Vertical movement of water masses in the western part of the Sea of Okhotsk

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Abstract

Recent observations of the well studied dichothermal layer (with T < 0 °C) in the Sea of Okhotsk provides an update of its inner structure. In the 1990s, CTD vertical soundings with 1 m resolution found cases of “double” or “triple” dichothermal layers on the continental slope and in the deepest part of the Sea of Okhotsk. The genesis of those phenomena is linked with pre-winter cooling of the water column, following convection and brine rejection under ice floes, and frontal interactions between water masses. Based on new data to explain dichothermal structure, we note an obvious discrepancy between calculated winter convection depth and real descending horizons for subzero temperatures reaching few hundreds meters at the southwestern part of the Sea of Okhotsk. Because of the lack of applied theory to account for vertical movements in the Sea of Okhotsk, an experiment using year-round mooring data was conducted for its study. From August 2006 to October 2007, the N-5 mooring was deployed at the northern tip of Sakhalin Island in the western part of the Sea of Okhotsk at mid-shelf depth around 100 m close to the region where the East Sakhalin Current originates. A year’s run of vertical current data showed clear seasonal signals averaged over the whole depth layer current changing from downwelling in the summer to the upwelling during cold period of the year. The vertical structure showed a complex nature with heterogeneous vertical movements occurring at relatively shallow depths on the Sakhalin shelf. Differences in vertical current structure are discussed for the fall, winter, spring, and summer seasons alternately with vertical movements through the year.

Introduction

Despite the well-known Sea of Okhotsk’s cold intermediate or dichothermal layer (DTL), discovered in 19th century by Makarov (1894), which is characterized by subzero temperatures, little attention has been paid to its inner structure. The vertical movement of water masses from the surface to the bottom during winter convection after surface cooling, and brine rejection under ice floes, are one of the most obvious processes explaining the presence of negative temperatures at different depths in the Sea of Okhotsk, and especially in the western part, due seasonal ice distribution.

Water, having a negative temperature in winter, located beneath the surface layer and later insulated during summer warming, is called the cold intermediate layer (dichothermal layer). Before the era of CTD measurements, it was difficult to obtain a detailed picture of the water column due to the scarcity of vertical measurements by water bottle sampling. With the introduction of CTD sensors and probes, the internal vertical structure of the water could be observed with meter and submeter vertical resolution (UNESCO-MHI, 1993). From detailed CTD measurements in the western part of Sea of Okhotsk, temperature inversions inside the cold interlayer or “double”, sometimes “triple”, cold interlayers have been found in mostly stable water stratification during the summer (Kantakov, 1995). Besides the discovery of dual thermal structures inside the dichothermal layers, the residual depth of convection after winter in the western part of the Sea of Okhotsk is often exceeded in calculations, which makes it necessary to explore the role of the mechanisms of vertical motion of water masses here. To explain the oceanic conditions responsible for the appearance of double dichothermal layers and to explain the over-estimation of the convection depths missed with calculations, we have processed a number of CTD data, and the vertical velocity of water masses in the western part of the Sea of Okhotsk was measured.

This article attempts to present new facts which will allow us to understand the role of the vertical motions of water in the subarctic Sea of Okhotsk from the points of view of physical and biological oceanography, climatic changes and hydrography of the sea.

Data and Methods

The study region of the Sea of Okhotsk, showing the arrangement of standard and additional oceanographic stations with the N-5 mooring site, are given in Figure 1. The physical parameters of the marine environment were measured in the free drift of vessels equipped with different sensors such as the Neil Brown Mk-III, ICTD FSI and Guildline. The N-5 mooring, equipped with an ADP with frequency of 0.500 MHz, was deployed on August 27, 2006 and recovered on October 8, 2007 by SakhNIRO's R/V *Dmitry Peskov*. Most of the CTD data were collected during joint expeditions of SakhNIRO with the Pacific Oceanological Institute (POI, Vladivostok) and the Far-Eastern Hydrometeorological Institute (FEHRI, Vladivostok) during the 1990s.

