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The numerical simulation of seasonal variability of the upper circulation in the Okhotsk Sea

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Abstract

The general circulation of the Okhotsk Sea and its seasonal variability are studied using a three dimensional general circulation model. Model currents agree well with geostrophic currents derived from satellite data (AVISO) except the Kuril Basin and the southern part of the central Okhotsk Sea with dominant eddy activities. The volume transports of the second branch of the East Sakhalin Current, the West-Kamchatka Current, the Middle Current (north branch) and the inflow of the Kuril-Kamchatka Current through the Fourth Strait show same seasonal changes with a maximum in January and a minimum in summer. The West-Kamchatka Current is driven by the northward Sverdrup flow and the inflow through the Fourth Kuril Strait, feeding the Middle Current (north branch). The Middle Current (south branch) is driven by the Sverdrup flow and the inflow through the Kruzenshterna Strait. The inflow through the eastern Kuril straits and outflow through the western Kuril straits intensify the general cyclonic circulation of the Okhotsk Sea in winter as well as the wind and wind stress curl. A dramatic current reversal from a cyclonic to an anticyclonic circulation in the Shelihov Bay is initiated by the start of northeasterly monsoon wind in autumn. The heat and fresh water fluxes are dominant forces to drive the circulation of the northern shelf with the Northern Okhotsk Current and its countercurrent. Tidal forcing effects can be seen in significant reinforcements of cyclonic circulations in the Kuril Basin, Shelihov Bay and northern continental shelf with the Northern Okhotsk Current and its countercurrent.

Key words : *Okhotsk Sea, seasonal variation, ocean circulation, upper layer, simulation*

1. Introduction

The Okhotsk Sea (Fig. 1a) is located in the North Western Pacific. It is separated from the Pacific Ocean by a chain of the Kuril Islands and Kamchatka Peninsula. In the south and west, it is bounded by the coast of Hokkaido Island, eastern coast of Sakhalin Island and the coast of the Asian continent. The sea is elongated from the south-west to the north-east with a latitudinal extent (43°43'N - 62°42' N) and longitudinal extent (135°10'E - 164°45'E.). The Okhotsk Sea is connected with the Pacific Ocean through numerous straits of the Kuril Islands and with the Japan Sea through the Soya and Nevelskoy Straits .

There are many studies on the general circulations of the Okhotsk Sea from the end of 19th century to the end of 20th century. Among these studies, the study by Verhunov (1997) provided a most comprehensive description of the general circulation of the Okhotsk Sea. The schematic circulation in Fig. 1b was depicted on the basis of the study by Verhunov (1997). Fig. 1b shows that the surface circulation of the Okhotsk Sea is generally cyclonic. On the background of the general circulation, there are local anti-cyclonic and cyclonic circulations, and eddies with smaller scales in various areas such as the TINRO Basin, west of the southern tip of Kamchatka, and the area of the Kuril Basin. However, the schematic current system in Fig. 1b does not necessarily seem to represent real features of the surface current system of the Okhotsk Sea due to insufficient observations. The physical aspects such as the seasonal variation of the current system and its mechanism were not also sufficiently studied except the Sakhalin shelf, Hokkaido shelf and the southern part of the Okhotsk Sea including the Kuril Basin and Kuril Islands, where intensive surveys were conducted in recent years (Katsumata and Yasuda, 1999; Katsumata et al, 2002; Mizuta et al, 2003; Mizuta et al, 2005; Fukamachi et al., 2006; Fukamachi et al. 2009; Simizu and Ohshima, 2002; Shimada et al., 2005; Simizu and Ohshima, 2006; Ohshima and Simizu, 2008).

In contrast to the studies in the western and southern part of the Okhotsk Sea, regions of the West-Kamchatka shelf, northern shelf and north-eastern part of the Okhotsk Sea are poorly investigated, although the circulation in the eastern part seems to have a strong influence on the circulation

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*1 Far Eastern Regional Hydrometeorological Research Institute, Russia

*2 Research Institute for Applied Mechanics, Kyushu University, Japan of the western part. One of purposes of this study is to clarify the circulation and its seasonal variability in these areas.

Another purpose of this study is to clarify the effects of inflow through the straits on the Okhotsk Sea circulation. As for the water exchange between the Okhotsk Sea and Pacific Ocean, only five among thirty straits of the Kuril Islands – the Fourth Kuril, Krusenshterna, Bussol, Friza and Ekaterina – play leading roles. Data of volume transports through the straits of the Kuril Chain are published in Kurashina et al. (1967), Bogdanov (1968), Zyrjanov (1974), Vanin and Jurasov (1998), Katsumata and Yasuda (1999), Katsumata et al (2001), Katsumata et al (2002) and Katsumata et al (2004). However, there are no generally accepted values of transports through the Kuril Straits. The accuracy of data of the volume transports has not yet been confirmed. This study will estimate these volume transports using a numerical model and compare those values with observed ones. The effects of inflow through the straits on the Okhotsk Sea circulation were left open questions.

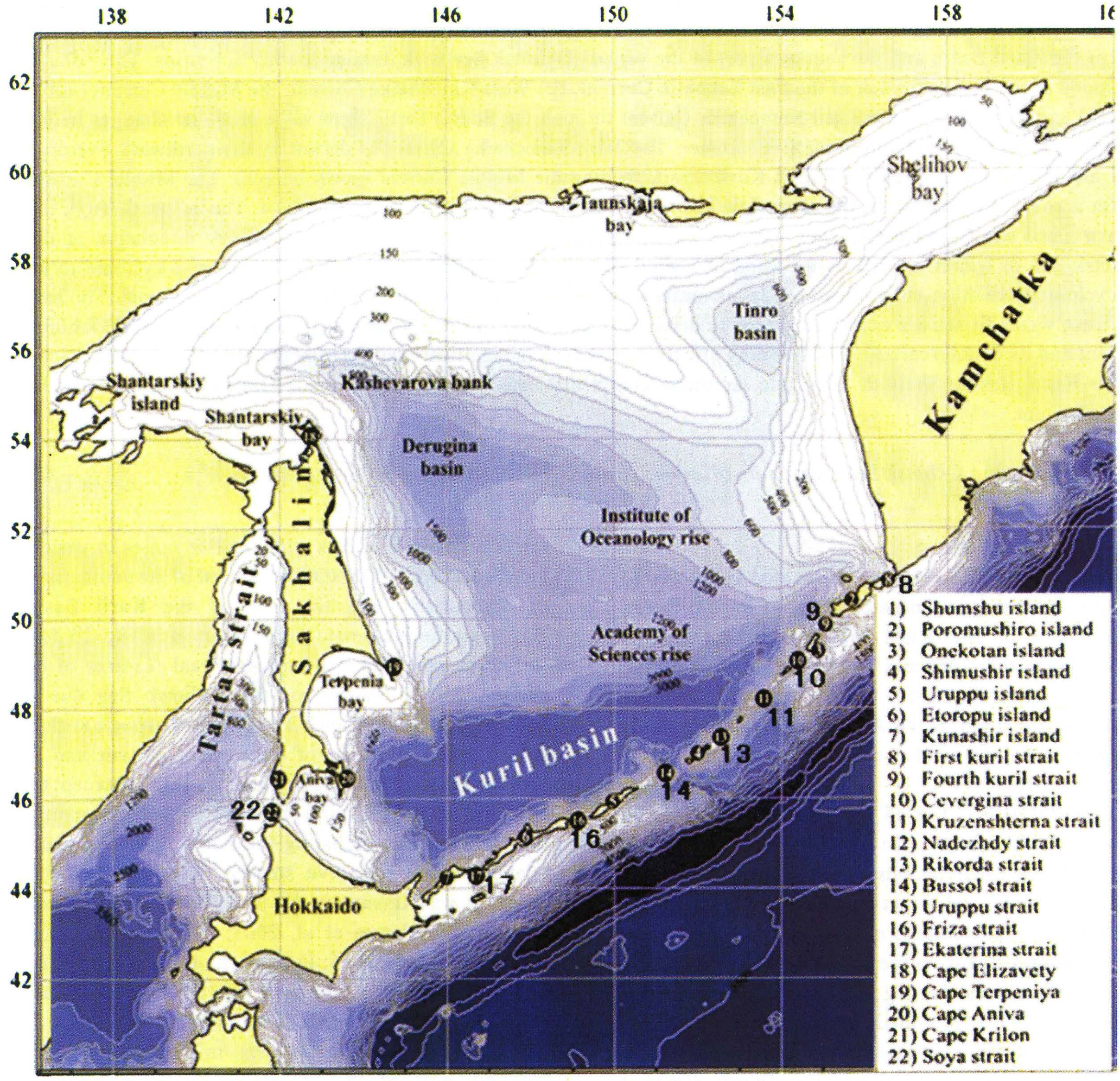


Fig. 1a. The Okhotsk Sea

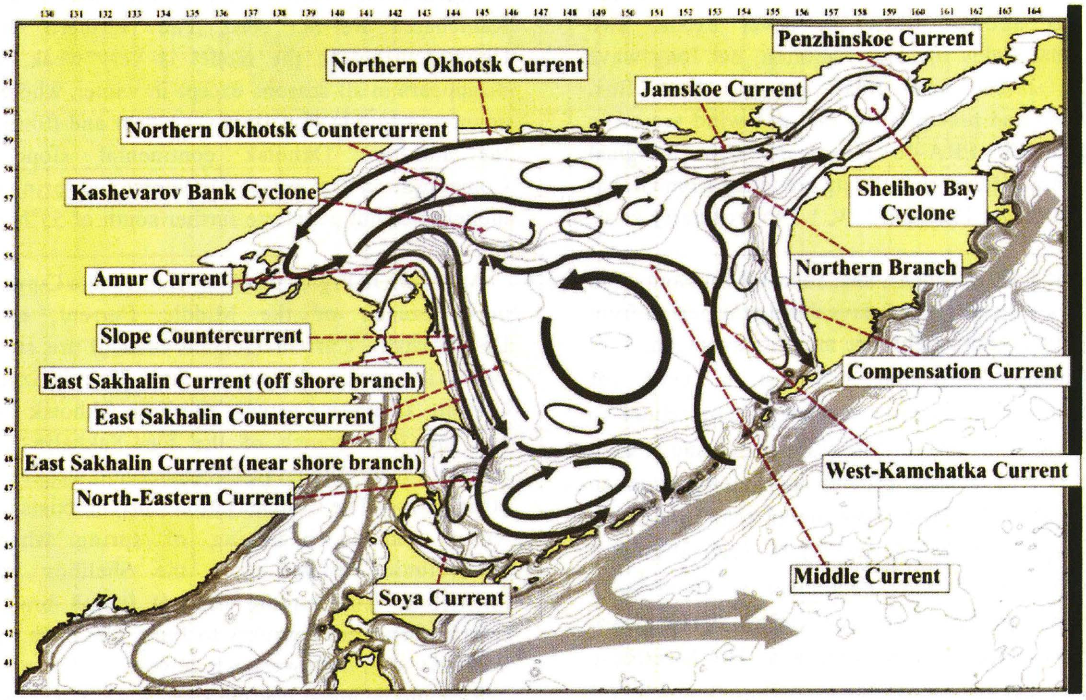


Fig. 1b. Schematic surface circulation of the Okhotsk Sea

Additionally, the role of wind, heat and salt fluxes, and tides as well as the inflow through the straits on the formation of general circulation in the Okhotsk Sea are not well clarified yet. This study will be devoted to solve these problems.

