Interannual variations of the East-Kamchatka and East-Sakhalin Currents volume transports and their impact on the temperature and chemical parameters in the Okhotsk Sea

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Introduction

The Okhotsk Sea is one of the marginal seas of the North Pacific Ocean, and is bounded by the Kamchatka Peninsula, Siberia, Sakhalin Island, Hokkaido and the Kuril Islands. It is connected with the Japan Sea through the La Perouse (Soya) and Tartar Straits and with the Pacific Ocean through the Kuril Island Chain. The physical and chemical parameters in the intermediate waters of the Okhotsk Sea are determined by the supply of the Dense Shelf Water (formed in the coastal polynyas as result of cooling and brine injection under ice), the inflow of dense transformed subtropical waters from the Japan Sea in spring through La Perouse Strait, and the water exchange between the Okhotsk Sea and the subarctic Pacific. The increase/decrease in water exchange between the subarctic Pacific and the Okhotsk Sea and the decrease/increase in the supply of Dense Shelf Water (DSW) result in the decrease/increase in dissolved oxygen (DO) and increase/decrease in temperature, dissolved inorganic carbon (DIC) and nutrients in intermediate waters of the Okhotsk Sea (Andreev and Zhabin, 2000; Andreev and Kusakabe, 2001; Andreev and Baturina, 2005).

Andreev and Baturina (2005) have shown that between 1948 and 2000 in the Kuril Basin of the Okhotsk Sea there is an average increase in isopycnal depth (H) of $26.8\sigma_\theta$ and $27.0\sigma_\theta$ with a rate of 2.0 ± 0.9 m yr^{-1} and 1.4 ± 1.0 m yr^{-1}, respectively. At σ_θ= 27.0 the increase in H coincides with an increased temperature (0.010 ± 0.004°C yr^{-1}). The interdecadal variations and trend in DO show a good correlation with the intensity of the Aleutian Low pressure cell, represented by the North Pacific Index in winter (Andreev and Kusakabe, 2001). In the intermediate water layer of the Kuril Basin (σ_θ = 26.8 and σ_θ = 27.0) there is an average decrease in the DO concentration at a rate of –0.9 ± 0.4 µmol kg^{-1} yr^{-1} (Andreev and Baturina, 2005). The interannual variations in the DO, DIC and temperature in the Kuril Basin area could be explained by the variations in the Alaska Gyre intermediate waters supply (by the Alaskan Stream and East-Kamchatka Currents) to the western subarctic Pacific (Andreev and Baturina, 2005). In addition to the water exchange between the subarctic Pacific and Okhotsk Sea, the variations in the formation and transport rates of the DSW (by the East-Sakhalin Current) probably can generate the interannual DO and temperature signals observed in the Kuril Basin region of the Okhotsk Sea.

In this study we investigate the interannual variations in the East-Kamchatka and Oyashio Currents (EKC/Oyashio) and East-Sakhalin Current (ESC) volume transports and their impact on temperature and chemical parameters in the Kuril Basin of the Okhotsk Sea (Fig. 1). We demonstrate that there is a strong correlation between the interannual changes of EKC/Oyashio and ESC transport rates computed by using the Sverdrup relation and the temporal variations in the sea level at coastal stations in winter. The variations in EKC/Oyashio volume transport are responsible for the observed temperature and DO interannual changes in the intermediate waters of the Okhotsk Sea.

Data and Methods

To analyze the temporal changes of temperature and chemical parameters in the intermediate waters of the Okhotsk Sea, the data sets of the NOAA Oceanographic Data Center, Japan Oceanographic Data Center, Institute of Ocean Sciences (Line P oceanographic data) and the Pacific Oceanological Institute were used. Sverdrup volume transports in the Okhotsk Sea and subarctic Pacific were calculated from the wind stress data provided by the NOAA-CIRES Climate Diagnostic Center NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) Reanalysis Project. The sea level measurements at the coastal stations of the Kamchatka Peninsula (Petropavlovsk-Kamchatsky), Kuril (Severo-Kurilsk) and Sakhalin (Vzmorie) islands (Fig. 1) were provided by the Sakhalin Meteorological Agency. Sea level data were corrected for the variations in atmospheric pressure.

