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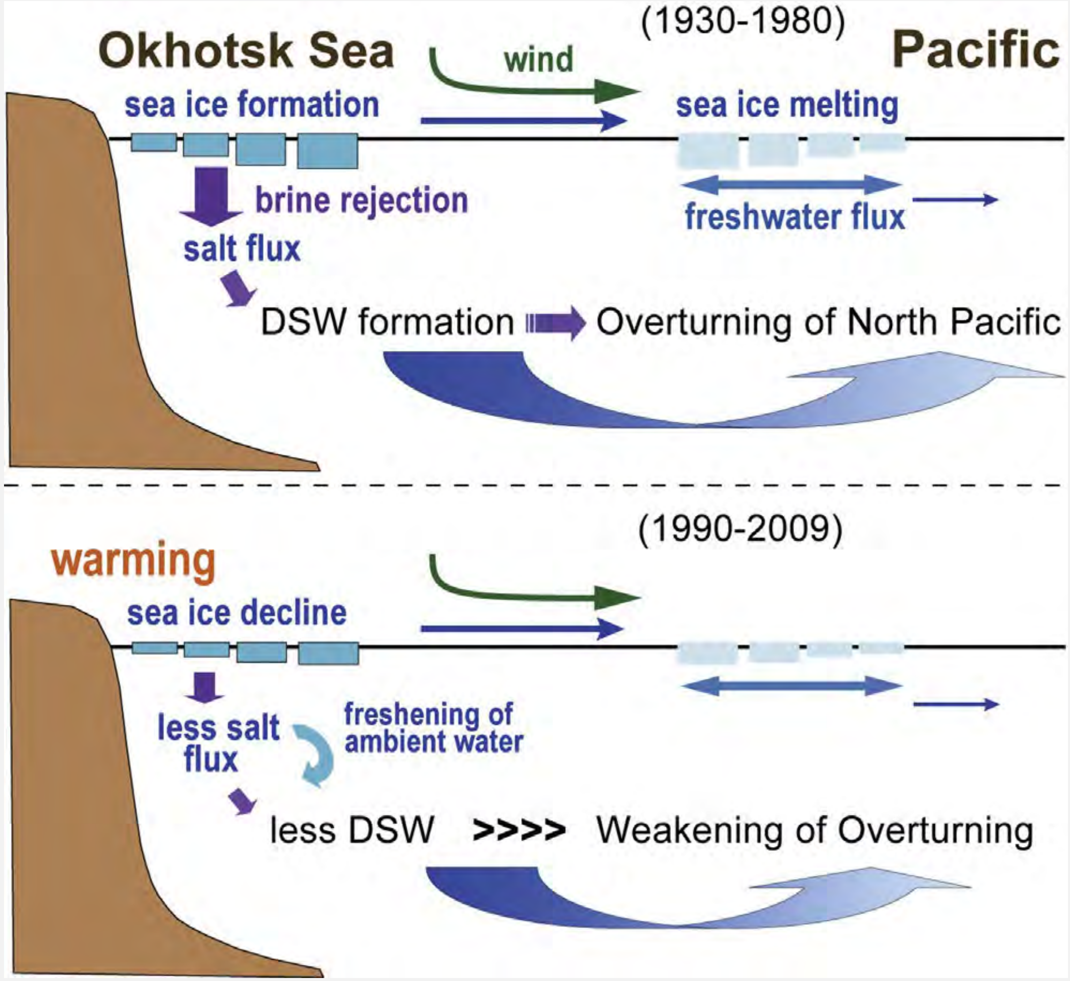
Recent changes in producing of the Intermediate water in the Okhotsk Sea

Problem

Hypoxia events become more frequent in the upwelling areas at the USA western coast that is caused by lowering of dissolved oxygen content in the North Pacific Intermediate Water. One of the reasons of this lowering could be a weakening of this water mass ventilation by the high-density water originated from the Okhotsk Sea, but any evidences of this process are necessary.



Hypothesis on ventilation of the North Pacific Intermediate Water by the high-density water originated from the Bottom Shelf Water of the northern Okhotsk Sea (Ohshima et al., 2014)

Problem

The high-density Bottom Shelf Water is formed on the northern Okhotsk Sea shelf in the process of freezing. Its density is high enough for sinking into the intermediate layer. But is it really able to cross the sea to the Kuril Straits and how is it transformed on that way?

Concerning the climate change, long-term changes of this water production and properties are considered and possible mechanisms of these changes are discussed.

Hypothesis on ventilation of the North Pacific Intermediate Water by the high-density water originated from the Bottom Shelf Water of the northern Okhotsk Sea (Nishioka et al., 2014)

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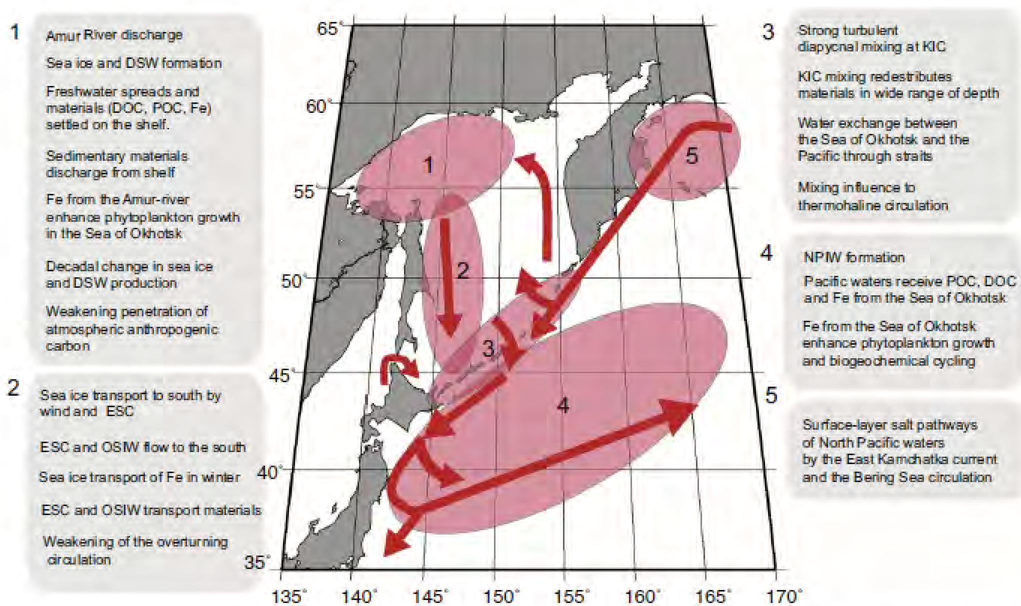


Fig. 2. Physical and biogeochemical processes in the Okhotsk–Pacific system. DSW: Dense Shelf Water, ESC: East Sakhalin Current, OSIW: Okhotsk Sea Intermediate Water, KIC: Kuril Islands chain, POC: Particulate Organic Carbon, DOC: Dissolved Organic Carbon.

Goals

- to determine how fresh portions of the Intermediate water are formed at the shelf and slope of the Okhotsk Sea and how they transfer across the sea to the North Pacific.

- to evaluate changes of this process in recent times, with special attention to changes of the intermediate layer ventilation with this mechanism.

Data. Direct shipboard observations

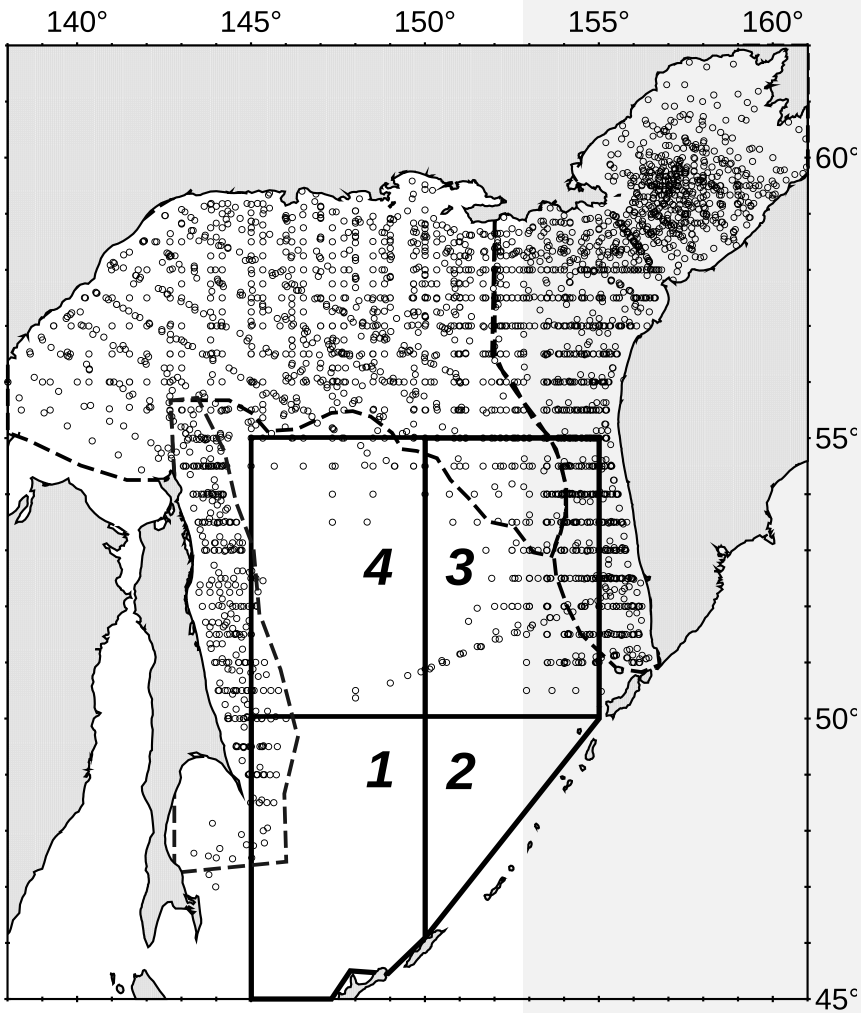
The Okhotsk Sea is well-surveyed by Pacific Fish. Res. Center (TINRO) that conducted annual oceanographic surveys since 1994. The data of direct observations aboard the research vessels are processed by several ways:

1) Annual volume is estimated for the Bottom Shelf water with the high density capable to sink to the inter-mediate layer (σ_θ > 26.6, 26.7, 26.8, 26.9, 27.0, and 27.1). Its year-to year changes and tendencies are determined.

2) Fresh portions of the Intermediate water formed by cascading of the dense water from the shelf are found within the intermediate layer as lenses with the local minimum of temperature.

3) They are identified using signs of their temperature, salinity, depth, and location. Tracks of their transfer across the Okhotsk sea are traced. Variations of their temperature, salinity and DO along the tracks are evaluated.

4) Long-term changes of temperature and salinity in the core of the fresh portions are traced and the changes of oxygen content at certain isopycnes are determined for certain areas of the deep-water Okhotsk Sea.



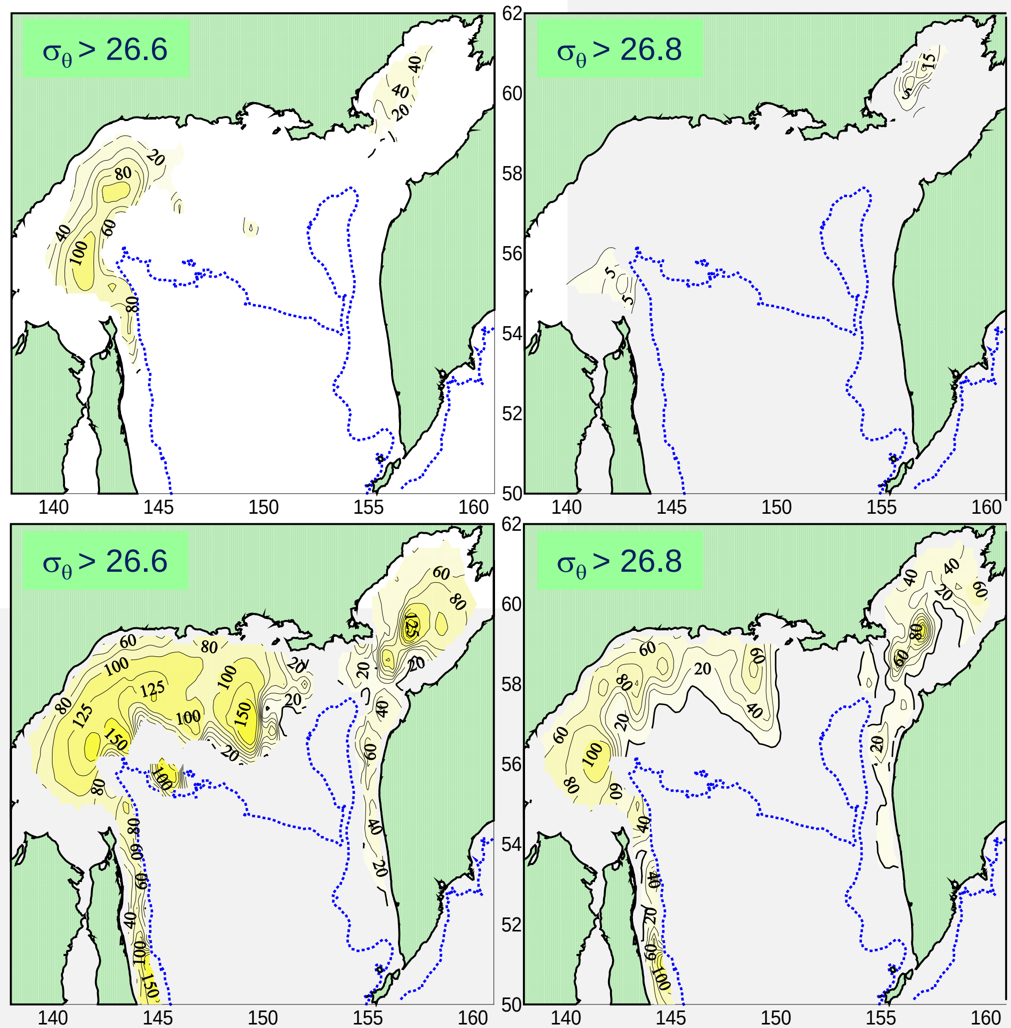
Oceanographic stations on the Okhotsk Sea shelf observed in 1994-2017 and the deep-water areas for annual averaging of the oxygen data

1. Dynamics of the high-density Bottom Shelf Water on the northern shelf

Year-to-year changes of the high-density water on the northern Okhotsk Sea shelf correspond to the changes of the Okhotsk Sea ice cover: the more the ice, the more the water is produced annually

after warm, low-ice winter (1997)

after cold, icy winter (1998)



Thickness of the high-density Bottom Shelf Water layer with $\sigma_\theta > 26.6$ and $\sigma_\theta > 26.8$ in spring of 1997 and 1998

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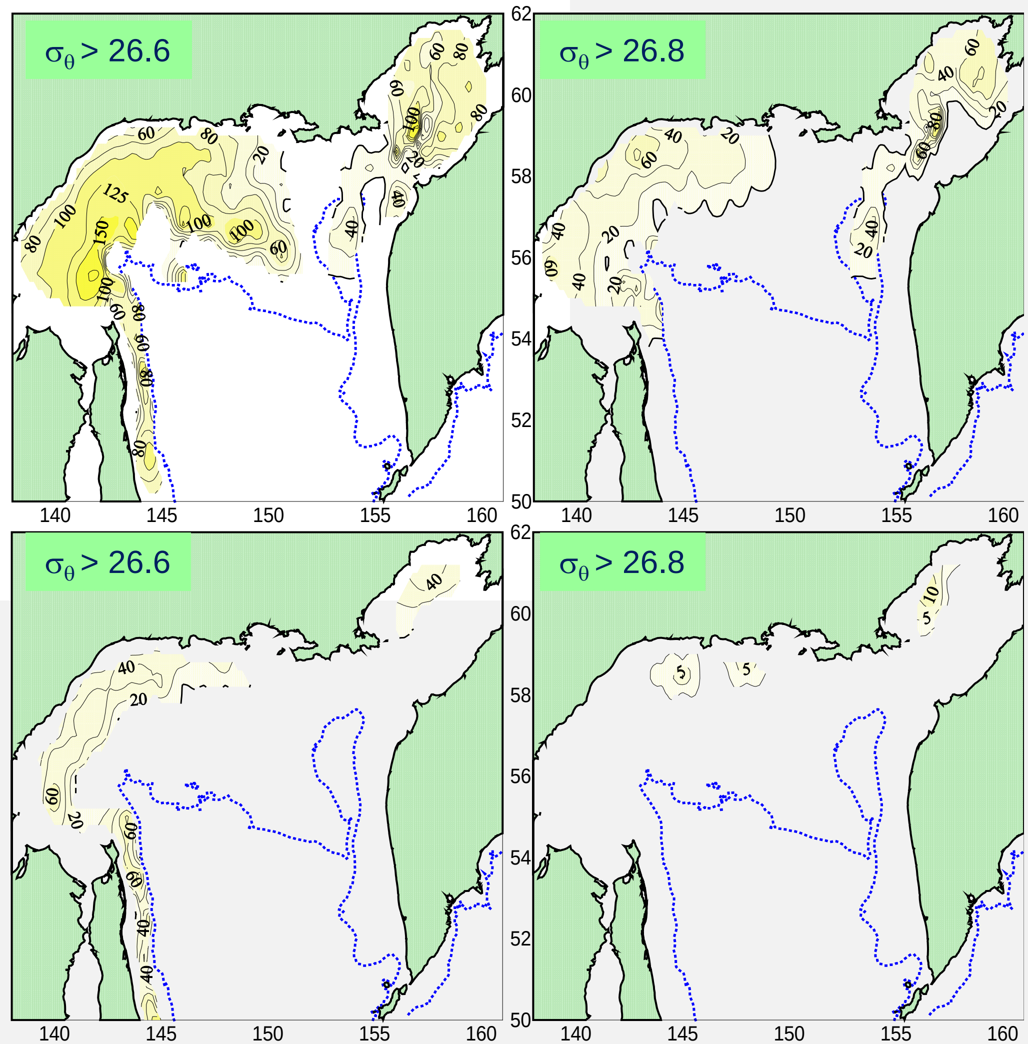
Year-to-year changes of the high-density water on the northern Okhotsk Sea shelf correspond to the changes of the Okhotsk Sea ice cover: the more the ice, the more the water is produced annually

after moderate winter (2005)