2. Numerical model

An ocean circulation model, RIAMOM (RIAM ocean model), developed at the Research Institute for Applied Mechanics (RIAM), Kyushu University, is used in this study. The RIAMOM is a three-dimensional, z-coordinate primitive equation OGCM with a free surface. The RIAMOM has a free surface that allows external gravity waves. The external gravity waves require much smaller time steps, especially for a deep ocean. A mode splitting method is adopted to avoid this problem, i.e., the governing equation is divided into a vertically integrated equation and a structure (baroclinic) equation (Blumberg and Mellor, 1987). The time filtering of Shuman (1957) is adopted to avoid computational splitting in time, permitting a longer barotropic time step. The time integration is executed by a leapfrog scheme. For more details of the RIAMOM are found in Lee et al. (2003).

The model domain is bounded by the lines of 129°E, 165°E and 40°N, 65°N (Fig. 2). The horizontal grid intervals are 1/18° in both latitudinal and longitudinal directions and the maximum number of vertical levels is 70. The vertical grid intervals are 10 to 125 m from the surface to 2500 m depth and 250 m below 2000 m. The model bottom topography is based on the GEBCO One Minute Grid (IOC, IHO and BODC, 2003).

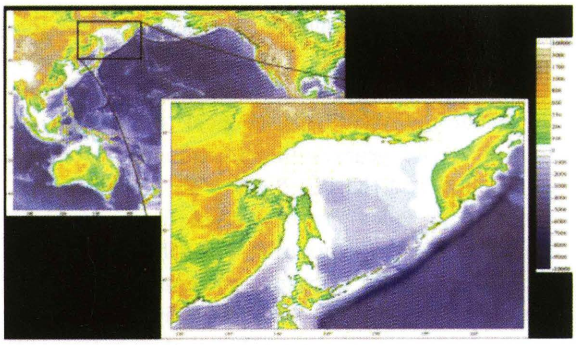


Fig. 2. Model domain

Three dimensional fields of water temperature and salinity in winter season as initial conditions are taken from the World Ocean Atlas 2001 (WOA01). The initial values of currents and sea level are taken to be zero.

The temperature, salinity and velocity along southern and eastern open boundaries are taken from results of the Pacific Ocean (1/6°) model which was integrated using the Earth Simulator, but not published yet. Heat flux at the surface is calculated using the formula by Barnier (1998).

Two dimensional fields of ice cover are taken from NOAA Optimum Interpolation 1/4 Degree Daily SST Analysis. The treatment of sea ice is simplest. We assume that the water temperature cannot go down below -2.0°C and no heat flux through the ocean surface is allowed when ice cover exists. Two dimensional fields of solar radiation, net long wave radiation, latent heat flux, sensible heat flux, evaporation and precipitation rate and wind are taken from ECMWF ERA-40 reanalysis. Climatological monthly Amur River runoff data are taken from Global River Discharge, 1807-1991, V. 1.1 (Vorosmarty et al., 1998).

Fields of SST, ice cover, heat flux, EP flux and wind stress are averaged every 5 days during the period from 1981 to 2000. Other fields are monthly averaged.

Biharmonic horizontal diffusion is used for momentum equations with the coefficients equal to $2.0*10^{16}$ cm^4/s. The Gent-McWilliams scheme is used for tracers with a back ground coefficients equal to $2.0*10^5$ cm^2/s. A mixed layer model (Noh and Kim, 1999) is applied to the RIAMOM for vertical mixing process. Bottom friction coefficient is given by a non-dimensional value of 0.0026, and no-slip boundary condition is applied at all sidewalls. The barotropic time interval is 5 seconds. The baroclinic time interval is 40 times larger than the barotropic one.

Three kinds of experiments are carried out. One is a climatological experiment forced by climatological monthly mean forcing in Section 3 and another is an experiment for model validation in Section 4, which is compared with satellite derived current fields for the period from 1980 to 2008. The other is the sensitivity experiment to external forcing in Section 5.

The model of the climatological experiment is integrated for 40 years with climatological monthly mean forcings and the last 5 years are averaged and analyzed. The model is controlled by a message passing interface (MPI) program. The MPI process was designed for 2-D parallel communication and implemented for efficient parallel computing on the supercomputer machines. The whole values calculated at each CPU are communicated in the buffer zone. The model was integrated on the SR11000 in Tokyo University. The model uses 15 nodes (240 CPUs). One year integration needs 14 hours of CPU time.

The model dataset analyzed are monthly averaged data of sea level, temperature, salinity and velocity; daily averaged fields of temperature, salinity and velocity (3 hour averaged fields of surface velocity).

3. Seasonal variability of the circulation in the Okhotsk Sea

The seasonal currents and circulations of the Okhotsk Sea in the climatological experiment are shown in Fig. 3. Most of them are seen in Fig. 1b which are depicted schematically. Major currents and circulations in Fig. 3 are schematically shown in Fig. 4 where the Northern Okhotsk Countercurrent and the Compensation Current along the west coast of Kamchatka are not seen. The Northern Okhotsk Countercurrent in the model is very weak, almost disappears in all seasons except in winter, whereas the countercurrent in Fig. 1b is very clear and flows along the northern Okhotsk continental slope. The Compensation Current seen in winter and spring in this model does not penetrate further south of 55°N unlike Fig. 1b.

As shown in Fig. 3, the West-Kamchatka Current, the north branch of the Middle Current and the East-Sakhalin Current (second branch) are strongest and exist during the whole year. The Penzhinskoe Current, Jamskoe Current, Northern Okhotsk Current and the first branch of the East-Sakhalin Current intensify from August to December and weaken in the other period. The Compensation Current exists only in winter and in beginning of spring when the anticyclonic circulation in the Shelihov Bay is intensified. The Middle Current (south branch) is clearly seen from February to June. The Soya Current is clearly seen during the whole year.

It should be noted that the Kuril Basin is occupied by eddies without mean circulation during most of a year.

3.1 Volume transports of major currents

To know the seasonal variability of the circulation in the Okhotsk Sea, we focus on the seasonal changes of the volume transports of these currents and circulations above. To do this, we calculate the depth integrated monthly mean volume transport through the vertical section across the main stream of each current. The vertical section used for the calculation of the volume transport of the first branch of the East-Sakhalin Current is determined by (143°E, 53°N) - (144°E, 53°N), that of the second branch of East-Sakhalin Current (144°E, 53°N) - (146°E, 53°N). Those of the West-Kamchatka Current and the Middle Current (south branch) are (152.5°E, 56°N) - (155.5°E, 56°N) and (150.5°E, 53°N) - (150.5°E, 55°N), respectively. Those of the Middle Current (north branch) over the north Okhotsk continental slope and the Northern Okhotsk Current are (150.5°E, 55°N) - (150.5°E, 57.5°N) and (142°E, 58°N) - (142°E, 59°N), respectively. Monthly variations of volume transports of currents mentioned above are shown in Fig. 5.

The volume transports of the first branch of the East Sakhalin Current and the Northern Okhotsk Current start to intensify from September and become peaks in November in accordance with the development of the winter northerly monsoon wind. Those of the second branch of the East Sakhalin Current, inflow of the Kuril-Kamchatka Current through the Fourth Kuril Strait show the same seasonal change with a maximum in January and a minimum in summer, which are similar to those of the West-Kamchatka Current and the