Results and Discussion

East-Kamchatka/Oyashio and East-Sakhalin currents volume transports

Positive wind stress curls over the northern North Pacific and Okhotsk Sea in winter, determined by the strength and position of the Aleutian Low and Siberian High, force the cyclonic circulations in these basins. The ESC and EKC/Oyashio currents are the western boundary currents of the wind-driven cyclonic gyres in the Okhotsk Sea and the northern North Pacific, respectively. Spin up/down of the cyclonic gyres in the Okhotsk Sea and subarctic Pacific driven by the wind stress curl results in the increased/decreased ESC and EKC/Oyashio volume transports and increase/decrease in sea level at the coastal stations of the Sakhalin and Kuril Islands and Kamchatka Peninsula.

The interannual variations in the volume transports of the EKC/Oyashio and ESC calculated by the Sverdrup relation show a good correlation with the change in sea level at the coastal stations of Kamchatka Peninsula, Kuril Islands and Sakhalin Island in winter (Fig. 2, Andreev and Shevchenko, 2008). The cross-correlation coefficients between the volume transport of the EKC/Oyashio and the sea level at Stns. Petropavlovsk-Kamchatsky (1965–2002) and Severo-Kurilsk (1968–1995) are equal to 0.69 and 0.60, respectively. The cross-correlation coefficient between the volume transport of the ESC and the sea level at Stn. Vzmorie (1952–1988) is 0.72.

The wide northern shelf can interrupt the Sverdrup balance in the Okhotsk Sea and significantly reduce the wind-driven volume transport of the ESC due to bottom friction (Simizu and Ohshima, 2006). In our study, the change in EKC Sverdrup transport driven by bottom friction over the shelf is not taken into consideration.

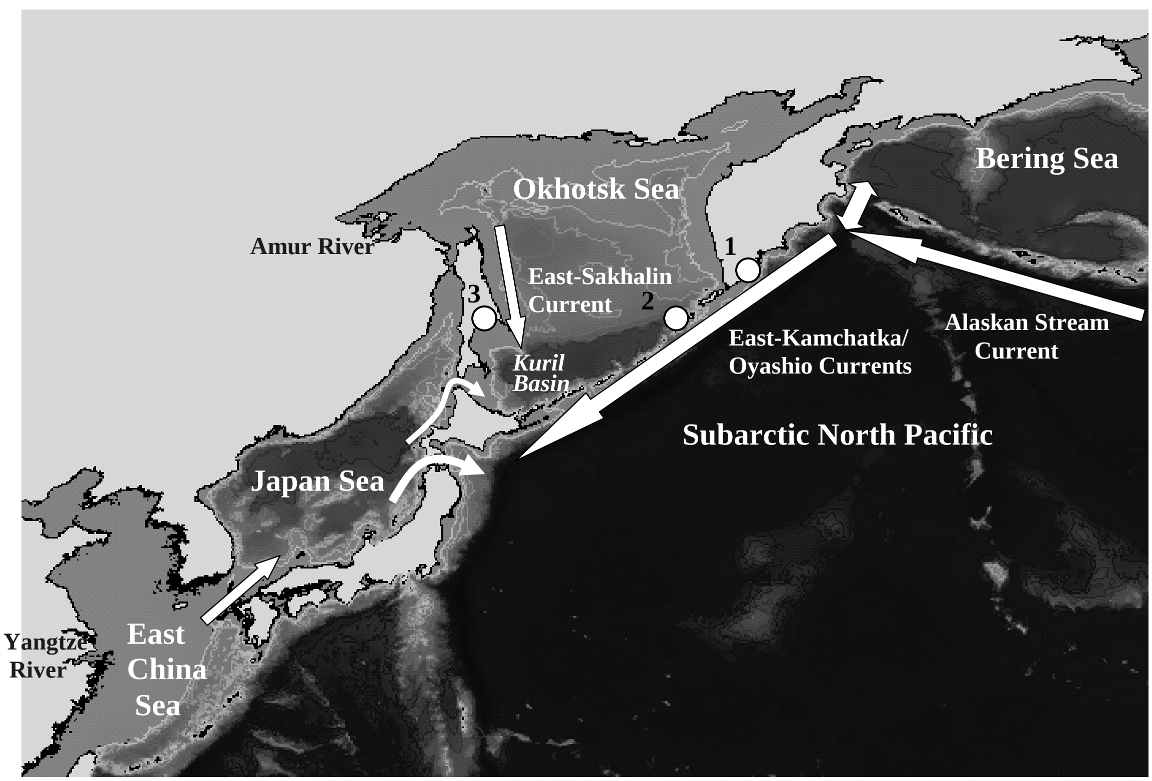

Fig. 1 Schematic representation of currents in the northwestern North Pacific and the location of coastal sea level observation stations. Number 1 refers to Petropavlovsk-Kamchatsky, 2 to Severo-Kurilsk, and 3 to Vzmorie.