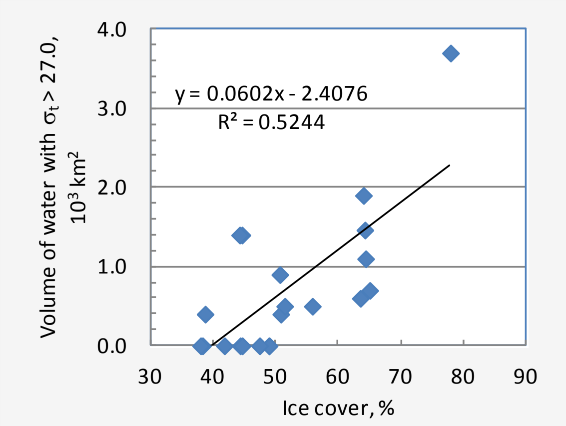
after extremely warm winter (2014)



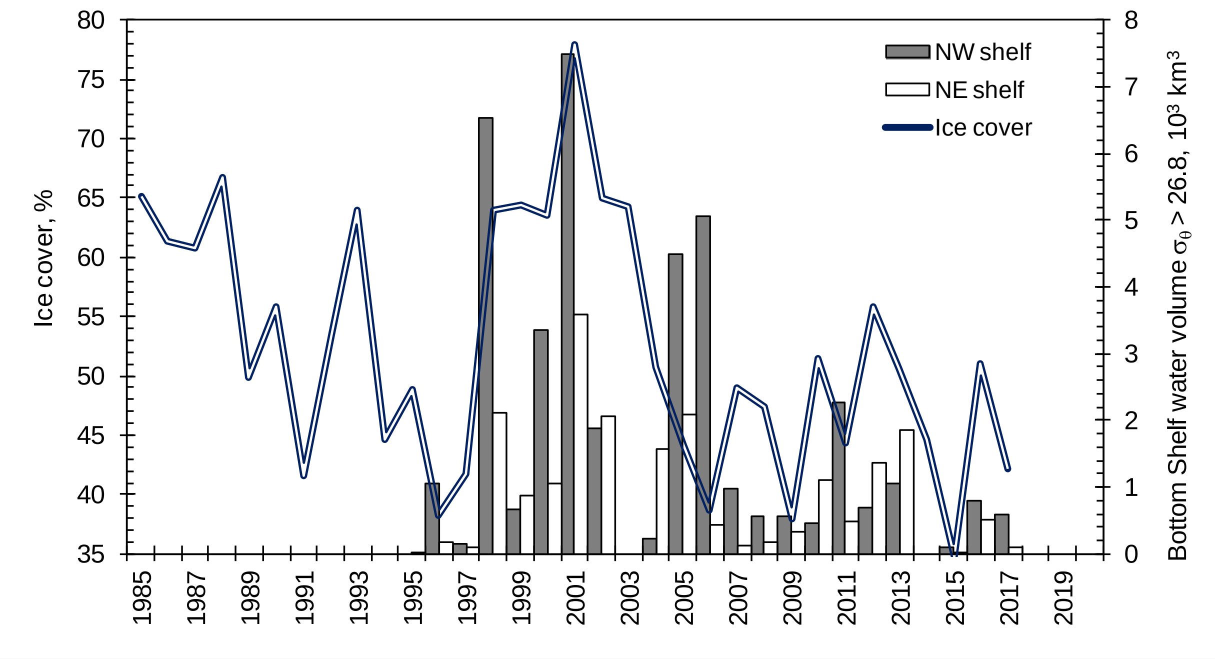
Thickness of the high-density Bottom Shelf Water layer with $\sigma_\theta > 26.6$ and $\sigma_\theta > 26.8$ in spring of 2005 and 2014

1. Dynamics of the high-density Bottom Shelf Water on the northern shelf

Year-to-year changes of the high-density water on the northern Okhotsk Sea shelf correspond to the changes of the Okhotsk Sea ice cover: the more the ice, the more the water is produced annually. Tendencies to decreasing of both parameters are observed in the last two decades.



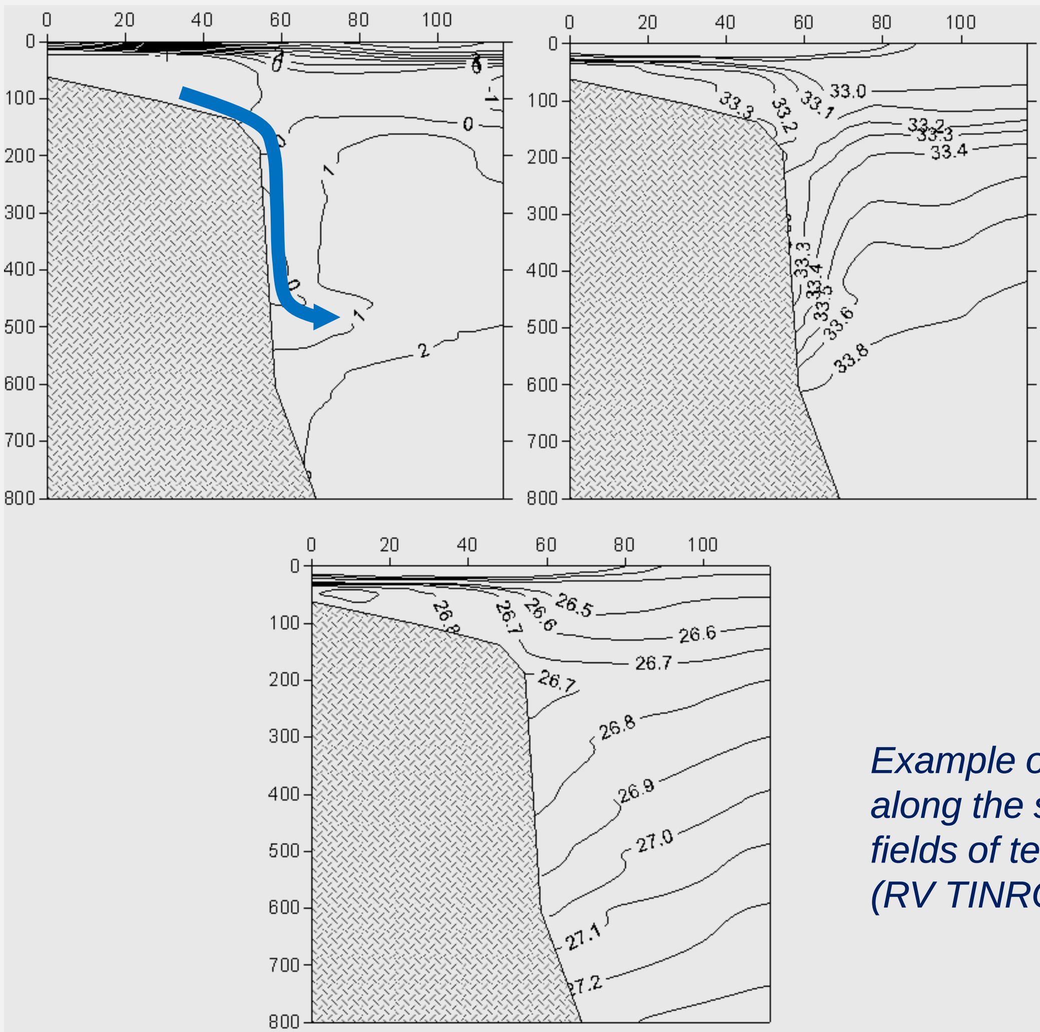
Correlation between the mean annual ice cover in the Okhotsk Sea and the volume of the high-density Bottom Shelf Water on its northern shelf in spring ($\sigma_\theta > 27.0$)



Year-to-year changes of the mean annual ice cover in the Okhotsk Sea and the volume of the high-density Bottom Shelf Water on its northern shelf in spring (no data for 2003). Both ice cover and high-density water production decrease recently