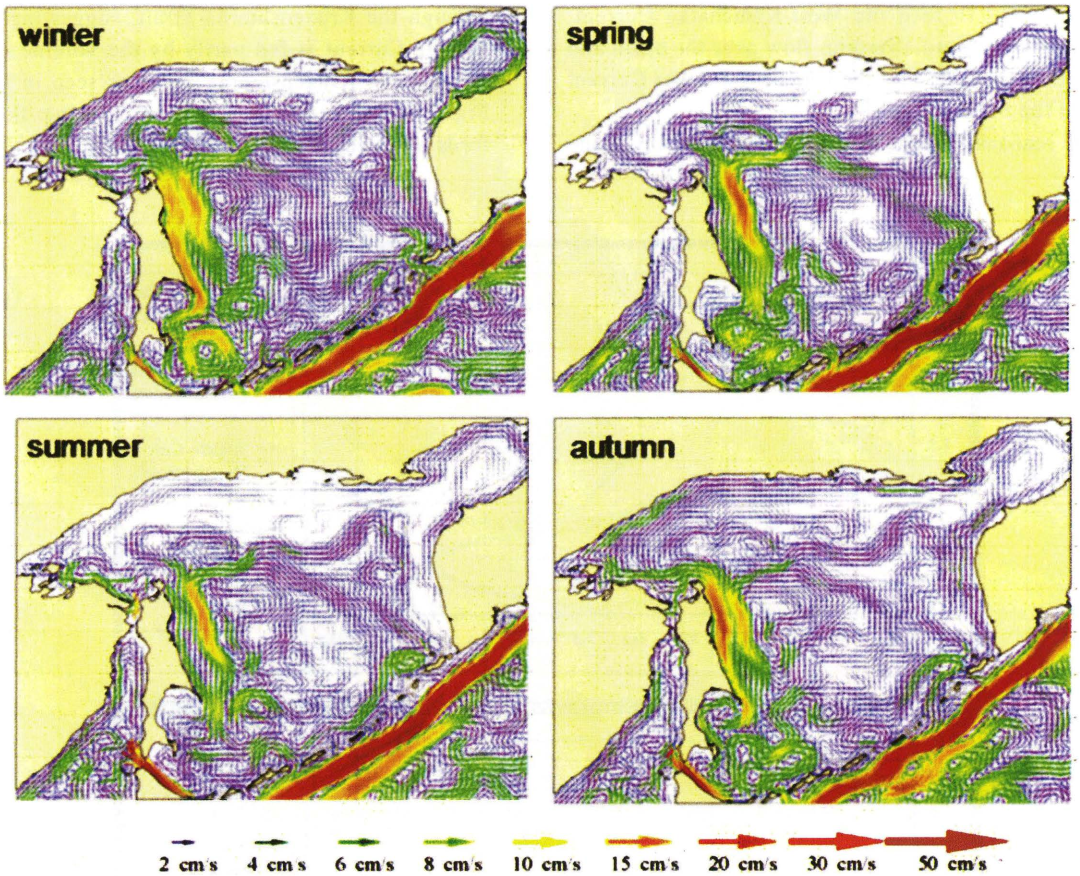


Fig. 3. The seasonal circulations in the Okhotsk Sea in the upper layer

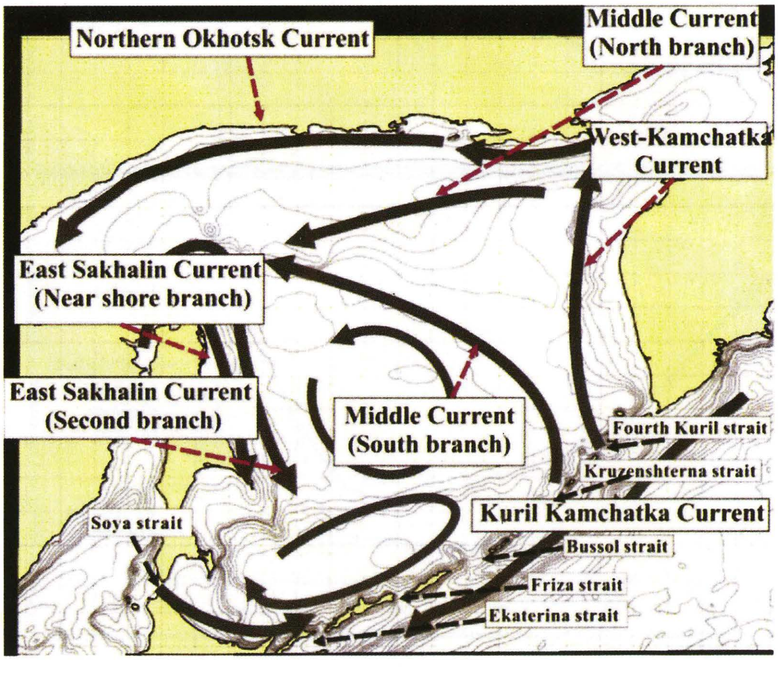


Fig. 4. Schematic view of major currents and circulations of the Okhotsk Sea

Middle Current (north branch). This suggests two possible flows to feed the West-Kamchatka Current: One is the northward Sverdrup flow over the basin and the other is the inflow of the Kuril-Kamchatka Current through the Fourth Kuril Strait.

The seasonal change of the volume transport of the Middle Current (south branch) is similar to that through the Kruzenshterna Strait, suggesting that the Middle Current is fed partly by the volume transport through the Kruzenshterna Strait as seen in spring in Fig. 3 as well as by the northward Sverdrup flow which feeds partly the West-Kamchatka Current.

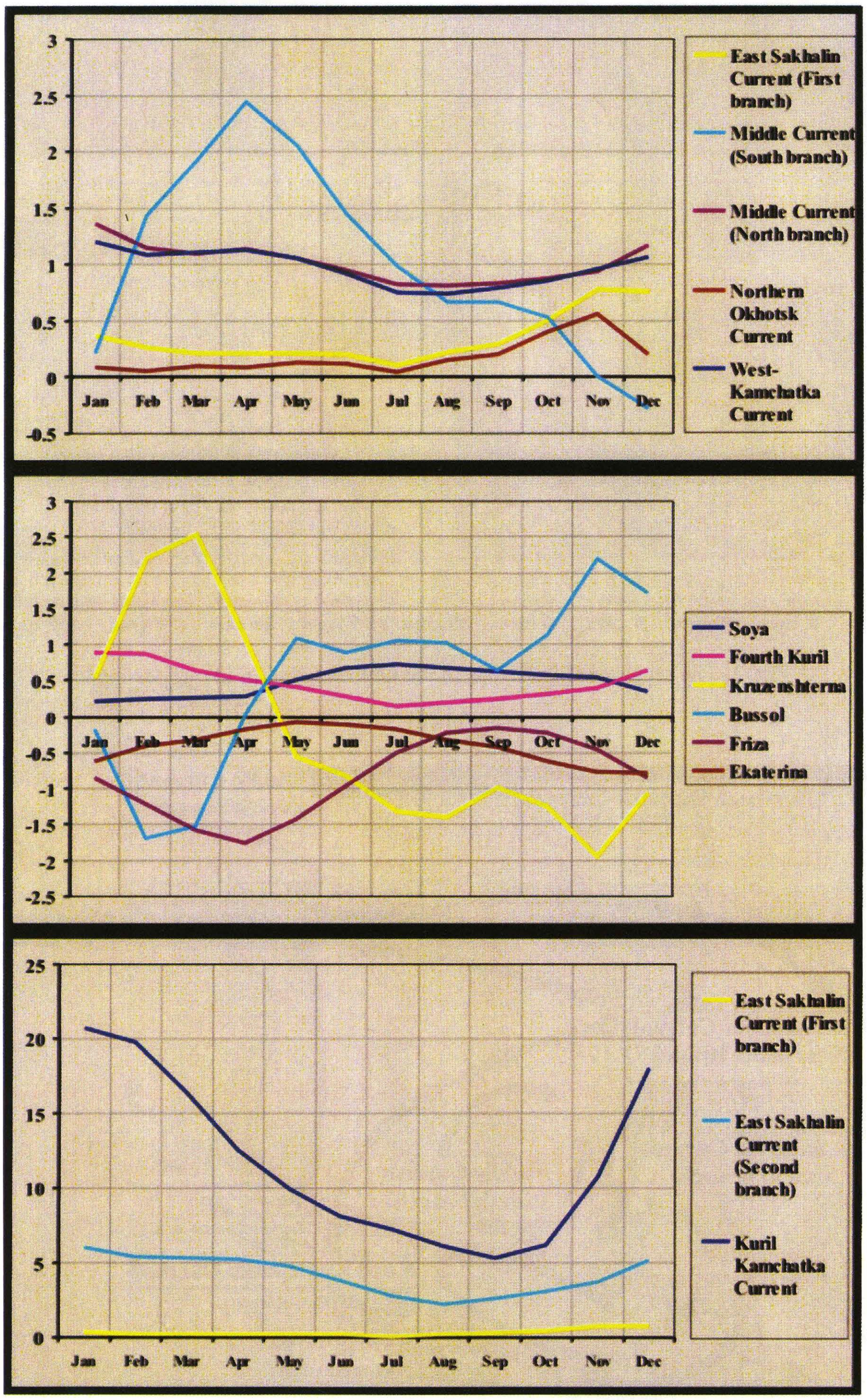


Fig. 5. Seasonal variations of volume transport (Sv, 10^6 m^3/s) of major currents and major straits.

It should be noted that the inflow transport through the Kruzenshterna Strait reaches a maximum (in March) one month prior to that of the Middle Current (south branch), suggesting that it takes a month for the signal of the inflow variation through the strait to reach the check point of the Middle Current (south branch) volume transport. The small peaks of the West-Kamchatka Current and the Middle Current (north branch) in April may be caused by the strong inflow through the Kruzenshterna Strait. The coincidence of the seasonal changes of the volume transport of the West-Kamchatka Current and the Middle Current (north branch) implies that the Middle Current (north branch) is mostly fed by the West-Kamchatka Current.

3.2. Seasonal current reversal in the Shelihov Bay

The schematic circulation pattern in Fig. 1b shows a cyclonic circulation in the Shelihov Bay. However the circulation in the Shelihov Bay depends strongly on the prevailing winds and therefore has a dramatic current reversal as shown in Fig.6. There is an anticyclone in the Shelihov Bay in winter time as Luchin (1987) and Figurkin (2002) reported the existence of the anticyclonic circulation in winter. On the other hand, Pomazanova (1970), Luchin (1987) and Moroz (1998) showed the existence of a cyclonic circulation in the warm period. The same results are shown in this study. A cyclonic circulation occupies the whole Shelihov Bay in the warm period from June to November. As the northeasterly monsoon wind season starts, the current reversal starts, generating two circulations in the Shelihov Bay in the cold period (from October to May): an anticyclone in the central and southern part and a cyclone in the northern part. The explanation for this phenomena is as follows: The strong northeasterly wind in winter induces strong coastal currents which flow out from the Shelihov Bay along south and north coasts. The West-Kamchatka Current feeds a northeastward current that flows into the interior region of the Shelihov Bay to compensate two coastal currents flowing out from the bay. As a result, an anticyclonic circulation is formed in the central and southern part of the bay and a cyclonic circulation in the northern part. In summer time when the wind is weak, the West-Kamchatka Current flows northward along the west coast of Kamchatka and flows into the Shelihov Bay along the coast of the bay, forming a cyclonic circulation. The current finally feeds the Penzhinskoe Current and Jamskoe Current.