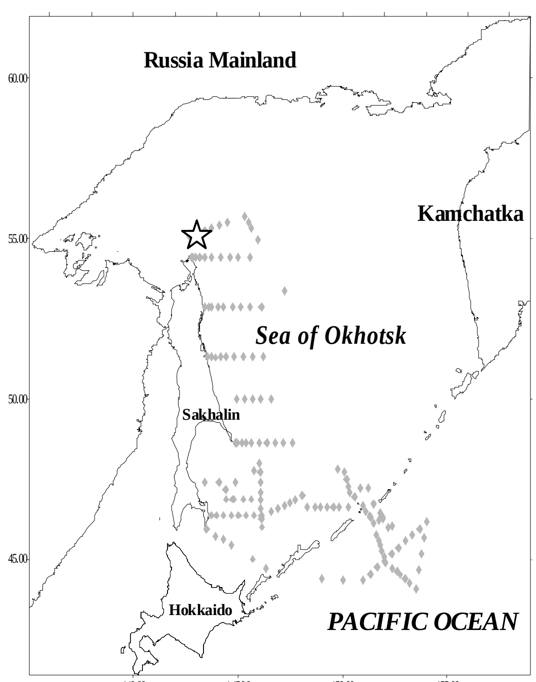

Fig. 1 Location of CTD stations in 1996–2000 during the joint expeditions between SakhNIRO, POI and FEHRI, and the N-5 mooring (star) in 2006–2007.

Convection calculations were carried out according to Arkhipkin (1992). A spatial flow pattern in the western part of Sea of Okhotsk was obtained using the dynamics method from the "zero" surface of 1000 db (Timofeev and Panov, 1962).

Study of the currents, including the vertical component, was conducted using three-component Doppler profilers (Cabrera *et al.*, 1987; Polonichko *et al.*, 2000), which made it possible to investigate both the horizontal and vertical velocities of the flows *in situ*.

Results and Discussion

Figure 2 presents a typical vertical temperature distribution in the western part of Sea of Okhotsk based on the standard horizon measurements and characterizing the northeastern shelf/slope of Sakhalin. Two main features are apparent – the dichothermal layer has a united body, and temporal changes from summer to autumn are insignificant (Fig. 2). However, during the soundings with greater depth resolution, frequent inversions are seen. One such example is shown in the Figure 3.

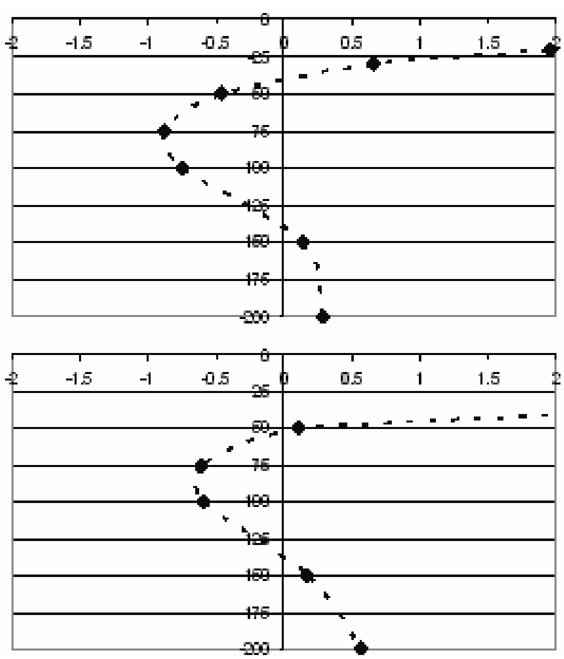

Fig. 2 An example of the vertical temperature distribution (°C) of an average DTL at standard horizons in June (upper), and in October 1994 (bottom) in the western part of the Sea of Okhotsk, Sakhalin NE shelf area (Source: FEHRI–SakhNIRO data).