2. Cascading of the high-density water and forming fresh portions of the Intermediate water

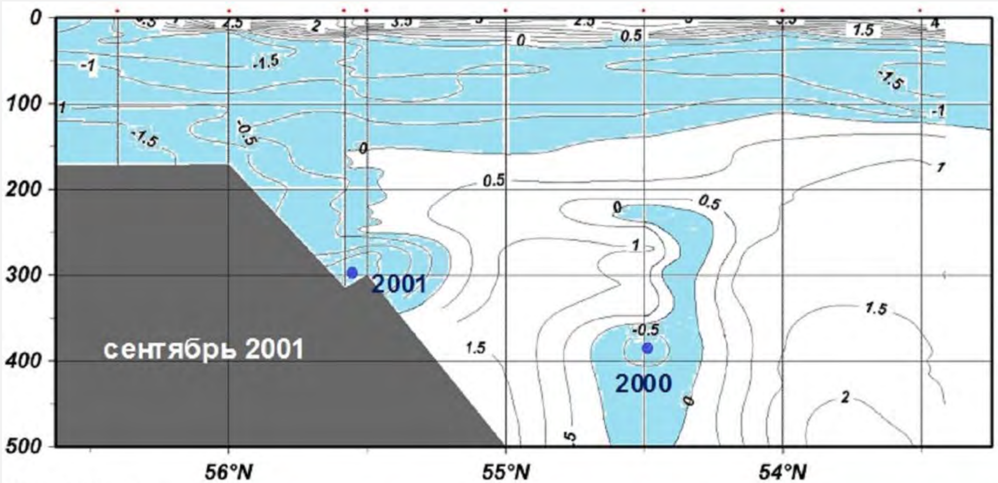
Sometimes cases of the high-density water cascading from the northern Okhotsk Sea shelf could be observed. Their density is enough for sinking into the intermediate layer, usually to 300-500 m, that is deeper than the depth with the same density in the open sea due to kinetic energy of the cascading.

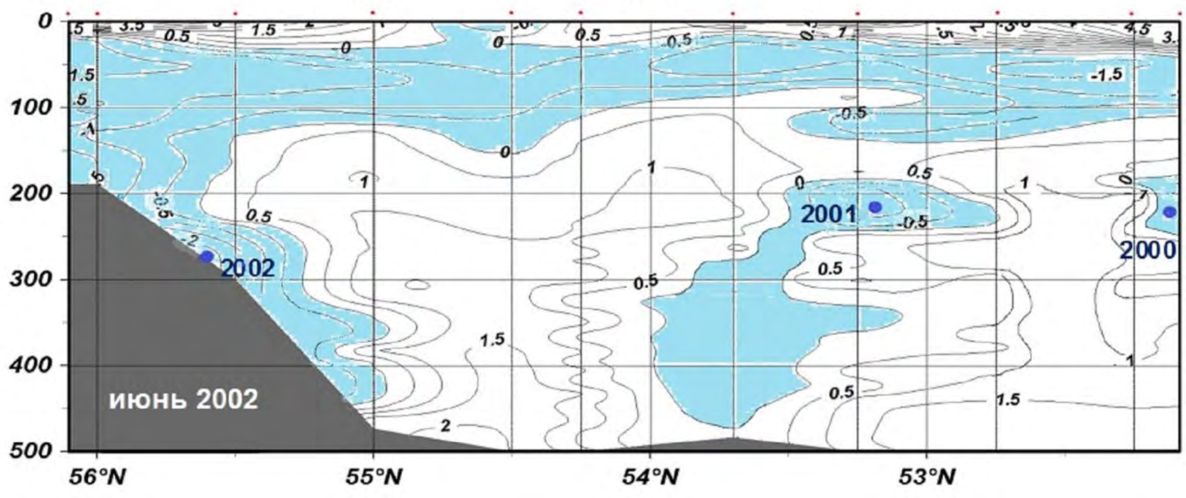


Example of the high-density water cascading along the slope of the northern Sakhalin in the fields of temperature, salinity and density (RV TINRO, section along 54°30 N, May 1996)

2. Cascading of the high-density water and forming fresh portions of the Intermediate water

After the cascading, fresh portions of the Intermediate water could be seen within the intermediate layer as cold lenses. The portions formed in different years are distinguished by their temperature, salinity, and density (but not by their depth that is highly-variable, obviously because of internal waves). Direction of their movement could be estimated from changes of their position between surveys.



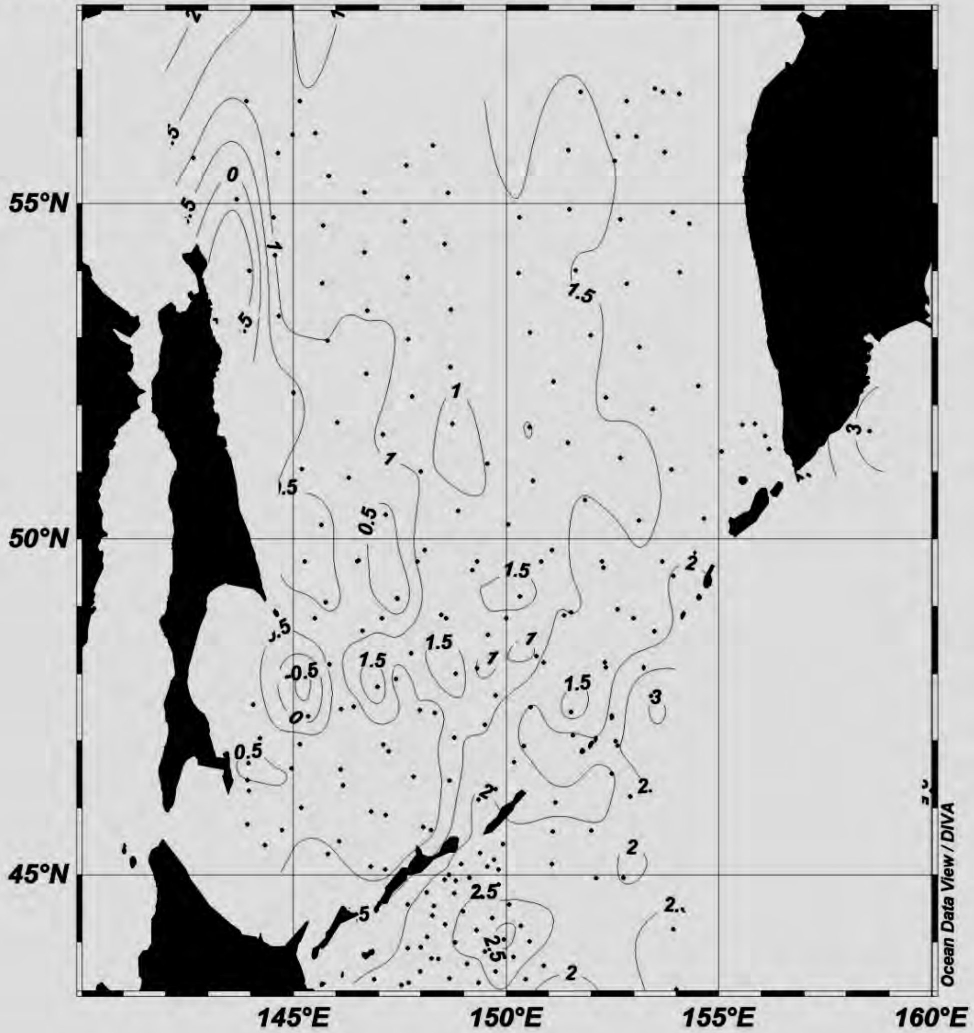


Fresh portions of the Intermediate water as cold lenses on the sections along 144º E in 2001 and 2002.

Cores of the cold lenses are marked, the years of their forming as the Bottom Shelf water are shown