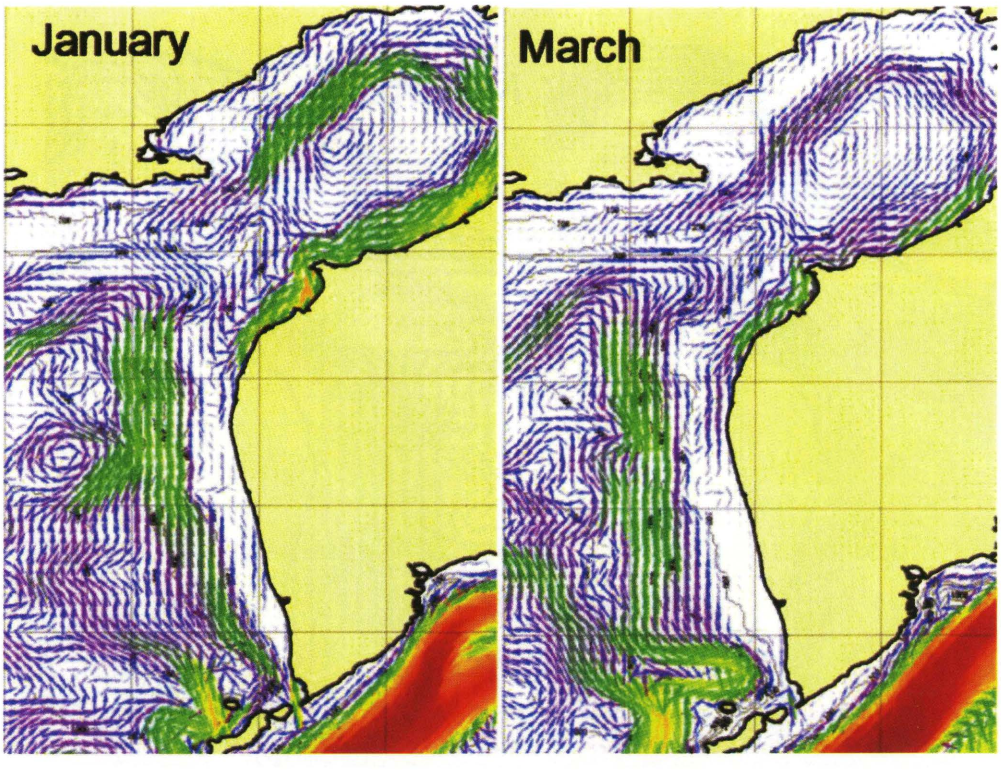


Fig. 6-1. The seasonal variation of the surface circulation in the eastern part of the Okhotsk Sea (January and March).

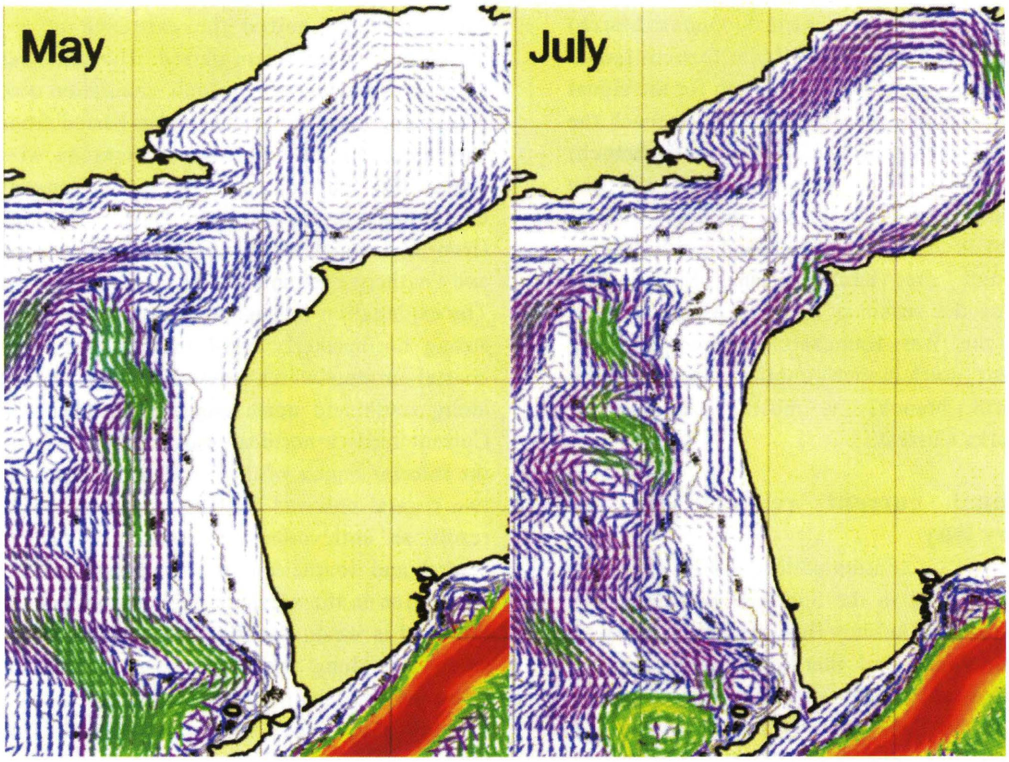


Fig. 6-2. The seasonal variation of the surface circulation in the eastern part of the Okhotsk Sea (May and July)

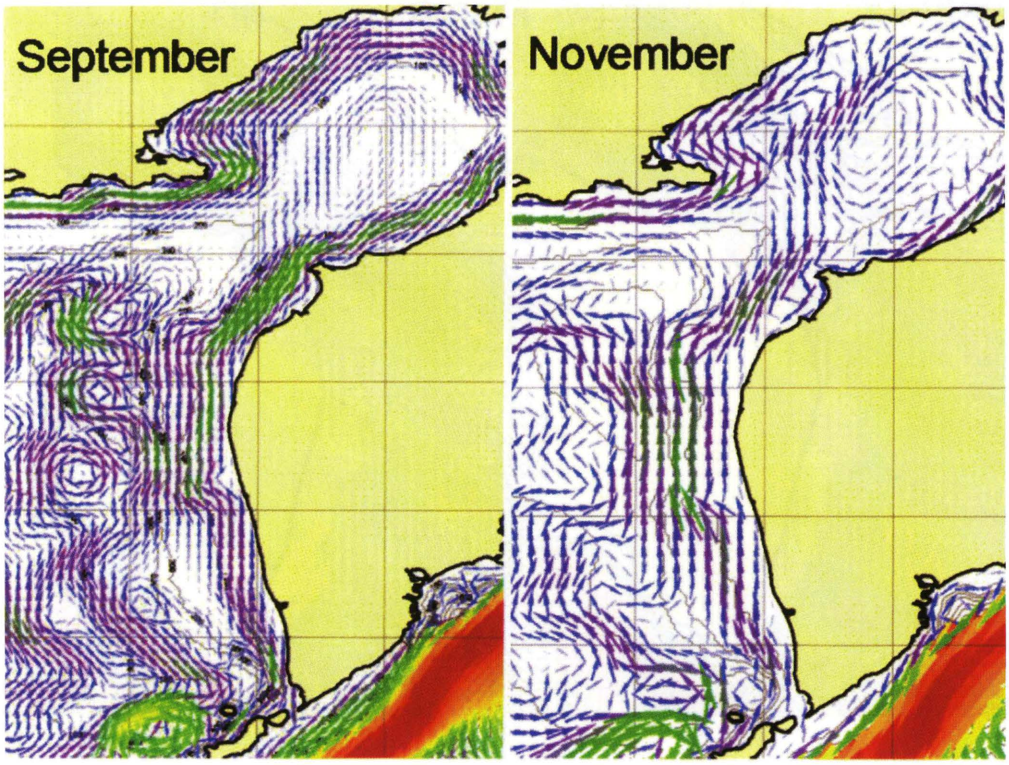


Fig. 6-3. The seasonal variation of the surface circulation in the eastern part of the Okhotsk Sea (September and November)

3.3. Northern Okhotsk Sea

The Northern Okhotsk Current and Northern Okhotsk Countercurrent form a cyclonic circulation on the northwestern Okhotsk shelf in Fig. 1b. However, the cyclonic circulation on the northwestern Okhotsk shelf in this study becomes very weak as seen in Fig. 7. During summer time, the Amur River fresh water flows southward along the north-western part of the Okhotsk Sea forming an anticyclonic vortex near the Tatar Strait and disappears by autumn. In autumn, the Northern Okhotsk Current reaches a maximum in speed (15 cm/sec) and in volume transport (0.5 Sv), occupying the entire area of the northwestern Okhotsk shelf.

However, results of oceanographic expedition of TINRO-centre (Figurkin and Zhigalov, 1999; Zhigalov, 2005; Figurkin and Shapiro, 2006) show intensive coastal currents such as the Northern Okhotsk Current and its countercurrent in fall and winter time, which are much stronger than those in this experiment. In summer time the circulation becomes weak, but with numerous eddies. This may be due to a disadvantage of the numerical model (RIAMOM) which does not include processes of sea ice formation and melting.