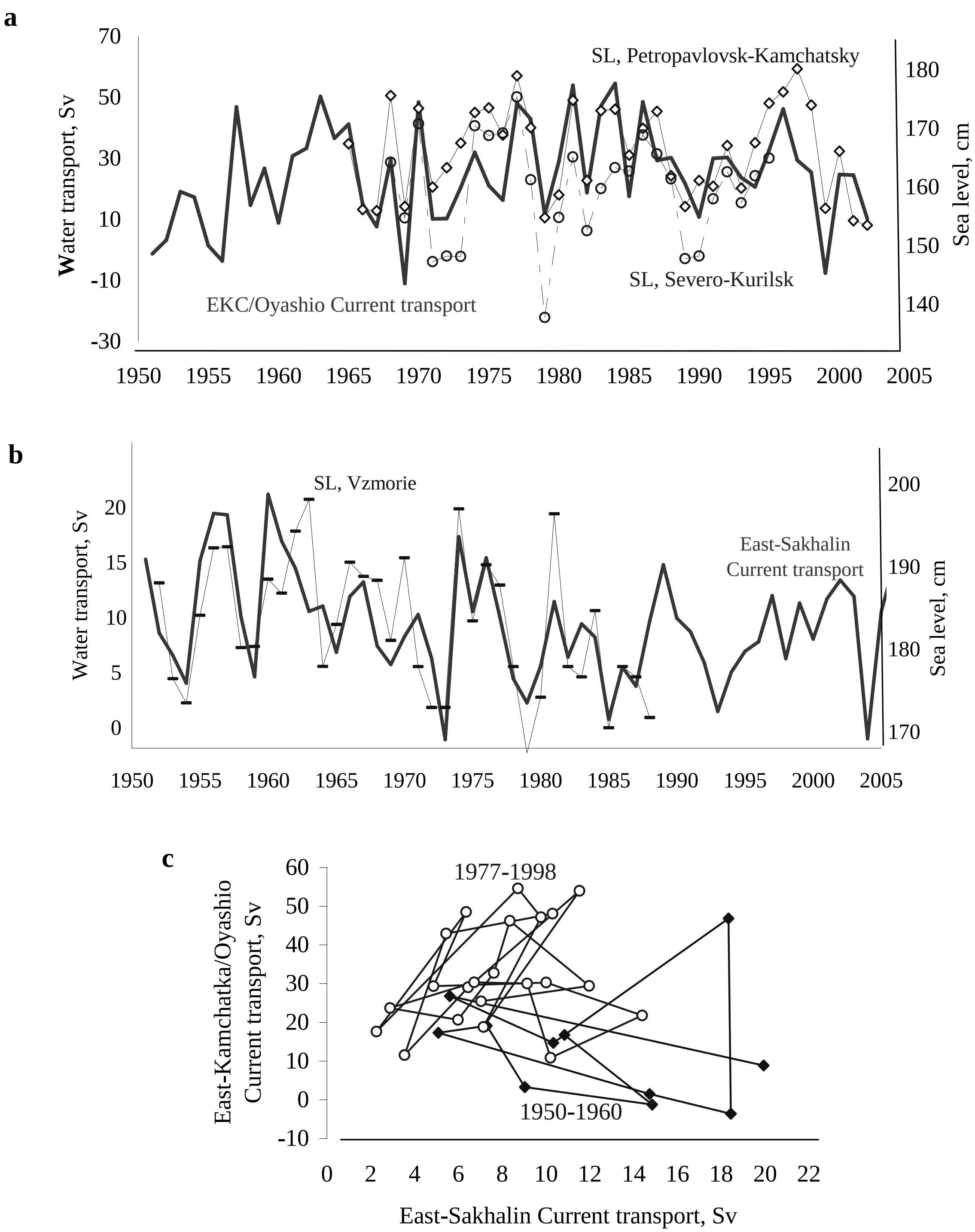

Fig. 2 (a) Temporal variations of the EKC/Oyashio volume transport and sea level (SL) at the Stns. Petropavlovsk-Kamchatsky and Severo-Kurilsk in winter, (b) temporal variations of the ESC volume transport and the sea level at the Stn. Vzmorie in winter, and (c) EKC/Oyashio volume transport versus ESC volume transport in winter.