2. Cascading of the high-density water and forming fresh portions of the Intermediate water

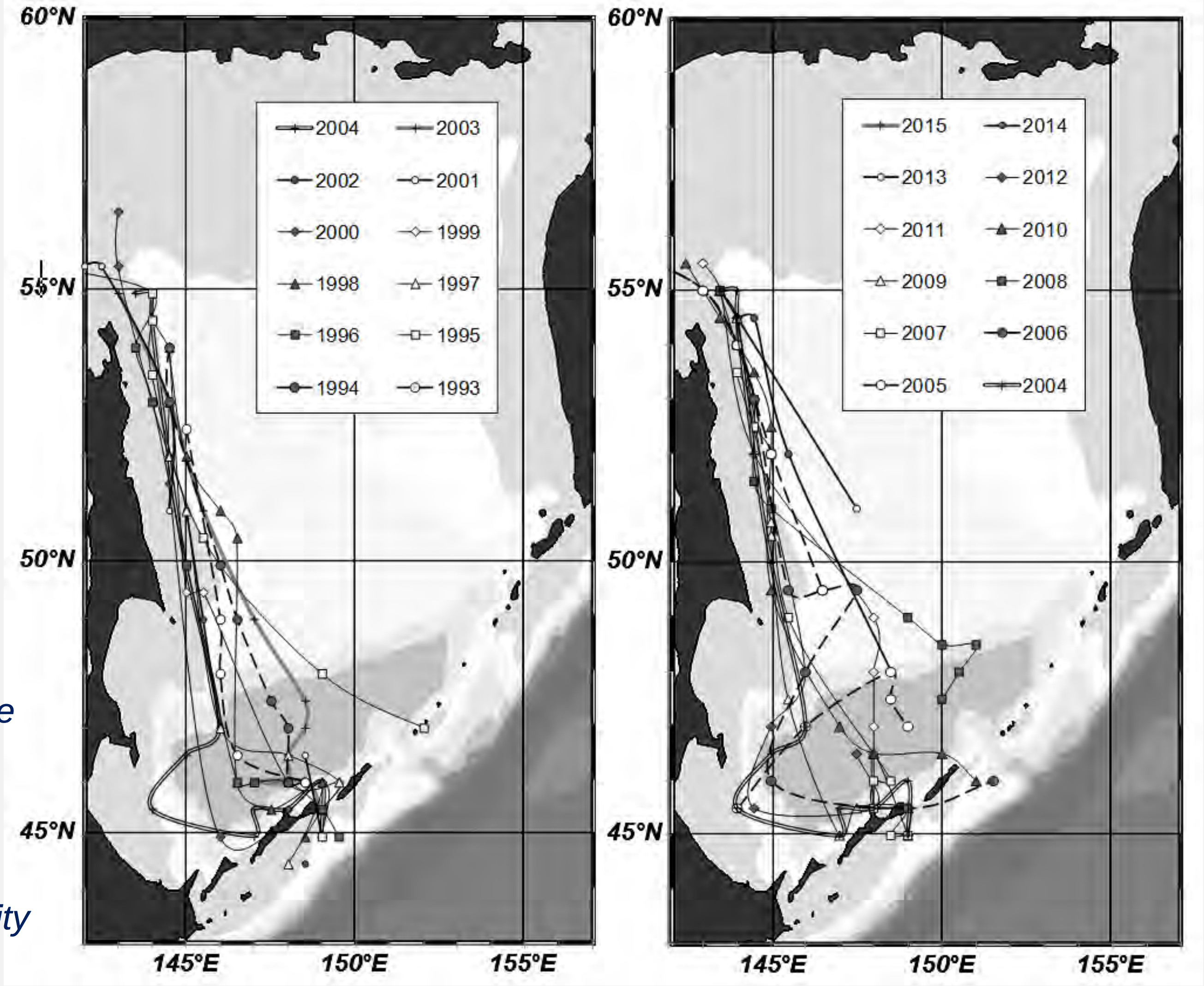
As result of many cases of the fresh portions forming, the whole deep-water part of the Okhotsk Sea is filled by the cold lenses formed in different years, mostly at the northeastern Sakhalin but in other sections of the shelf edge, too.



Example of potential temperature distribution on the isopycnic surface σ_θ *26.8 in 2011. Lenses of the new-formed portions of the Intermediate water are observed frequently at northeastern Sakhalin, northward, eastward, and southward from Cape Patience, and northward from Iturup Island*

3. Tracks of fresh portions of the Intermediate water and their properties variation along the tracks

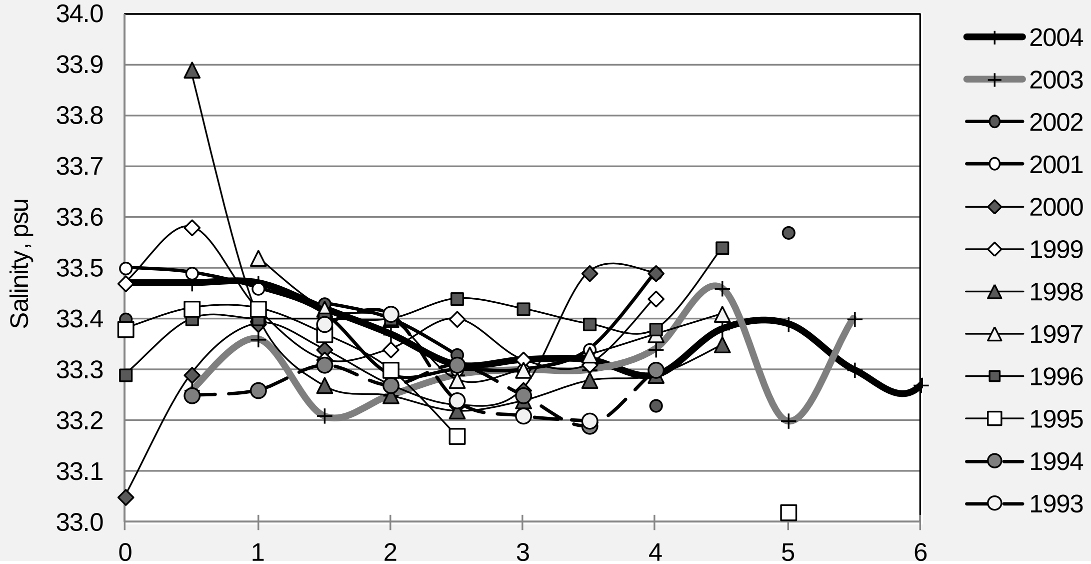
Tracks of certain lenses, formed in different years in the main area of their forming (at northeastern Sakhalin), are traced. They all move southward, following the cyclonic circulation, and in 2.5-6 years leave the Okhotsk Sea through the southern Kuril Straits, mostly through the Vries Strait.

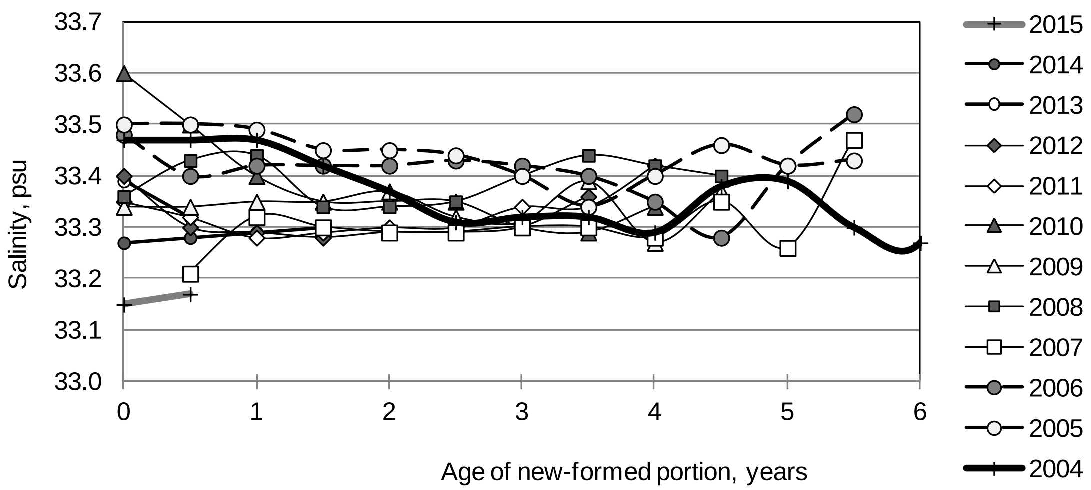


Tracks of the fresh Intermediate water lenses determined by annual monitoring of the cold lenses position within the intermediate layer, taking into account their salinity and density

3. Tracks of fresh portions of the Intermediate water and their properties variation along the tracks

Temperature in the core of fresh portions is naturally fast rising during their transfer across the Okhotsk Sea, but salinity is rather stable and changes significantly only at the area of their forming and in the Kuril Straits