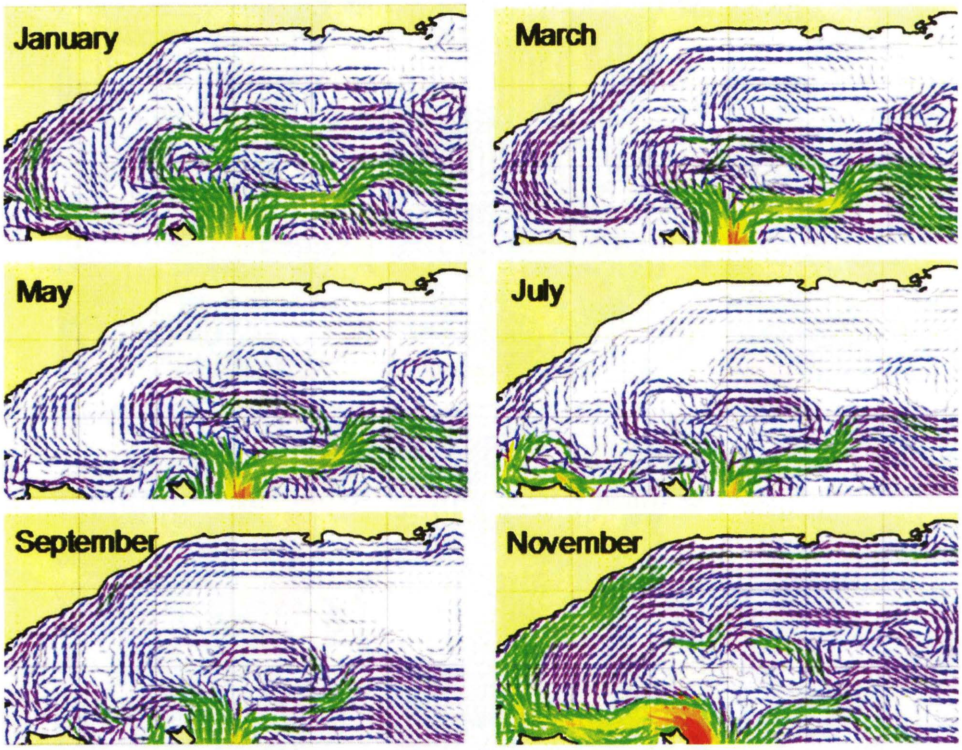


Fig. 7. The seasonal variation of the surface circulation in the north Okhotsk shelf

3.4 Western and southwestern Okhotsk Sea

The western and southwestern part of the Okhotsk Sea (Sakhalin shelf, Kuril Basin) were intensively surveyed and studied by the Japan-Russia-US Joint study group from 1998 to 2001. Ohshima et al. (2002) revealed that the East Sakhalin Current consists of two branches: the first branch near the coast at depths of 50–150 m with typical speed of 30–40 cm/s, and the second branch over the shelf slope at 300–900 m depths with typical speed of 20–30 cm/s. Mizuta et al. (2003) estimated the annual mean volume transport of the East Sakhalin Current to be 6.7 Sv with a maximum (12.3 Sv) during February and a minimum (1.2 Sv) during October.

Simizu and Ohshima (2002) suggested that the first branch of the East Sakhalin Current can be interpreted as arrested topography waves (ATW): a coastal current driven by the alongshore wind stress (Csanady, 1978). The first branch is also driven by the fresh water flux from the Amur River in summer and autumn, resulting in the intensification of southward current in the surface layer with small effect of volume transport (Mizuta et al., 2003; Tachibana et al., 2008).

Ohshima et al. (2004) showed that the Sverdrup balance holds roughly in the cyclonic gyre over the northern half-basin of the Okhotsk Sea (50°–53°N) and that the major part (second branch) of the East Sakhalin

Current can be regarded as the western boundary current of this gyre. Simizu and Ohshima (2006) successfully simulated both branches of the East Sakhalin Current using the Princeton Ocean Model with realistic bottom topography.

The major features of the circulation in the western and southwestern part of the Okhotsk Sea in this study consist of the Amur Current, East-Sakhalin Current, East-Sakhalin Countercurrent, North-Eastern Current, Soya Current and the eddies over the Kuril Basin as shown in Fig. 8. Results in this study are generally consistent with features of the Okhotsk Sea circulation. The East Sakhalin Current in this study is also consistent with its real feature. The seasonal variation of the volume transport of the East Sakhalin Current has a tendency similar to that by Mizuta et al. (2003), but the amplitude is almost half of it. The volume transport of the first branch has a maximum in November and a minimum in July. The second branch takes a maximum volume transport in January, which is two months later than the first branch and a minimum in August. The two months lag suggests that the second branch is driven by the wind stress curl over the interior region of the Okhotsk Sea as pointed out by Oshima et al. (2004).

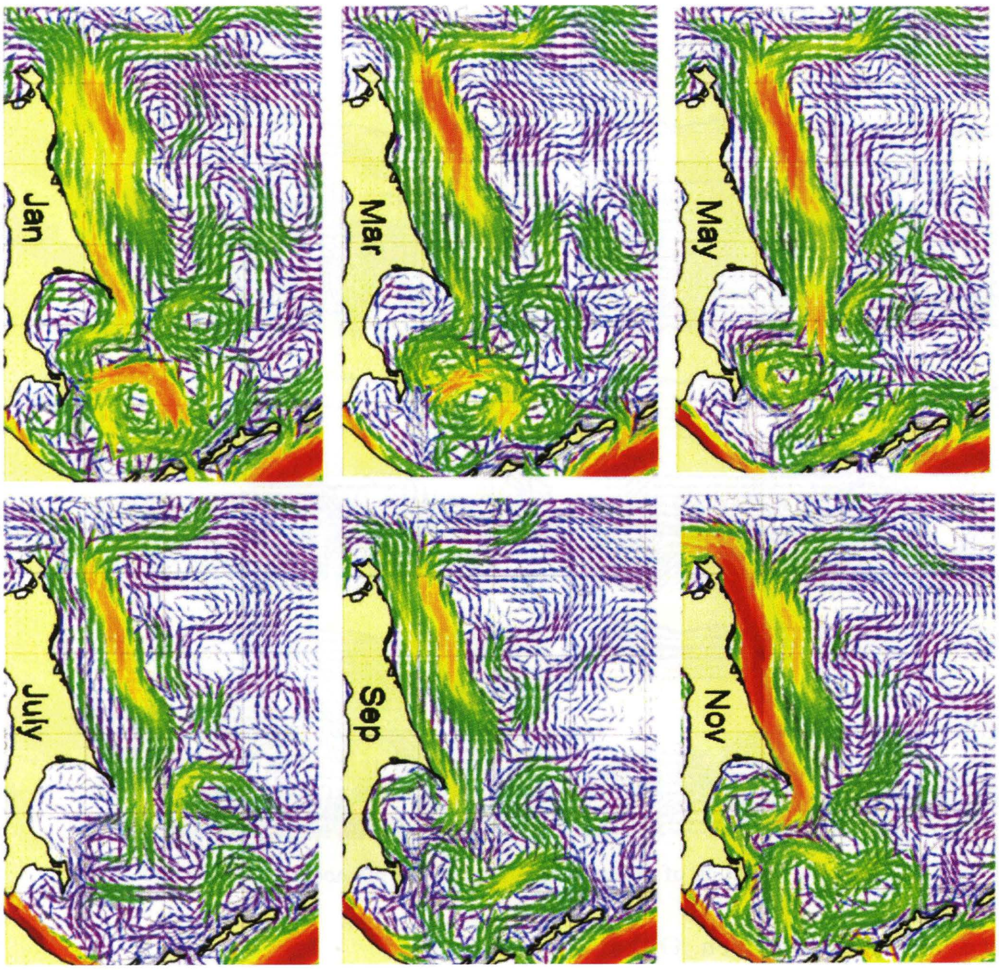


Fig. 8. The sesonal variation of the surface circulation on the East Sakhalin shelf.

The Amur River fresh water reaches Hokkaido, in accordance with Watanabe (1963). The East-Sakhalin Countercurrent exists during a year. The Soya Current, flowing into the Okhotsk Sea from the Japan Sea through the Soya Strait, has a maximum transport in summer as shown in Fig. 5. The Kuril Basin is occupied by plenty of eddies in all seasons except autumn when an anticyclonic circulation is dominated.

3.5 Volume transport through the Soya and Kuril Straits

The Kuril Islands with approximately 1200 km extent consists of 28 relatively large islands and many small ones. The total width of the Kuril Straits is about 500 km. About 43.3% of total width is occupied by the Bussol Strait (depth of sill is 2318 m), 24.4% by the Kruzenshterna Strait (depth of sill is 1920 m), 9.2% by the Friza Strait and 8.1% by the Fourth Kuril Strait.

Calculated seasonal variations of the volume transport through the Fourth Kuril, Kruzenshterna, Bussol, Friza, Ekaterina and Soya Straits are shown in Fig. 9. During a year, the water flows into the Okhotsk Sea through the Soya and Fourth Kuril Straits and flows out from the Okhotsk Sea into the Pacific through the Friza and Ekaterina Straits. The water flows into

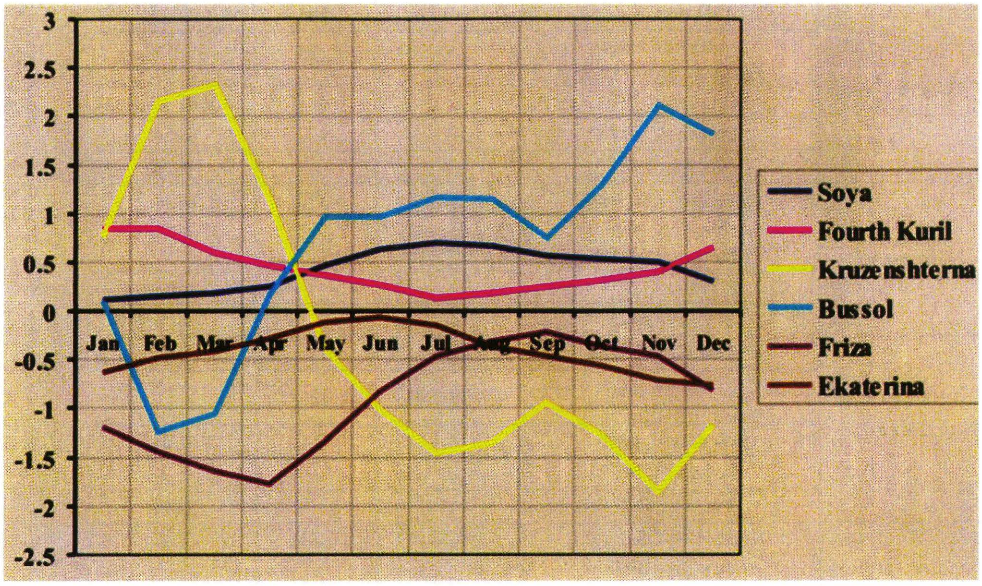


Fig. 9. Seasonal variations of volume transports through Kuril and Soya Straits (negative – outflow from the Okhotsk Sea, positive – inflow into the Okhotsk Sea)