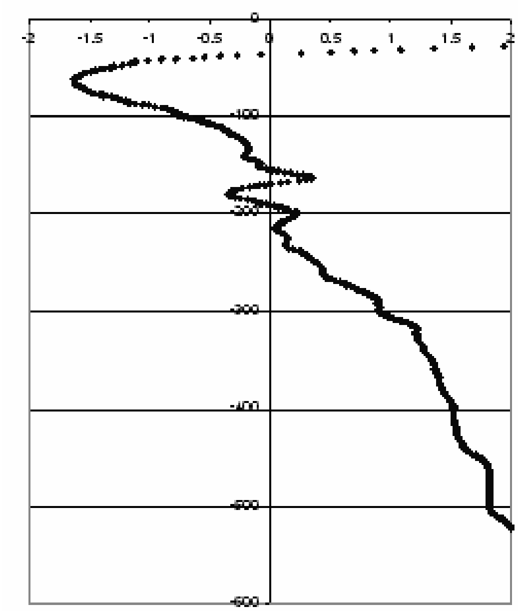

Fig. 3 Vertical temperature distribution (°C) on the slope at the western part of the Sea of Okhotsk, using 1-m resolution sounding, June 17, 2000. (Source: FEHRI–SakhNIRO data, R/V *Pavel Gordienko*).

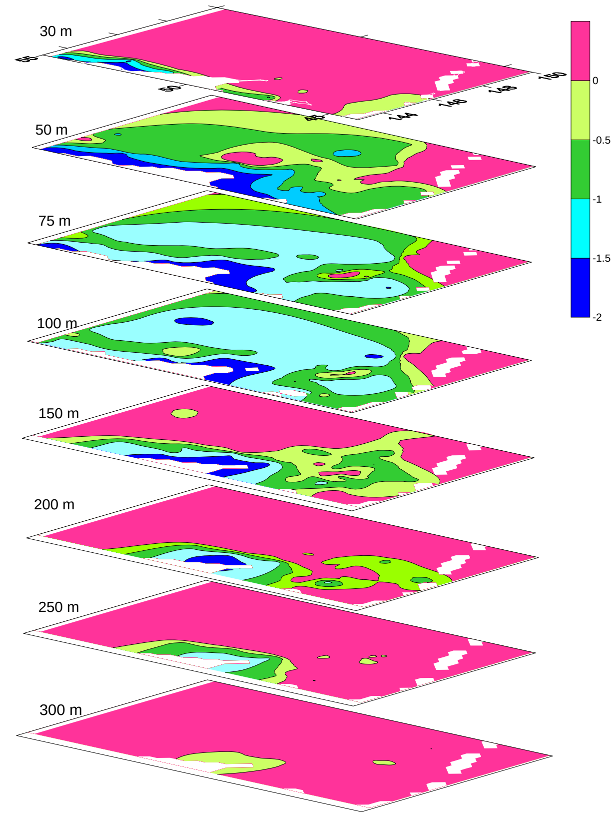

Fig. 4 Subzero temperature distribution (°C) at selected standard horizons, western part of the Sea of Okhotsk, June 1996 based on Figure 1 CTD stations (Source: POI–SakhNIRO 1996 data).

If the vertical distribution has temperature inversions (Fig. 3), how are the inversions arranged spatially, for example, in the western part of Sea of Okhotsk? In order to understand the distribution of inversions inside the DTL, 1996 data have been processed from the joint POI-SakhNIRO expedition. For clarity and ease of presentation, the arrangement of inversions inside the DTL temperature distributions on the standard horizons superimposed on one another from top (30 m) to bottom (300 m) are shown in Figure 4. Such superpositioning of the different horizons shows regions of temperature inversions inside the DTL, but it is obvious, that there is no spatial predominance of inversions inside the layer –this is apparently local phenomena according the 1996 data analysis (Fig. 4). Nevertheless, new facts about the vertical distribution of temperature inversions in the DTL pose a new question – Why do the temperature inversions penetrate more deeply than calculated?

Knowing the characteristics of the ice thickness in the western part of the Sea of Okhotsk, we know that theoretically convection does not penetrate deeper than 250–300 m. But we actually do observe the presence of DTL depths on the order of 500 m. How can we explain such measurements? Are they showing a flow downward or are they the remainders of the past year, or year before last? (What causes the DTL to "think", *i.e.*, have a "dichothermal layer memory", which reflects the convection level of previous year?)

Here, we analyze convection during the cold period of the year. How is it shown for the Sea of Okhotsk? Besides the winter type of classical convection for the cooling and freezing areas, the Sea of Okhotsk possesses convection during the summer period when the flow of salt with the Soya Current inside Sea of Okhotsk leads to the lowering of waters at its southwestern basin near the South Kuril Islands. Here, we can observe an underwater waterfall with a horizontal scale tens of kilometers and hundred meters vertically, which also makes it necessary to think about the reasons for vertical motions in the Sea of Okhotsk.