There is no statistically significant correlation ($r = -0.10$) between the interannual variations in the EKC/Oyashio volume transport and the ESC volume transport for a 60-year period (1949–2008). Such a correlation was observed during brief (10–20 years) periods determined by the strength and position of the Aleutian Low and Siberian High in winter. Between 1950 and 1960 the spinup of the cyclonic circulation in the subarctic North Pacific (and an increased transport of the EKC/Oyashio) was accompanied by a slowdown of the ESC transport. Between 1977 and 1998 the increased/decreased ESC transport corresponded to the increased/ decreased EKC/Oyashio transport (Fig. 2c).

Impact of the EKC/Oyashio and ESC on temperature and dissolved oxygen

The interannual changes in the depth of the $26.8\sigma_\Theta$ isopycnal, the temperature on the $27.0\sigma_\Theta$ isopycnal and DO on the $26.8\sigma_\Theta$ and $27.0\sigma_\Theta$ isopycnals in the Kuril Basin of the Okhotsk Sea between 1950 and 1995 can be described by a linear combination of the EKC/Oyashio and ESC volume transports (Figs. 3a, b and c).

The cross-correlation coefficients between the volume transport of the EKC/Oyashio (filtered by a 3-yr running mean) and the depth of the $26.8\sigma_\Theta$ isopycnal, the temperature on the $27.0\sigma_\Theta$ isopycnal and DO on the $26.8\sigma_\Theta$ and $27.0\sigma_\Theta$ isopycnals are 0.71, 0.65, –0.54 and –0.66, respectively. An intensification of the subarctic cyclone gyre (and an increase of the EKC/Oyashio volume transport) decreases the residence time of the Alaskan waters at the northern boundary, and therefore, the intermediate and surface waters become less modified (by cooling and tidal mixing) while they move off the Aleutian Islands and Kamchatka coast. This leads to an increased temperature and decreased DO, and deepening of isopycnals in the Okhotsk Sea. The deepening of the isopycnals, driven by the increased EKC/Oyashio volume transport is probably related to an excess supply of eastern subarctic surface waters ($\sigma_t \sim 25.5$–26.0).

The cross-correlation coefficients between the interannual variations in the ESC volume transport (filtered by a 3-yr running mean) and the depth of $26.8\sigma_\Theta$, temperature on the $27.0\sigma_\Theta$ isopycnal and DO on the $26.8\sigma_\Theta$ and $27.0\sigma_\Theta$ isopycnals in the Kuril Basin area are –0.40, –0.42, 0.49 and 0.40, respectively. The enhanced ESC volume transport corresponds to increased DO, decreased temperature and the shallow depth of $26.8\sigma_\Theta$. The relationships between the Sverdrup transport of the ESC, computed by using wind stress curl and the temperature and DO on the $26.8\sigma_\Theta$ and $27.0\sigma_\Theta$ isopycnals in the Kuril Basin, can be due partly to changes of the DSW formation rate forced by northwest winds in winter.

There are significant discrepancies between the calculated (using the volume transports of ESC and EKC/Oyashio) and the observed temperature and DO in 2000, 2003 and 2004 years (Fig. 3). These discrepancies reflect the changes in DO and temperature of the upstream region (Alaska Gyre area) (Andreev and Baturina, 2006). The intermediate waters of the Alaska Gyre are impacted by a huge (low oxygen and high temperature) eastern subtropical pool (Andreev and Baturina, 2006). The eastern subtropical waters are transported northward by the California undercurrent and then by the Alaska Current and Alaskan Stream Current into the western subarctic Pacific and Okhotsk Sea. The temporal variations in DO and temperature in the Alaska Gyre area show a good correlation with the intensity of the Aleutian Low pressure cell, represented by the North Pacific Index (an averaged sea-level atmospheric pressure in the northern North Pacific in winter (Andreev and Baturina, 2006). Intensification of the Aleutian Low results in the increased northward meridional wind stress at its eastern boundary and enhanced transport of low oxygen eastern subtropical waters into the subarctic region. Figure 3d shows the interannual variations in the difference in DO concentration between the Okhotsk Sea and Alaska Gyre waters ($\Delta DO_{OS\text{-}AG}$). The intensification of the EKC/Oyashio decreases $\Delta DO_{OS\text{-}AG}$ while enhanced ESC volume transport leads to the increased $\Delta DO_{OS\text{-}AG}$.