Table 1-1. Volume transport through the Soya Strait

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Okhotsk Sea model 1/18°	0.18	0.10	0.20	0.32	0.51	0.68	0.71	0.67	0.65	0.67	0.70	0.55	0.49
Dynamic Method													
Leonov, 1960													0.42
Diagnostic Model													
Yurasov, 1987		0.54						2.16					
Vasiliev and Dudka, 1994											0.4		
Vasiliev and Khrapchenkov, 1996								0.98				0.63	
Constant current velocity through the strait													
Aota M. 1975								1.3					
Instrumental Measurement													
Aota 1985, 1991						1.2		0.96		0.65			
Supranovich et al., 2001								1.02					
Tanaka et al. 1996								1.18					
SSH difference + Instrumental Measurement													
Saveliev et al., 2002	-0.1	0.04	0.25	0.62	0.73	0.91	1.06	1.18	1.14	0.91	0.48	0.04	0.6

Table 1-2. Volume transport through the Kuril Straits

Straits		Aug	Dec	Mean
Fourth Kuril	RIAMOM OS 1/18°	0.15	0.62	0.39
	Vasiliev and Khrapchenkov, 1996	-0.5	-0.7	
	Zyryanov, 1974			0.62-0.86
	Zyryanov, 1975			0.68
	Kozlov, 1972			10.92
Ekaterina	RIAMOM OS 1/18°	-0.21	-0.52	-0.36
	Vasiliev and Khrapchenkov, 1996	-0.01	-0.01	
	Zyryanov, 1975			-0.5
	Kozlov, 1972			-0.8
Friza	RIAMOM OS 1/18°	-0.43	-0.91	-0.67
	Vasiliev and Khrapchenkov, 1996	(-0.99;0.48)	(-1.02;0.5)	
	Bogdanov, 1968			0.86
	Zyryanov, 1975			-1.32
	Kozlov, 1972			0.86
Bussol	RIAMOM OS 1/18°	1.38	1.35	1.36
	Vasiliev and Khrapchenkov, 1996	-0.9	-1.8	
	Rogachev and Verhunov, 1996			<9.8
	Kurashina et al., 1967			5
	Zyryanov, 1975			-0.3
	Kozlov, 1972			5
	Vanin and Yurasov, 1998			-3.9
	Katsumata and Yasuda, 1999			-20
	Katsumata et al, 2002			-2.5
	Katsumata et al, 2004			-8
Kruzenshtern	RIAMOM OS 1/18°	-1.48	-1.30	-1.39
	Khrapchenkov and Vasiliev, 1996	-0.2		
	Talley and Nagata, 1995			4
	Zyryanov, 1974			1.4-1.6
	Zyryanov, 1975			1.4
	Kozlov, 1972			-16.2
	Katsumata et al., 2001			upper level - 1.6 bottom level - - 1.3
Nadezhdy	RIAMOM OS 1/18°	-0.08	0.13	0.03
	Vasiliev and Khrapchenkov, 1996	-2	-2.55	

the Okhotsk Sea through the Kruzenshterna Strait from January to April, and flows out from May to December. The seasonal variation of the volume transport through the Bussol Strait is inversely proportional to that through the Kruzenshterna Strait. The mean volume transport from the Okhotsk Sea through the Ekaterina Strait is 0.4 Sv with a minimum (0.1 Sv) in June and a maximum (0.8 Sv) in December. The mean volume transport through the Fourth Kuril Strait is 0.45 Sv with a minimum (0.15 Sv) in July and a maximum (0.85 Sv) in January. The mean volume transport through the Friza Strait is 0.9 Sv with a minimum (0.2 Sv) in September and a maximum (1.8 Sv) in April. The mean volume transport through the Soya Strait into the Okhotsk Sea is 0.4 Sv with a minimum (0.1 Sv) in January and a maximum (0.7 Sv) in July.

There are many researches devoted to the volume transport through the Soya Strait as shown in Table 1-1 which summarizes past studies of the volume transport through the Soya Strait.

Past studies suggest that the volume transport through the Soya Strait flowing into the Okhotsk Sea has a seasonal variation with a minimum in winter and a maximum in summer. The minimum value ranges from -0.1 to 0.54 Sv and the maximum value ranges from 1 to 2 Sv. The tendency of the seasonal variaition corresponds well to the present study, but the amplitude of seasonal variation is larger than the present study.

As for the water exchange between the Okhotsk Sea and Pacific Ocean, only Fourth Kuril, Krusenshterna, Bussol, Friza and Ekaterina Straits play leading roles (Luchin, 1987). The results of past studies until 2000 are presented in the report by the director of FERHI Regional Center of oceanographic data Rykov N.A. (personal communication). According to this report, the generally accepted values of volume transport through the Kuril Straits do not exist. Estimates of the volume transports differ much in sign and magnitude between studies (Table 1-2). There are only several papers with data of the volume transport through Kruzenshterna Strait based on ADCP current data (Katsumata et al., 2001) and Bussol Strait (Katsumata et al, 2002, 2004). The reliable comparison of volume transports through the Kuril Straits between observations and this study seems to be a future issue.

4. Model validation

In this study, Delayed Time Maps of Sea Level Anomalies & geostrophic velocity anomalies (DT-MSLA) data with 1/4° gird intervals and a repeat cycle of 7 days, provided by the Archive "Validation and Interpretation of Satellite Oceanographic data (AVISO in France), are used to calculate surface current velocities for the validation of the simulation. Data were downloaded from Ssalto/Duacs multimission altimeter products. DUACS (Data Unification and Altimeter Combination System) is a part of the CNES multi-mission ground segment (SSALTO). It processes data from all altimeter missions: OSTM/Jason-2, Jason-1, Topex/Poseidon, Envisat, GFO, ERS-1&2 and even Geosat. At this time DUACS is using three different altimeters. Data from January 1993 to December 2000 are used in this study.

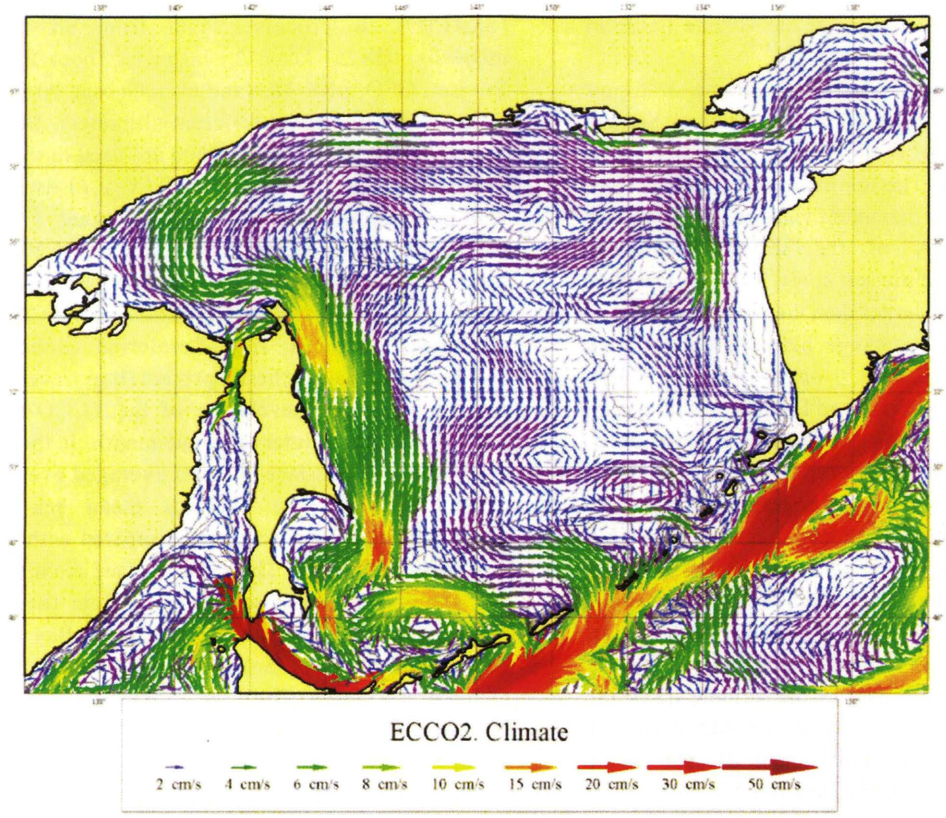
Absolute geostrophic current $V(x,y,t)$ is assumed here as a sum of mean geostrophic current $\overline{V}(x,y)$ and geostrophic velocity anomalies $V'(x,y,t)$. The mean geostrophic current is calculated from results of the ECCO2 (Estimating the Circulation and Climate of the Ocean, Phase II: High-Resolution Global-Ocean and Sea-Ice Data Synthesis) project (http://ecco2.org/).

The horizontal resolution of the ECCO2 data is 1/4°and the output interval is one month. In the present study, the mean surface currents averaged over 8 years (1993 to 2000) are used as mean sea surface geostrophic currents which are compared with those of this study in Fig. 10. The mean surface circulations in this study correspond well to those from the ECCO2 except the circulation in the Shelihov Bay and the strength of the East Sakhalin, Middle and Northern Okhotsk Currents. The East Sakhalin, Middle and Northern Okhotsk Currents in this study are much stronger than those in the ECCO2. The geostrophic velocity anomalies from altimeter data and the mean sea surface currents from the numerical model of ECCO2 are combined to get absolute geostrophic velocity in every month for 8 years.

