	1243	1311	896	977
200	1361	1481	1505	1487	1465	902	842	872	1514	1597	1705	
250		2021	2001	2010	1893	747	1846	1951	2065	2188	2309	
300		2563	2501	2577	2318	2265	2322	2489	2659	2828	2973	
400		3554	3085	3203	2877	2850	2913	3105	3341	3609	3886	
500		5216	5025	5118	4267	4350	4503	4819	5129	5658		
600		6740	6500	6593	6270	6342	6499	6851	7118	7764		
700		10249	9977	10042	9739	9828	8653	8980	9311			
800		11688	11414	11539	11271	11397	11604	11989	12391			
900		14445	14038	14179	13940	14117	14456	14912				
1000		16709	16376	16563	16351	16564	16996	17497				
1100		15348	18672	18961	18844	19127	19592					
1200		20389	20419	20940	21005	21344	21830					
1300		22707	22919	23786	23808	23964						
1400		25147	25469	26472	26269							
1500		27457	27542									

Important features of Tables 2 and 3 are that a reduction in heat transfer of 3 × 10^3 MJ·m^{-2} can deepen the pycnostad water down to 400 m, with a total ice production of 30 cm. With the help of wind forcing creating anti-cyclonic circulation in the blowing off of the surface mixed layer, the necessary heat flux from the surface by cooling will be largely reduced. For validation of this possibility, estimates of heat flux at severe cooling events are needed.

Note the fact that although sea ice does not exist on the pycnostad water, it should not be understood as evidence for the disproof of the ice potential calculation. During a deep convection event, newly formed frazil ice and the surface mixed layer are to be blown off from the convection region but denser water produced by ejected brine can form a downwelling plume to drive convection.

Contribution of tidal mixing to winter convection

The unique feature of winter convection in the eastern part of the Okhotsk Sea is that the convection region is connected to the tidally mixed waters on the shallow coastal shelf and in the Kuril Straits. As the strong tidal current prevails in the coastal shelf from the west coast of Kamchatka through Shelikov Bay to the northern coast of the Okhotsk Sea, and in the Kuril Straits, vertically mixed water can be distributed around these areas and be advected along horizontal circulation. However, since the pycnostad water and convection with ice formation can only be observed in January, tidal mixing cannot be the major driving factor in the formation of pycnostad water and winter convection.

Conclusion

Judging from the factors preconditioning and driving deep convection (Table 1), the pycnostad water in the eastern part of the Okhotsk Sea can be seen as evidence of ongoing winter convection. The wind stress of strong northerly winter monsoons over the Okhotsk Sea drives the cyclonic circulation of the sea, including the East Sakhalin Current and the West Kamchatka Current, and accumulates and piles up the surface water and drift ice to the western side of the sea. This may be a possible mechanism for maintaining the open ocean polynya in the eastern half of the Okhotsk Sea.

The volume of water increased as the result of deep convection is the water having a σ_0 range of 26.75~27.1, which corresponds to the density of Okhotsk Sea Mode Water for the inside of the Okhotsk Sea, and to that of intermediate layer of Oyashio Water for the outside of the Okhotsk Sea. Thus, stronger and/or longer winter convection will produce a larger volume of Okhotsk Mode Water or water of the intermediate layer of Oyashio Water, which can make the intermediate layer of Oyashio Water colder and less saline. This suggests that the extent of decreased sea ice accompanied by global warming can bring a colder and less saline intermediate layer of Oyashio Water into the Okhotsk Sea.

In considering the results of winter convection on watermass formation and modification in the eastern part of the Okhotsk Sea, we note that the water mass formed by winter convection:

1) is not a homogeneous water mass that can be represented by single water type, but a group of pycnostad water types with different T/S value pairs for different depths and with different horizontal density trends;
2) has a relatively large spatial extent, with a range of 10ºN × 3ºE (*ca.* 1000 km × 300 km), comparable or larger than that of the Labrador Sea or Gulf of Lions.

Thus, the water mass produced by winter convection at the open ocean polynya of the Okhotsk Sea will cause considerable interannual variability in temperature and salinity of the intermediate layer in response to the interannual variability of the winter climate in the region.

Kasai *et al.*'s (1997, 2007) analysis of the A-line dataset shows the enhancement of primary productivity in the Oyashio region after the 1998 regime shift, and the increased density gradient in the euphotic zone by increased temperature and/or lowered salinity in the surface layer can be the possible environmental conditions causing enhancement of primary production. The present study suggests that winter deep convection can be one of the physical processes causing these changes.

Subjects for future studies

This is a preliminary study, as analyses are limited to winter and at the stations of pycnostad sites. The deep convection resulting from cooling at the sea surface persists only for a period of a few days but occurs over regions of horizontal extent of order of 100 km (Thorpe, 2005). However, depending on its spatial scale, the resultant effect on water mass formation is not negligible, although the temporal nature of the phenomenon makes winter deep convection seem like a trivial transient event and hides its existence from synoptic features. Thus, it is a marvel that the WOA05 contains a fine shot of winter deep convection in the Okhotsk Sea.

Furthermore, as primitive equations used in general circulation models exclude convection with vertical acceleration, diagnosing or interpreting winter convection by ordinary general circulation models based on the premise of a hydrostatic ocean, are basically difficult. Thus, the development of a combined atmosphere–sea ice–ocean model that allows winter deep convection is necessary for assessing the effects of winter deep convection on climate variability associated with global warming.

The following items are subjects for study of the Okhotsk Sea to be performed in near future under international collaboration such as the PICES FUTURE (Forecasting and Understanding Trends, Uncertainty and Responses of North Pacific Marine Ecosystems) program:

1) The necessary preconditioning for winter convection, including possible maximum heat transfer from sea to air during cooling events;
2) The time change in temperature and salinity, including the effect of inflowing East Kamchatka Water;
3) The process of mixing and transport of ejected brine at ice formation sites on the shelf;

4) The freshwater supply to open water by stray drift ice;
5) The effects of tidal mixing and internal tides on the formation of pycnostad water;
6) The response of the convection process to interannual climate variability.

A full elucidation of the winter convection process needs to be addressed in field process studies, including the use of pop-up floats, modeling studies, and historical data analyses.

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