In addition to the DO, the routine oceanographic observations include the measurements of nutrients and DIC. Comparison of the differences in chemical parameters between the Okhotsk Sea (Kuril Basin region) and Alaska Gyre and the accuracy of its measurements (Table 1) shows that the DO is the best parameter to study the impact of northeastern Pacific waters on the western subarctic Pacific and Okhotsk Sea.

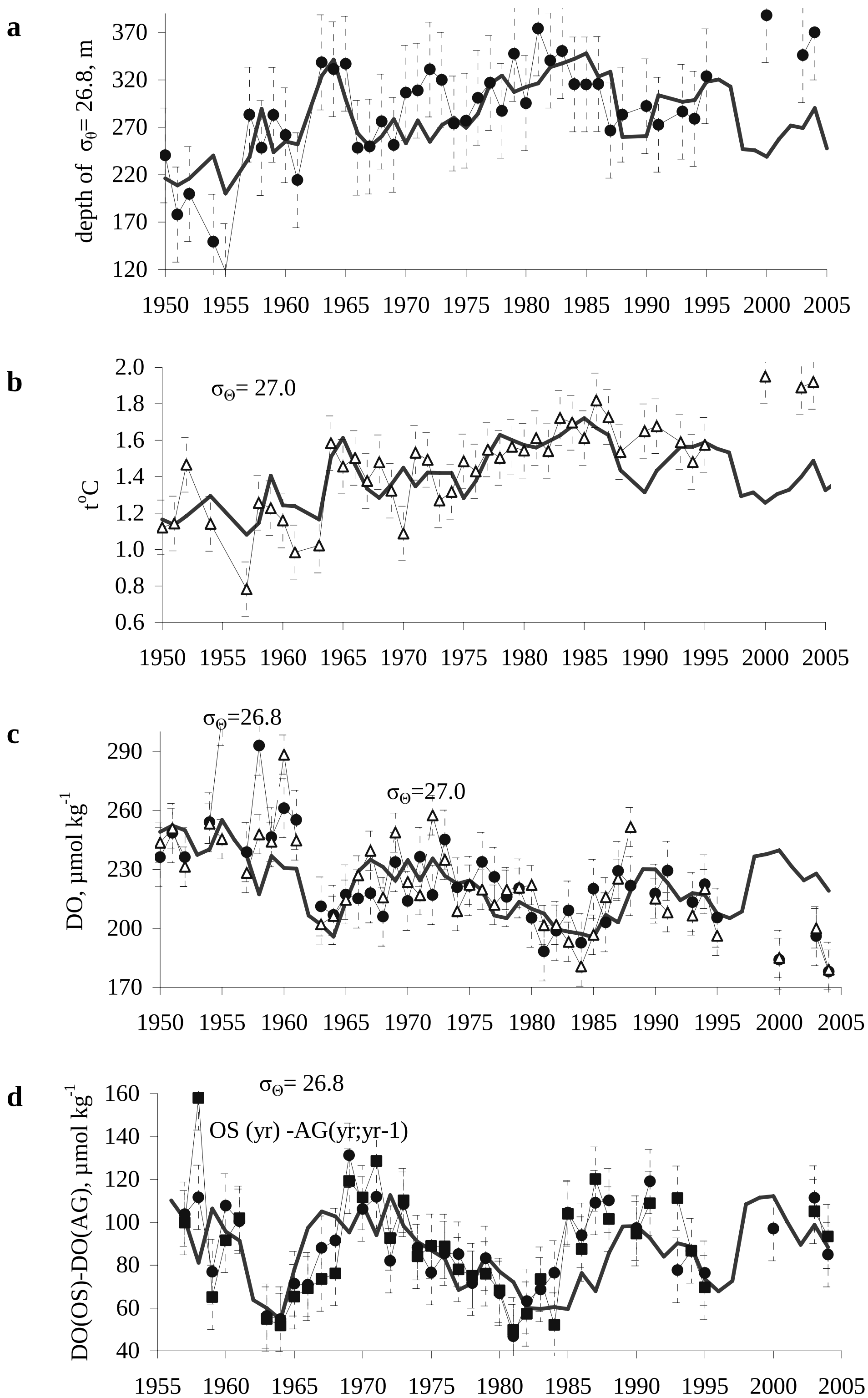

Fig. 3 Temporal variations in (a) the depth of the $26.8\sigma_\theta$ isopycnal, (b) the temperature on the $27.0\sigma_\theta$ isopycnal, (c) the DO on the $26.8\sigma_\theta$ and $27.0\sigma_\theta$ isopycnals, and (d) the difference in DO between the Okhotsk Sea (OS) and the Alaskan Gyre (AG) waters at $\sigma_\theta = 26.8$. Solid lines (a–d) show the isopycnal depth, temperature, DO and the difference in DO between OS and AG computed by the linear combination of the EKC/Oyashio and ESC volume transports (filtered by a 3-yr running mean). The errors bars are 95% confidence intervals for isopycnal depth, temperature and DO values.

Table 1 Difference in temperature and chemical parameters between the eastern subarctic Pacific (Alaska Gyre) and the Okhotsk Sea (Kuril Basin region) on isopycnals of 26.8σ_Θ and 27.0σ_Θ.

Parameter	**Alaska Gyre–Okhotsk Sea**	**Accuracy of measurements**
Temperature (°C)	3.0	± 0.001–0.005
Dissolved oxygen (µM)	–150	± 2–4
Dissolved inorganic carbon (µM)	50	± 2–3
Nitrate (µM)	6	± 0.2–0.6
Phosphate (µM)	0.4	± 0.02–0.06

Impact of the Bering Sea

The observed temperature and DO changes in the Okhotsk Sea waters can be related to Alaskan water modification in the Bering Sea (Andreev and Watanabe, 2002). Due to a strong halocline, the salt supply into the surface layer is the necessary component for subarctic North Pacific intermediate water ventilation. In the Bering Sea it can be added to seawater as brine during ice formation in the northern and western shelf areas. Interaction of the Bering Slope Current water with the DSW formed in the Bering Sea in winter can enhance the intermediate waters of the EKC with DO. Another source of salt for the surface layer of the Bering Sea is an advection of the more saline water from low latitude areas through the straits of the Aleutian Islands. Intensification of the Western Subarctic