Statistical evaluation of the comparisons between the absolute geostrophic velocity and model results are presented in Fig. 11 and 12. The correlations in the east Sakhalin, Kamchatka and northern Okhotsk shelves are high and those of the central part of the southern Okhotsk Sea and Kuril Basin are low. Fig. 13 shows comparisons between model velocity and the absolute geostrophic velocity for the northern part of Okhotsk Sea (defined as the region north of 52° N) and southern

Table 2. Statistical evaluation of comparisons between the absolute geostrophic velocity and model velocity

	U component			V component		
	whole area	northern part	Southern part	whole area	northern part	Southern part
number of data points	262444	137743	124701	262444	137743	124701
root-mean-squared errors (RMSE)	6.6	5.2	7.9	7.6	5.6	9.4
correlation coefficient	0.37	0.56	0.3	0.5	0.69	0.4
slope of regression line	0.28	0.29	0.29	0.35	0.35	0.31



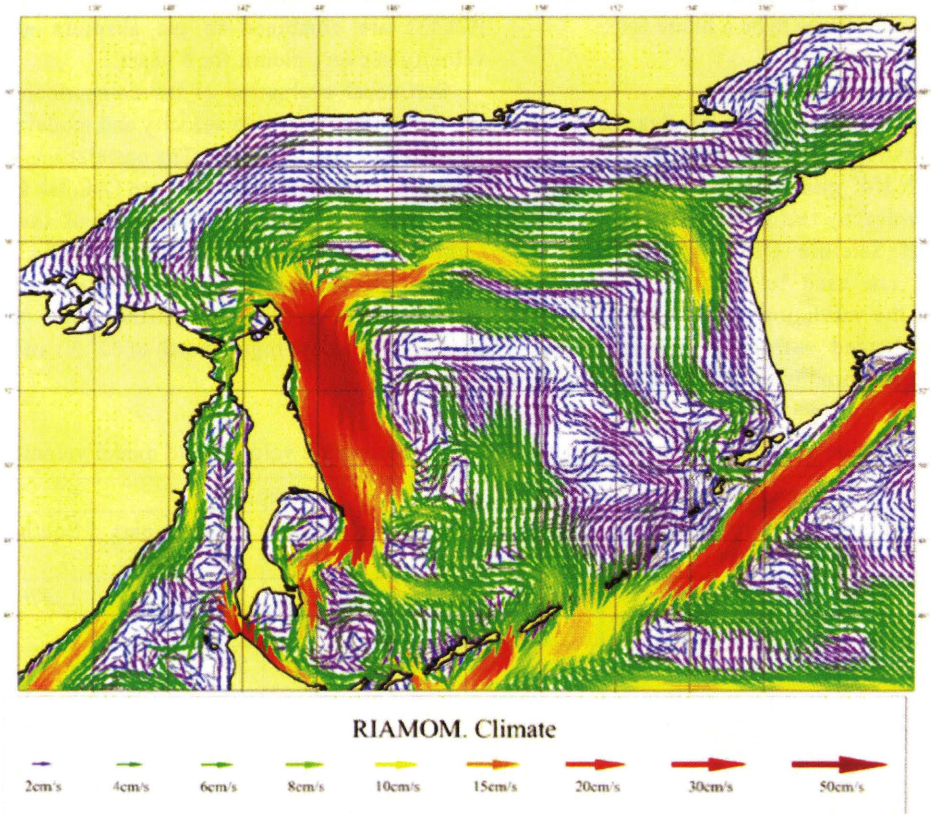


Fig. 10. Climatological mean surface currents from the ECCO2 data (upper) and this model (lower)

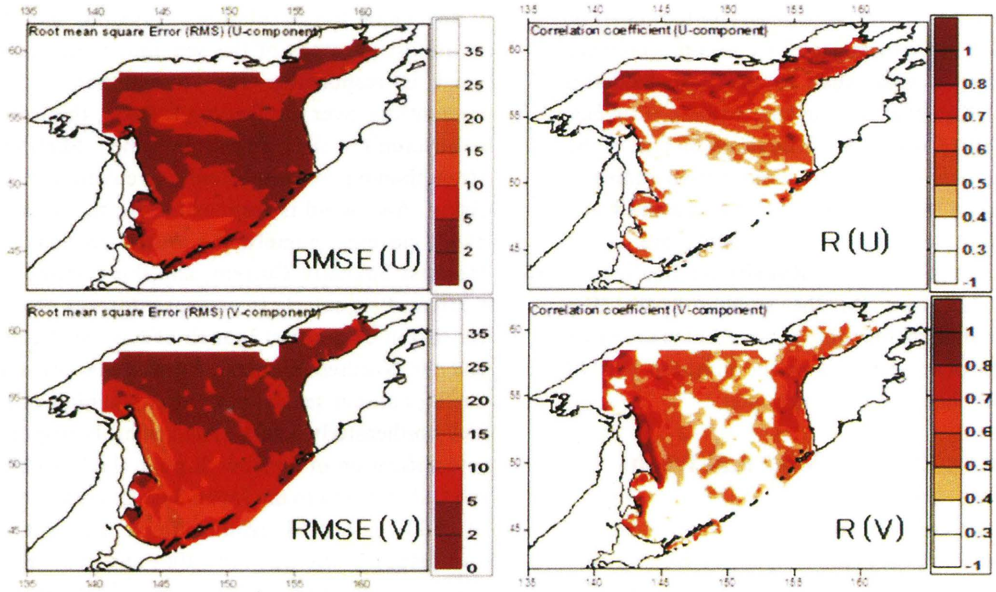


Fig. 11. Root mean square Error (RMSE) (left) and Pearson correlation (right) between absolute geostrophic velocity (AVISO+ECCO2) and model velocity.

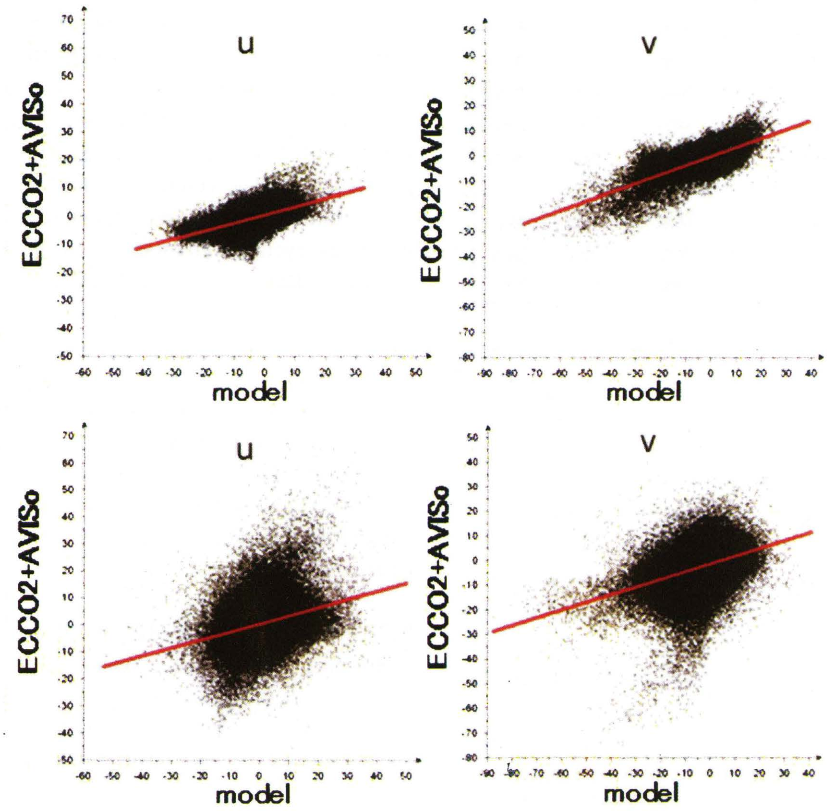
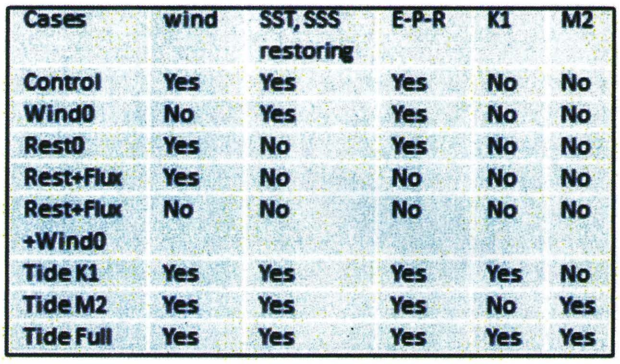


Fig. 12. Comparison between absolute geostrophic velocity (AVISO+ECCO2) and model velocity for the northern and southern Okhotsk Sea. The red lines represent regression lines calculated by principle component analysis. Velocity unit is cm/s.

part of the Okhotsk Sea (defined as the region south of 52° N). All statistics are in Table 2. The northern part of the Okhotsk Sea is characterized by currents which are persistent during a year, such as the East Sakhalin Current, West-Kamchatka Current, Middle Current, Northern Okhotsk Current, etc. The southern part of the Okhotsk Sea is characterized by many active eddies in the central part of the southern Okhotsk Sea and Kuril Basin. Therefore, correlation coefficients are larger and root-mean-squared errors (RMSE) are smaller for the northern part than for the southern part. The comparison implies that model velocity fields are more consistent with observed ones in the northern part of the Okhotsk Sea than in the southern part.

5. Sensitivities to wind, heat and fresh water flux and tides

To estimate the contribution of wind stress, heat and fresh water fluxes, tides, sensitivity experiments listed in the Table 3 are conducted. To obtain a realistic circulation and its seasonal variability, various possible factors are considered.



Cases	wind	SST, SSS restoring	E-P-R	K1	M2
Control	Yes	Yes	Yes	No	No
Wind0	No	Yes	Yes	No	No
Rest0	Yes	No	Yes	No	No
Rest+Flux	Yes	No	No	No	No
Rest+Flux +Wind0	No	No	No	No	No
Tide K1	Yes	Yes	Yes	Yes	No
Tide M2	Yes	Yes	Yes	No	Yes
Tide Full	Yes	Yes	Yes	Yes	Yes

Table 3. Cases conducted in sensitivity studies

Control – Climatological run as in previous chapters
Wind0 - No wind stress
Rest0 – restoring force is not used
Rest+Flux - restoring force is not used; net heat flux is constant in space and time, EPR flux is 0.
Rest+Flux+Wind0 - restoring force is not used; net heat flux is constant in space and time, EPR flux is 0, wind stress is zero.
Tide K1 – Tides TPXO7 K1 harmonic constituent is imposed (Egbert, G.D. and S.Y. Erofeeva, 2002)
Tide M2 – Tides TPXO7 M2 harmonic constituents is imposed (Egbert, G.D. and S.Y. Erofeeva, 2002)
Tide Full – Tides TPXO7 eight primary (M2, S2, N2, K2, K1, O1, P1, Q1) harmonic constituents (Egbert, G.D. and S.Y. Erofeeva, 2002)

(To examine the tidal effects, tidal forcing from the TPXO6 analysis (Egbert et al., 1994; Egbert and Erofeeva, 2002) is applied in surface height and depth-averaged velocity boundary conditions)

The results are briefly summarized. The main influence on the circulation is given by the wind field in almost all areas of the sea and in all seasons. The wind is responsible for strengthening of cyclonic circulations over the Deryugin Basin, the formation of anticyclonic circulation in the Shelihov Bay, strengthening of anticyclonic circulation in the Kuril Basin. Also wind is responsible for the intensification of all currents, namely, the West-Kamchatka Current, the East Sakhalin Current, and the Continental Slope Current. Particularly important influence of wind is the formation of the first branch of East Sakhalin Current and the Northern Okhotsk Current that are accelerated during autumn season with strengthening of northerly and northeasterly winds. Also wind is responsible for intensification of outflow through the Soya Strait from the Okhotsk Sea to the Japan Sea. Using restoring force of SST and SSS results in a stronger cyclonic circulation in the Shelihov Bay and generation of the first branch of the East Sakhalin Current. Imposing heat and fresh water fluxes leads to the formation of cyclonic circulation in the north Okhotsk Sea shelf (Northern Okhotsk Current and Northern Okhotsk Countercurrent).