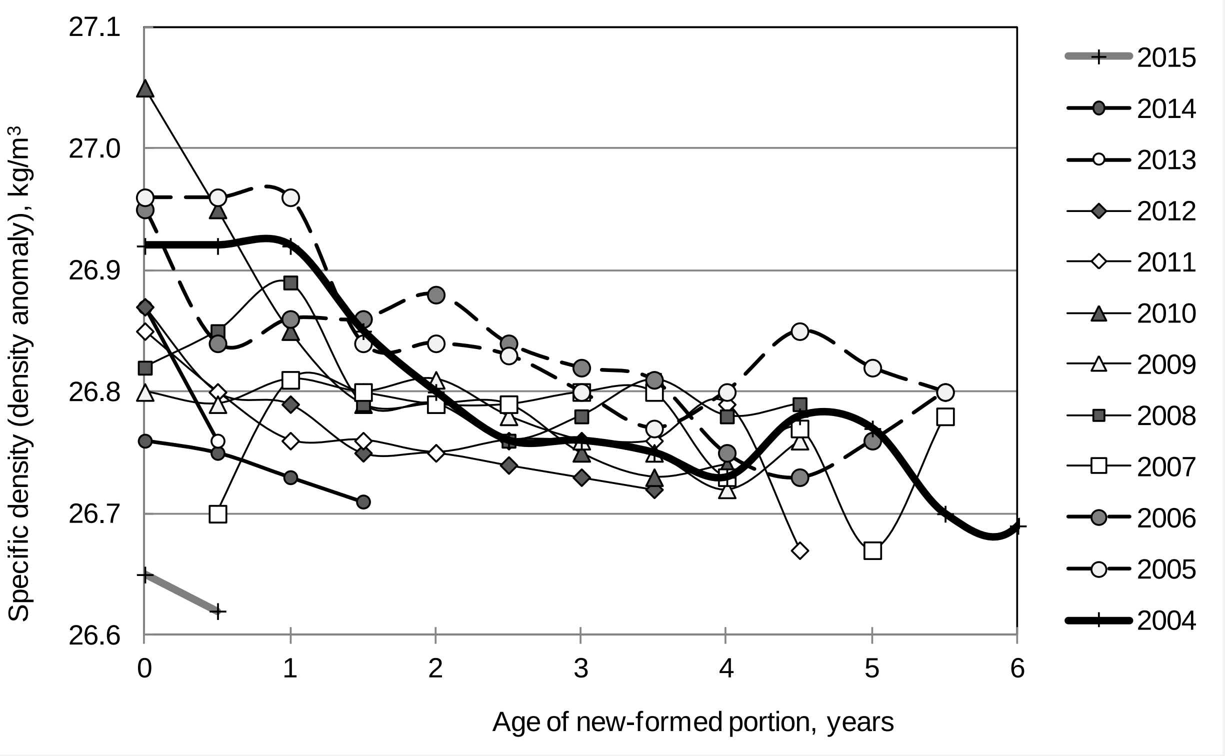




Salinity in the cores of the fresh Intermediate water lenses during their way across the Okhotsk Sea, by the years of the portions forming

3. Tracks of fresh portions of the Intermediate water and their properties variation along the tracks

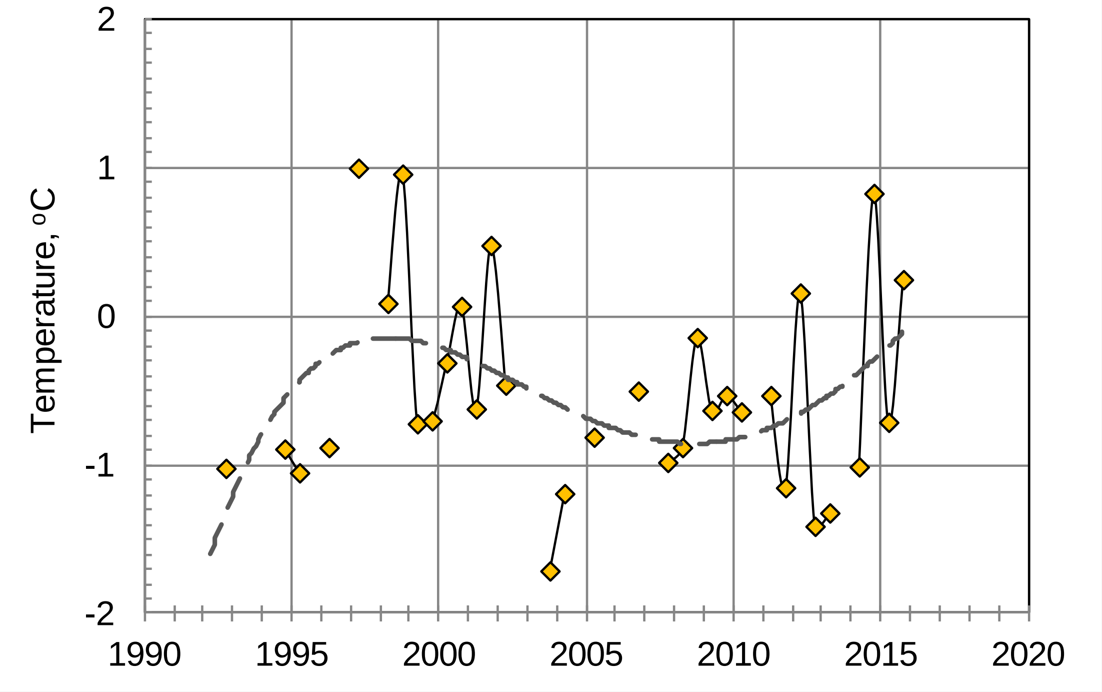
Density in the core of fresh portions decreases gradually during their transfer across the Okhotsk Sea, so the lenses have a tendency to rise



Density anomaly in the cores of the fresh Intermediate water lenses during their way across the Okhotsk Sea, by the years of the portions forming (since 2004)

4. Long-term changes of temperature and salinity in core of fresh portions of the Intermediate water and the changes of oxygen content in their background

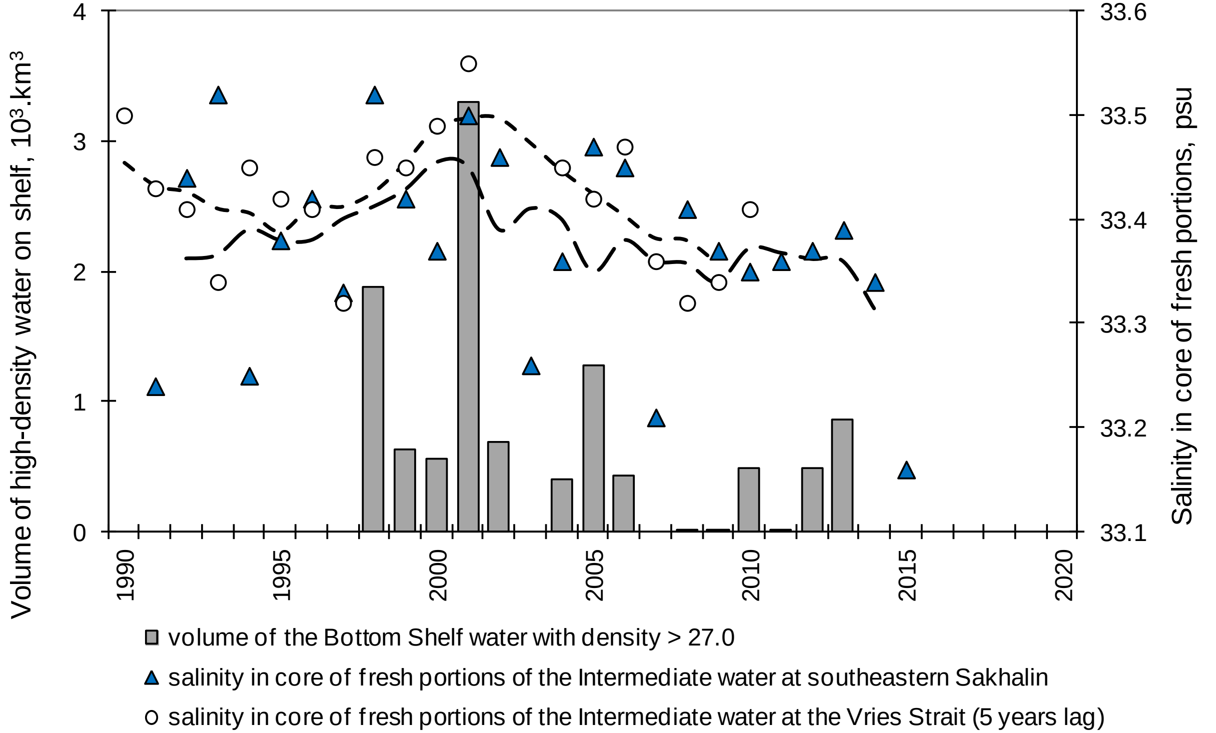
Temperature in core of the fresh portions (local minimum of temperature profiles) is very variable and does not correlate with any other parameters, including the ice cover. The possible reason is auto-compensation: the colder is the cascading water – the deeper it sinks and the warmer is the intermediate layer around



Year-to-year changes of the water temperature in core of fresh portions of the Intermediate water at northeastern Sakhalin

4. Long-term changes of temperature and salinity in core of fresh portions of the Intermediate water and the changes of oxygen content in their background