A similar picture in the winter period is also observed on the Kamchatka shelf and slope (Kashiwai, this report) when more salt water from the Pacific Ocean causes convection, but this exceeds the scope of our article. Therefore, we do not discuss it further, but keep it in mind for future investigations.

This allows us to concentrate on the following issue. If we observe the DTL practically the year round in the western part of the Sea of Okhotsk, then apparently there are conditions for its retention here, some of which we know a little about regarding the vertical components of currents in this region. It is known that the general cyclonic circulation of the surface flows in the Sea of Okhotsk water mass distribution (Leonov, 1960; Moroshkin, 1966; Chernyavsky, 1981) must lead to the rise of waters in the central Sea of Okhotsk basin, with the dichothermal layer disappearing, probably seasonally. However, it exists in the western part Sea of Okhotsk all year-round.

Aiming to measure the vertical component of the current velocities, the N-5 mooring with an ADP was installed at the northern tip of Sakhalin, just inside the zone of the beginning of the Eastern Sakhalin Current. At the same time, temperature was recorded at a depth of 100 m on the layer where the DTL should exist; current profiles at different horizons were also taken. The year-round duration of the velocities and temperature measurements are shown in Figure 5. It can be seen that the motion of the averaged vertical velocity possesses an expressed seasonal signal with positive vertical velocities (upward) for the cold period of year and negative ones (downward) during summer and early fall period.

Analyzing the layer below the seasonally heated upper one, we found that during observation period the vertical component was negative and directed towards the bottom without any seasonally induced changes in the magnitude and sign of the vertical velocities, except for interannual differences between the fall periods of 2006 and 2007, respectively (Fig.6). In addition, bottom temperature was negative all year (Fig.7). A period of about one month, between mid-October and mid-November 2006 had a signal, which indicates some reflection of weak warming near the bottom from subzero temperatures. Temperature was mainly stable between about –1.7° and –1.6°C for the rest of the year at this depth after peaking to –0.65°C in early December (Fig.7).

The year-round subzero temperatures at 100 m depth on the shelf strongly confirm and update previously obtained results (Gladyshev *et al.*, 2000, 2003; Mizuta *et al.*, 2003; Shcherbina *et al.*, 2003). The shelf and slope at the northwestern part of the Sea of Okhotsk is defined as a permanent source of water with subzero temperatures supplying the DTL in the western part of the Sea of Okhotsk.

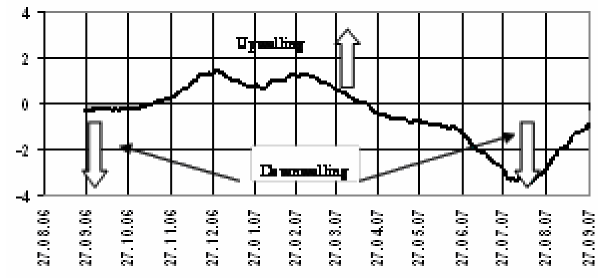

Fig. 5 Vertical (W) component of velocity measured by the N-5 ADP mooring. Note: The whole depth layer, averaging 0–100 m, is smoothed monthly data. Horizontal axis is from August 2006–September, 2007. Vertical axis is in cm s^{-1}.

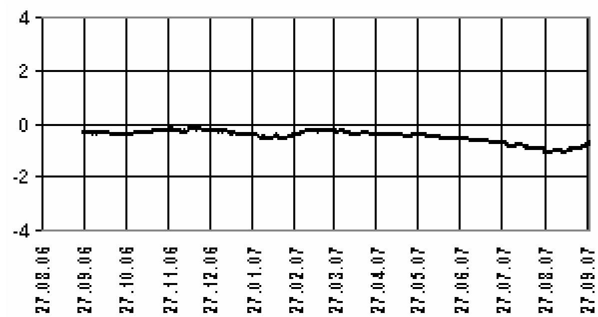

Fig. 6 Vertical (W) component of velocity measured by the N-5 ADP mooring Note: The subsurface layer averaging 30–100 m is smoothed monthly data. Horizontal axis is from August 2006–September, 2007. Vertical axis is in cm s^{-1}.