Gyre in the 1950s increased meridional transport of saline water from low to high latitudes in the central North Pacific, thereby triggering the formation of dense water and intermediate layer ventilation in the Bering Sea. During this period the EKC waters were a source of low temperature and high oxygen waters for the intermediate layer of the Okhotsk Sea (Andreev and Watanabe, 2002; Andreev and Baturina, 2006).

Impact of the Japan Sea

The Okhotsk Sea is connected to the Japan Sea through La Perouse (Soya) Strait. Warm saline water, originating from the Tsushima Warm Current in the Japan Sea, flows into the Okhotsk Sea and forms the Soya Current flowing southeastward along the coast of Hokkaido. Japan Sea surface and subsurface waters are significantly impacted by East China Sea (ECS) shelf waters. Our results suggest that the variations in the transport rate of the ECS subsurface (low oxygen and relatively high nutrients) waters in summer and fall are responsible for the interannual change of the DO in the intermediate waters of the Japan Sea (Andreev, 2008). Human impact on the Yangtze River waters leads to the increase of N* ([NO_3^-] –16 · [PO_4^{3-}]) concentrations in the upper waters of the Tsushima Current (Andreev, 2009), and probably the Soya Current.

Future study should clarify how changes in the chemical parameters of the surface and subsurface waters in the Japan Sea (driven by changes in the water transport through the Tsushima Strait and the human impact on the East China Sea waters) affect the biology and chemistry of the Okhotsk Sea waters.

Summary

The impact of the interannual variations in East-Kamchatka and Oyashio Currents (EKC/Oyashio) and East-Sakhalin Current (ESC) volume transports on temperature and chemical parameters in the Kuril Basin of the Okhotsk Sea was analyzed. It is shown that there is a strong correlation between the interannual variations in EKC/Oyashio and ESC Sverdrup transport and the temporal changes of the sea level at the coastal stations of the Kamchatka Peninsula, and Kuril and Sakhalin islands in winter. The variations in EKC/Oyashio and ESC volume transports are responsible for the observed temperature and DO interannual changes in the intermediate waters of the Kuril Basin of the Okhotsk Sea.

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