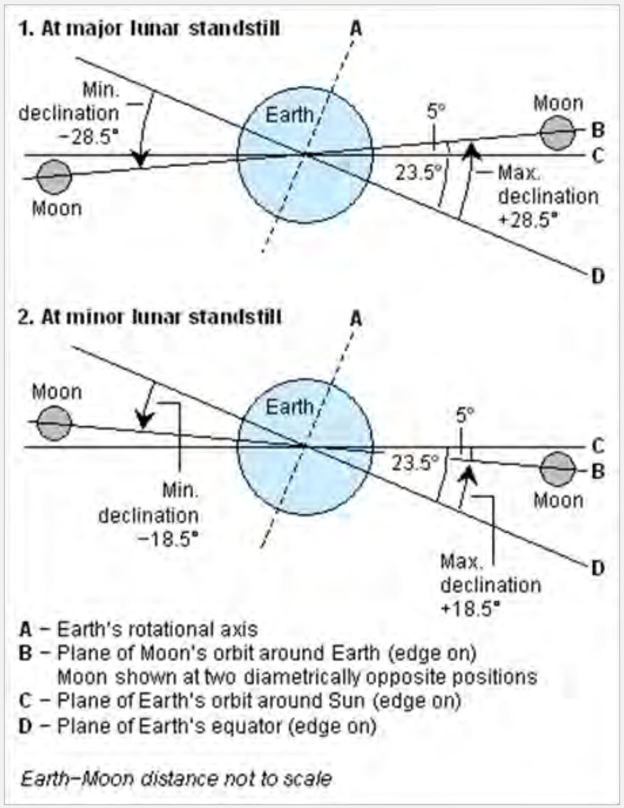
On the contrary, salinity in core of the fresh portions changes in well correspondence with fluctuations of the Bottom Shelf water volume. In this case: the more saline is the cascading water – the deeper it sinks and the more saline is the intermediate layer around. A tendency to salinity decreasing is observed recently that coincides with the negative trend of the high-density water volume

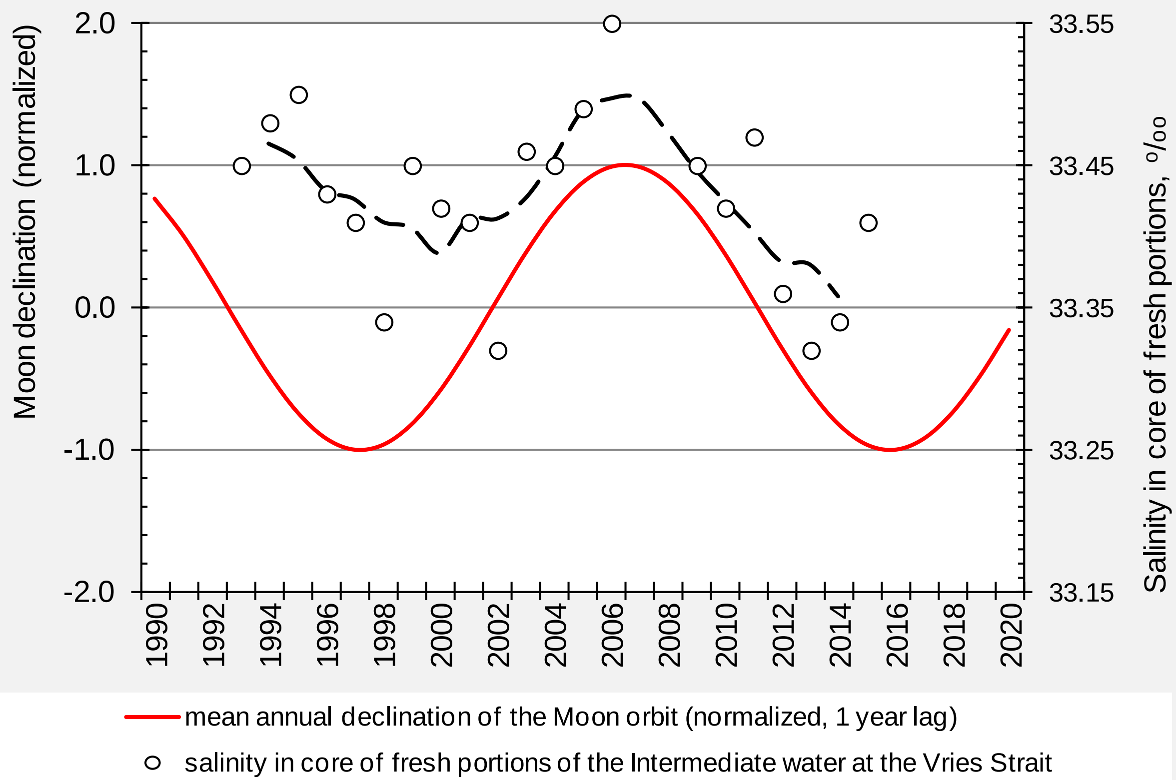


Year-to-year and smoothed changes of salinity in core of fresh portions of the Intermediate water at northeastern Sakhalin and at the Pacific entrance to the Vries Strait (with 5 years lag) vs changes of the Bottom Shelf water volume on the shelf

4. Long-term changes of temperature and salinity in core of fresh portions of the Intermediate water and the changes of oxygen content in their background

From the other hand, salinity in core of the fresh portions changes in good relationship with the Moon orbit declination that is well-known by its 18.6-year cycle. It could be reasoned by better mixing of the low-saline fresh portions with the surrounding waters in the years with positive declination

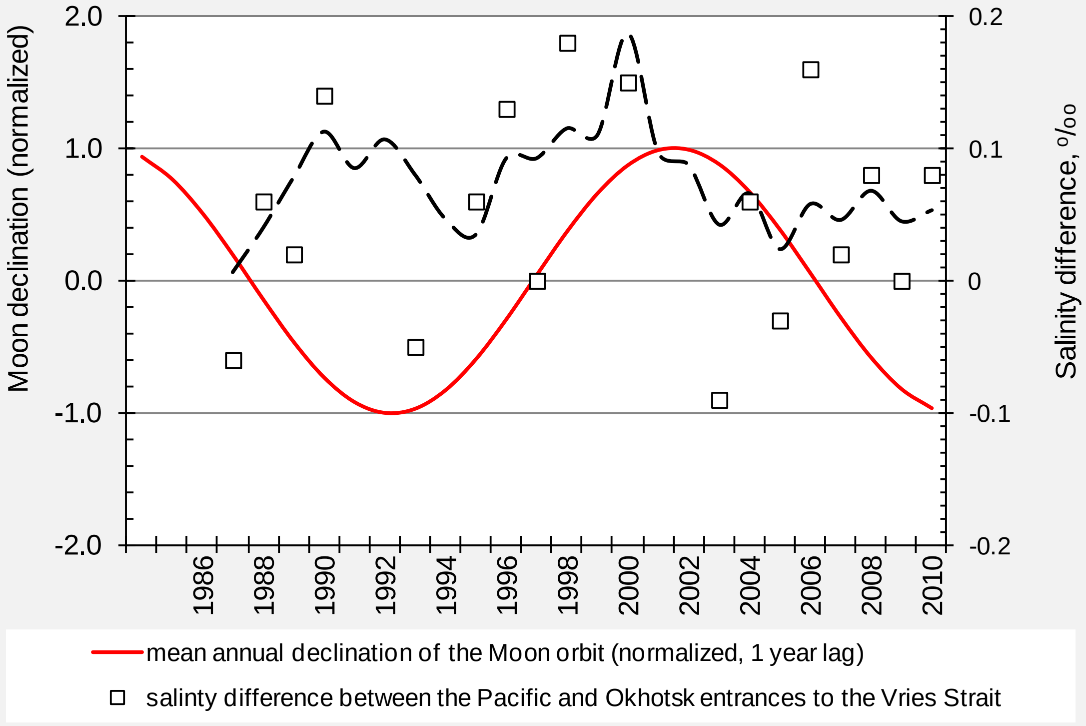




Year-to-year and smoothed changes of salinity in core of fresh portions of the Intermediate water at the Pacific entrance to the Vries Strait vs changes of the Moon declination

4. Long-term changes of temperature and salinity in core of fresh portions of the Intermediate water and the changes of oxygen content in their background