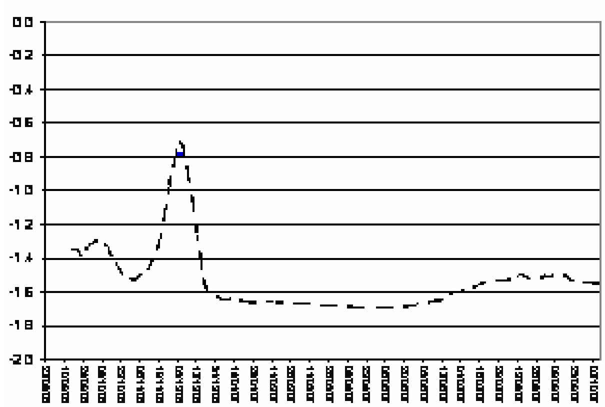

Fig. 7 Temperature dynamics (°C) at 100 m depth at the N-5 mooring site from August 2006 to October 2007.

Meanwhile a relatively strong warming signal inside the DTL coincided in time with the amplification of the East Sakhalin Current in the fall. It is known that in the western, but mostly in the northwestern, part of the Sea of Okhotsk, the current circulation system is a function of the year type (Figurkin, 2000). Cold years are characterized by the alongshore East

Sakhalin Current which is directed to the south (Ohshima *et al.*, 2002); an opposite picture should be obtained for the warm years when northward water flows mostly along the shelf and slope of Sakhalin. Currently, we have no measurements of the vertical components for the East Sakhalin Current directed to the north, or in the period when circulations are undergoing change.

Figure 8 shows locations of the “double” DTL at the shelf and continental slope of Sakhalin which are found in current convergence zones or at eddy borders in deep waters.

Comparing the dynamic topography map with the location of sea surface temperature fronts (Belkin and Cornillon, 2004), we note the agreement of belts of convergence with places of inversions inside the DTL, both in the deepest basin of the southwestern Sea of Okhotsk and in the waters around Terpeniya Peninsula. Examining the more generalized map of the Sea of Okhotsk frontal zones (Belkin and Cornillon, 2004), we conclude that the high temperature intrusions inside the DTL are generated at the frontal borders of water masses in the Sea of Okhotsk.

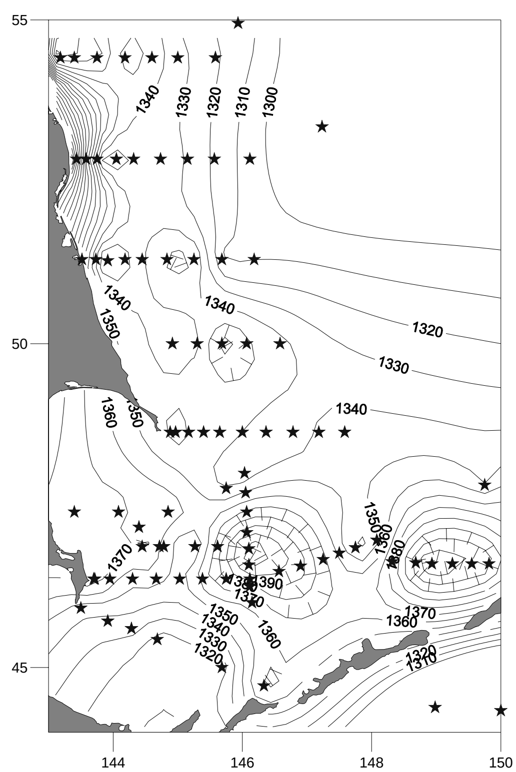

Fig. 8 Dynamic heights distribution (10/1000 db) in the western part of the Sea of Okhotsk, June 1996 (Source: POI–SakhNIRO data, R/V *Gagarinsky*).

Conclusions

Temperature inversions inside the DTL are located in the convergence zone and (or) near the thermal fronts in the Sea of Okhotsk. In the Sea of Okhotsk at least two types of the convections are obtained, linked with the transport of salt water during the warm period by the Soya Current or Pacific waters, and connected with cooling and brine rejection under ice floes during the late autumn and winter.