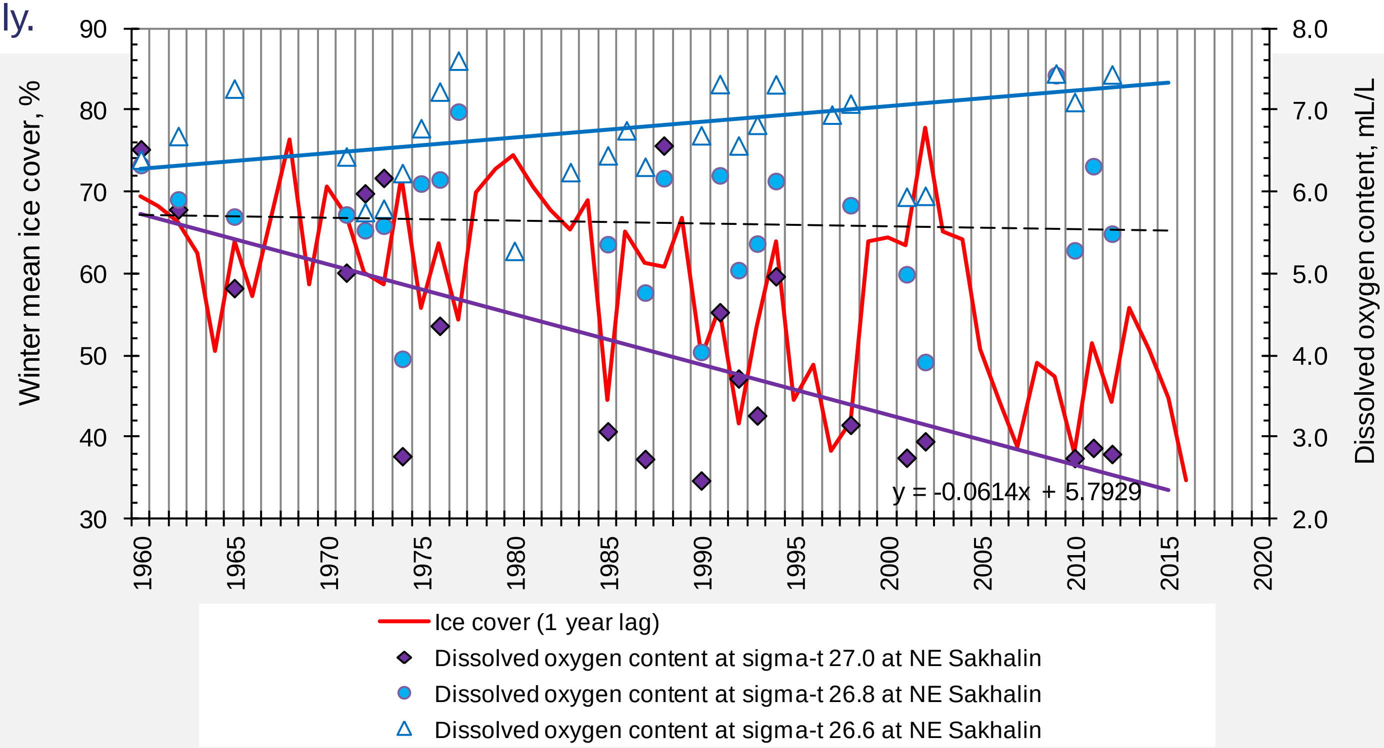
Note that the salinity dependence on 18.6-year cycle of tidal mixing (Moon orbit declination) does not concern directly the passing through the Kuril Straits. The changes within the straits could be very variable and even negative. Taking into account the 1 year time lag for the best correlation, it reflects a cumulative effect of tidal mixing along the way of fresh portions across the Okhotsk Sea



Year-to-year and smoothed changes of salinity difference for fresh portions of the Intermediate water at the western and eastern entrances to the Vries Strait vs 18.6-year cycle of the Moon orbit declination with 1-year lag

4. Long-term changes of temperature and salinity in core of fresh portions of the Intermediate water and the changes of oxygen content in their background

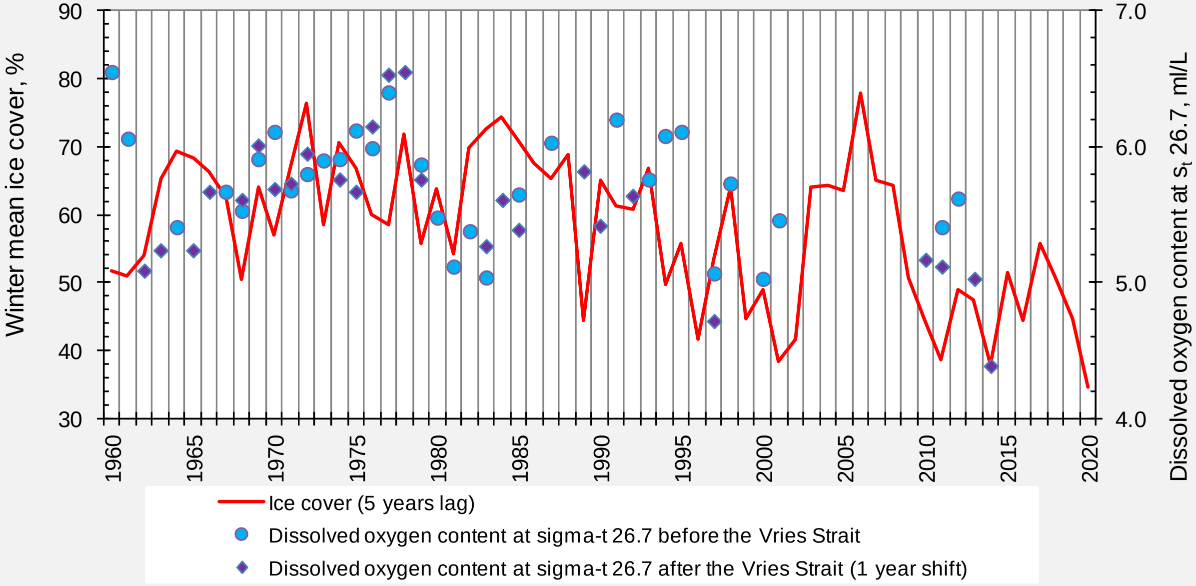
In spite of a tendency to weakening of the Intermediate water producing in the Okhotsk Sea, DO content at the usual surface of its fresh portions transfer (σ_θ 26.8) remains stable, obviously because of the same compensatory effect, as for temperature. Instead, DO becomes higher in the upper layer (σ_θ 26.6) and decreases in the deeper layer (σ_θ 27.0). Thus, active slope convection is necessary for ventilation of the lower part of the Intermediate water, but modern weak convection ventilates its upper part only.

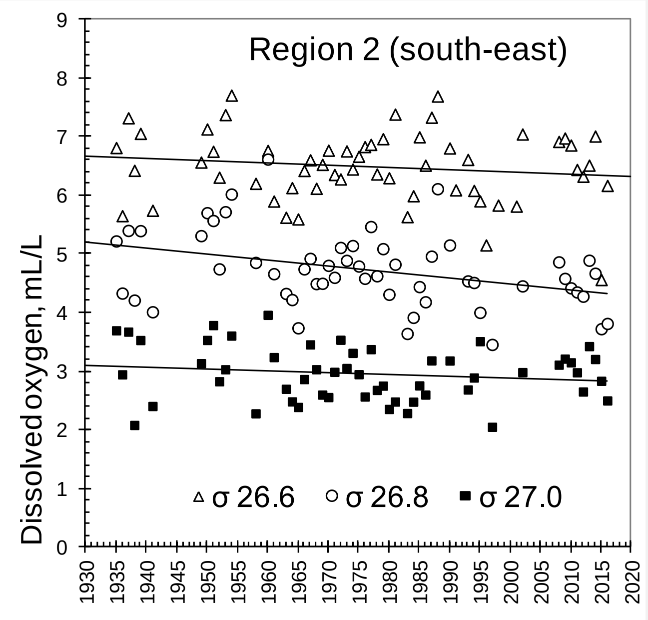


Year-to-year changes and trends of dissolved oxygen content at the isopycnic surfaces 26.6, 26.8, and 27.0 σ_θ within the intermediate layer of the Okhotsk Sea at northeastern Sakhalin vs changes of the mean winter ice cover with 1-year lag

4. Long-term changes of temperature and salinity in core of fresh portions of the Intermediate water and the changes of oxygen content in their background

On a distance from the area of producing, negative tendency of DO content spreads over the whole intermediate layer, obviously because of rising of fresh portions of the Intermediate water in the process of their transfer across the Okhotsk Sea.





Interannual changes of dissolved oxygen content at the isopycnic surface 26,7 σ_θ at the western and eastern entrances to the Vries Strait (points) vs changes of the mean winter ice cover of the Okhotsk Sea (line)

Mean annual values and trends for dissolved oxygen content at certain isopycnic surfaces in the southeastern Okhotsk Sea

Conclusions

1. Interannual changes of the high-density Bottom Shelf water volume producing in the northern Okhotsk Sea correlate well with changes of winter severity reflected in the ice cove changes. Recently tendencies to winter warming, ice cover decreasing, and the high-density shelf water producing weakening are observed.

2. The high-density water cascades from the northern Okhotsk Sea shelf to the intermediate layer, mostly at northeastern Sakhalin, and cold lenses of the new-formed Intermediate water are produced. These fresh portions are transferred southward and eastward across the Okhotsk Sea, following to its cyclonic circulation and reach the Kuril Straits (usually the Vries Strait) in several years.

3. Salinity of fresh portions of the Intermediate water depends on the cascaded volume of the high-density shelf water, but their temperature and oxygen content don't have such dependence because of these properties auto-compensation in conditions of their descending profiles withing the intermediate layer. Recently a tendency to increasing of salinity in the fresh portions prevails because of their producing weakening.

4. Periodicity connected with lunar 18.6-year cycle could be traced in changes of salinity for fresh portions of the Intermediate water, in particular after passing the Kuril Straits, that supposedly is related with tidal mixing influence on their transforming along the way across the Okhotsk Sea.

5. Dissolved oxygen content is rather stable in the layer of fresh portions of the Intermediate water in the area of their producing (at northeastern Sakhalin), possibly because of the auto-compensatory effect. However, DO content decreases in the lower part of the intermediate layer and slightly increases in its upper part. On a distance from the area of producing, negative tendency of DO content spreads over the whole intermediate layer, so a tendency to oxygen exhausting in the Intermediate water entering the Pacific from the Okhotsk Sea is observed recently.