Observations at the N-5 ADP mooring from 2006–2007 confirmed DTL waters submerging during the whole period of observations. The upper mixed layer had another type of vertical motion, switching from upwelling to downwelling in the cold and the warm period of year, respectively. These data need to be confirmed by other studies, including those of seasonal behavior of the open water levels. The changeability in the vertical motions of water inside the Sea of Okhotsk must be investigated in relation to its obvious influence on sea biota, especially for early ontogenetic stages, and to contemporary trends in climate oscillations and hydrography.

Observed convection depths of the DTL are deeper in the comparison with those calculated by theory for the western part Sea of Okhotsk, and requires separate and detailed studies. It is obvious that organizing a series of ice-breaker expeditions is needed to study the formation of convections under the ice and in polynyas in the Sea of Okhotsk in winter because there are no oceanographical, chemical or biological data during ice formation and seasonal melting.

References

Arkhipkin, V.S. 1992. Algorithms and FORTRAN programs for oceanological data analysis. MSU, Moscow, p. 83 (in Russian).

Belkin, I.M. and Cornillon, P.C. 2004. Surface thermal fronts of the Okhotsk Sea. *Pacific Oceanogr.* **2**: 6–19.

Cabrera, R., Deines, K., Brumley, B. and Terray, E. 1987. Development of practical coherent acoustic Doppler current profiler. Proc. Ocean’87. Halifax, NS, Canada. IEEE Oceanic Engineering Society. pp. 93–97.

Chernyavsky, V.I. 1981. Sea of Okhotsk circulation systems. TINRO Proc. No. 105, pp. 13–19 (in Russian).

Figurkin, A.L. 2000. Okhotsk sea shelf and slope waters circulations in cold seasons of the year. 9th PICES Annual Meeting. Hokkaido, Japan, p. 51 (Abstract).

Gladyshev, S.S., Martin, S., Riser, S. and Figurkin, A. 2000. Dense water production on the northern Okhotsk shelves: Comparison of ship-based spring-summer observations from 1996 and 1997 with satellite observations. *J. Geophys. Res.* **106**: 26,281–26,299.

Gladyshev, S.S., Talley, L., Kantakov, G., Khen, G., and Wakatsuchi, M. 2003. Ditribution, formation, and seasonal variability of Okhotsk Sea Mode Water. *J. Geophys. Res.* **108**: 3186.doi:10.1029/2001JC000877.

Kantakov, G. 1995. Vertical temperature distribution feature in an intermediate cool water layer of the Sea of Okhotsk. Workshop on the Okhotsk Sea and adjacent areas PICES Abstracts. June 19–24, 1995, Vladivostok, Russia, pp. 21–22.

Leonov, A.K. 1960. Regional Oceanography. Gidrometeoizdat, Leningrad, 766 pp. (in Russian).

Makarov, S.O. 1894. Vityaz i Tikhiy Okean, Vol. 1, p. 337; Vol. 2, p. 543 (in Russian).

Kashiwai, M. 2009. The occurrence of winter convection at the open ocean polyna in the eastern part of the Okhotsk Sea indicated by the World Ocean Atlas 2005. This report.

Mizuta, G., Fukamachi, Y., Ohshima, K.I. and Wakatsuchi, M. 2003. Structure and seasonal variability of the East Sakhalin Current. *J. Phys. Oceanogr.* **33**: 2430–2445.

Moroshkin, K.V. 1966. Water masses of the Sea of Okhotsk. Joint. Publ. Res. Serv. 43942, U.S., p. 98.

Ohshima, K.I., Wakatsuchi, M., and Fukamachi, Y. 2002. Near-surface circulation and tidal currents of the Okhotsk Sea observed with satellite-tracked drifters. *J. Geophy. Res.* **107**: 16-1–16-18.

Polonichko, V., Mullison, J. and Cabrera, R. 2000. Pulse-coherent acoustic Doppler profiler. *Sea Technol.* **2**: 76–78.

Shcherbina, A., Talley, L. and Rudnick, D. 2003. Direct observations of North Pacific ventilation: Brine rejection in the Sea of Okhotsk. *Science* **32**: 1952–1955.

Timofeev, V.T. and Panov, V.V. 1962. Indirect Methods for Classification and Analysis of Water Masses. Hydrometeoizdat, Leningrad, 351 pp. (in Russian).

UNESCO-MHI. 1993. Data analysis of the Oceanographic Station. Sebastopol, p. 136 (in Russian).