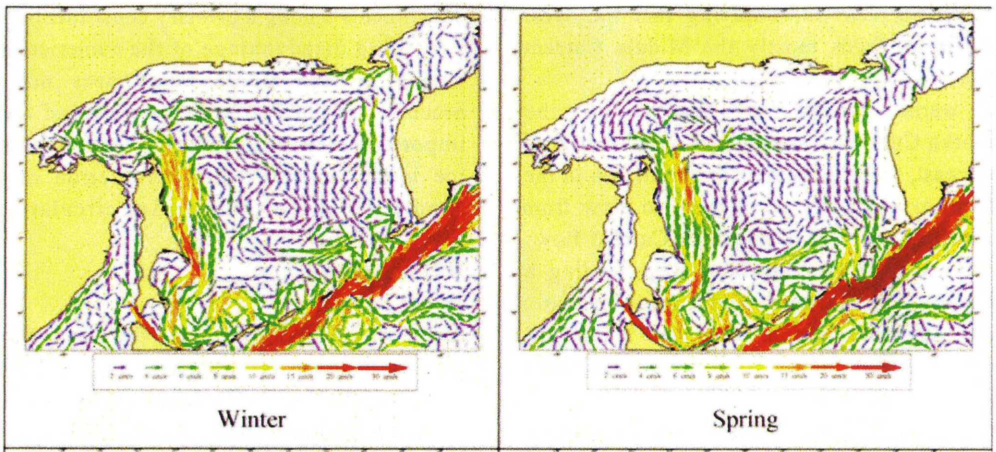
It should be noted that strong cyclonic circulations are seen during a year in the Kuril Basin and the Shelihov Bay in Fig. 13 which shows the seasonal variability of the circulation of the Okhotsk Sea in the tide full experiment (TPXO7 eight primary harmonic constituents (M2, S2, N2, K2, K1, O1, P1, Q1) of tide are imposed). The comparison Fig. 13 with Fig. 3 (the case without tidal forcing) shows that the tidal forcing generates cyclonic circulations in the Kuril Basin and Shelihov Bay. The contributions to the cyclonic circulation in the Kuril Basin are mainly given by the M2 and K1 tidal constituents among 8 primary constituents.

The inflow and outflow through the Kuril Straits and Soya Strait also have important influence on the circulation of the Okhotsk Sea. For example, seasonal variability of the Kuril Currents affects the seasonal variability of the West-Kamchatka and the Middle Currents.

5. Summary and discussions

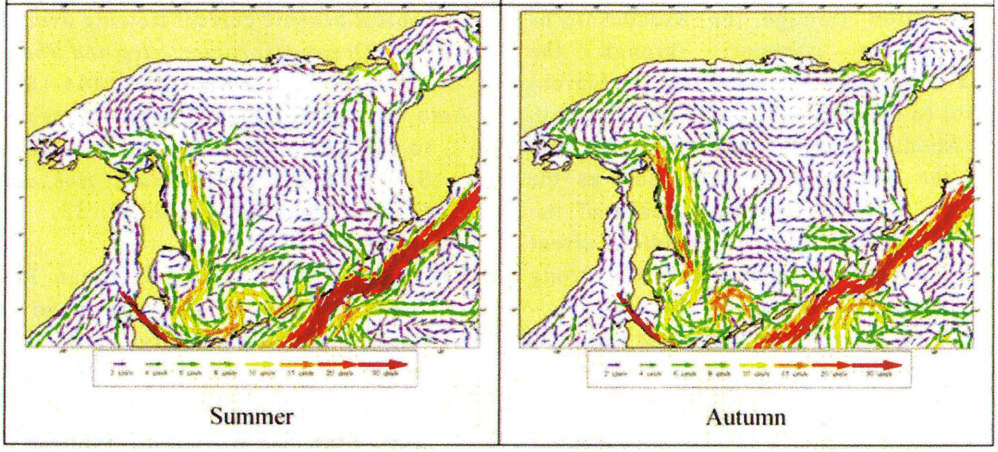
In this study, we focused our efforts on 1) identification of main features of the general circulation of the Okhotsk Sea, 2) clarifying of the seasonal variability of the general circulation, 3) validation of model results with observed data, 4) sensitivity studies to external forcing such as wind, heat flux, fresh water flux and tides.

Model results show that the circulation in the Okhotsk Sea is generally cyclonic, consisting of major currents, the West-Kamchatka Current, Middle Current (north and south branches), first and second branches



Winter

Spring



Summer

Autumn

Fig. 13. The seasonal variability of the circulation of the Okhotsk Sea in the tide full experiment (TPXO7 eight primary harmonic constituents (M2, S2, N2, K2, K1, O1, P1, Q1) of tide are imposed).

of the East Sakhalin Current and the Northern Okhotsk Current. All those currents flow over continental slopes and shelves, existing throughout a year. Other currents (Compensation Current, Penzhinskoe Current, Jamskoye Current, Northern Okhotsk Countercurrent, and Amur Current) appear only in special seasons. A dramatic current reversal from cyclonic to anticyclonic circulation in the Shelihov Bay in accordance with the start of northeasterly monsoon wind is also one of main features of the general circulation in the Okhotsk Sea.

The Northern Okhotsk Current and the first branch of the East Sakhalin Currents are formed by the mechanism of arrested topography waves as pointed out by Simizu and Ohshima (2006) which are generated in autumn and winter. The volume transports of these currents start to intensify from September and become peaks in November in accordance with the development of the winter monsoon wind. Then, the volume transports of these currents decrease gradually toward summer.

As Simizu and Ohshima (2006) pointed out that the second branch of the East Sakhalin Current can be regarded as a western boundary current in the Okhotsk Sea driven by a positive wind stress curl with a maximum strength in January in the central and eastern part of the Okhotsk Sea in monsoon season. Therefore, the volume transport of the second branch of the East Sakhalin Current reaches a maximum in January, two months later than that of the first branch.

The volume transport of the West-Kamchatka Current shows almost same seasonal change as the transport through the Fourth Kuril Strait, suggesting that the inflowing transport through the Fourth Strait feeds the West-Kamchatka Current. However, the volume transport through the Fourth Strait is about half of the West-Kamchatka Current. Remaining half should be fed by any other current. A possible candidate for this is the Sverdrup flow. Since the Sverdrup flow in the central and eastern part of the Okhotsk Sea is a broad northward current feeding the second branch of the East Sakhalin Current, the flow may increase the transport of the West-Kamchatka Current in the eastern part of the Okhotsk Sea. However, the quantitative analysis remains for future study.

The Middle Current (north branch) shows almost same seasonal variations in both amplitude and phase as the West-Kamchatka Current, implying that the West -Kamchatka Current feeds mostly the Middle Current (north branch).

In the warm season, a branch of the West-Kamchatka Current flows into the Shelihov Bay along the bay coast, feeding a cyclonic circulation in the bay. As strong northeasterly wind starts to blow from autumn, a branch of the West-Kamchatka Current flows into the central part of the Shelihov Bay, feeding a cyclonic circulation in the north and an anti-cyclonic circulation in the south which feeds the southward Compensation Current along the West-Kamchatka coast in autumn and winter.

The Middle Current (south branch) is fed partly by the volume transport through the Kruzenshterna Strait. The inflow transport through the Kruzenshterna Strait reaches a maximum (in March) one month prior to that of the Middle Current (south branch). The Middle Current (south branch) is also intensified by the northward Sverdrup flow as the West-Kamchatka Current. The small peaks of the West-Kamchatka Current and the Middle Current (north branch) in April may be caused by the strong inflow through the Kruzenshterna Strait.

Comparisons between the results in this study and observations have shown that model results are generally in good agreements with observed features of the general circulation of the Okhotsk Sea. As for the seasonal variability, model results are more consistent with observations in the northern part of the Okhotsk Sea than in the southern part.

Sensitivity studies to various external forcing have shown that the main impact on the general circulation of the Okhotsk Sea is given by the wind stress and curl. The impacts are seen in all areas of the sea and in all seasons. Wind is responsible for strengthening major currents, the cyclonic circulation over the Deryugin Basin, for the formation of anticyclonic circulation in the Shelihov Bay. The inflow and outflow through the Kuril Straits and Soya Strait also have important effects on the circulation of the Okhotsk Sea. The restoring of SST and SSS result in a stronger cyclonic circulation in the Shelihov Bay and intensification of the first branch of the East Sakhalin Current, respectively. Heat and fresh water fluxes lead to the formation of a cyclonic circulation over the north Okhotsk Sea shelf (Northern Okhotsk Current and Northern Okhotsk Countercurrent).

Thus, the wind stress intensifies the circulation throughout the Okhotsk Sea, and the restoring of heat and fresh water fluxes does on the northern shelf only, which is covered with ice in winter. Tidal forcing effects can be seen in significant reinforcements of the cyclonic circulations in the Kuril Basin, Shelihov Bay. The contributions to the cyclonic circulation in the Kuril Basin are mainly given by the M2 and K1 tidal constituents among 8 primary constituents.

A big disadvantage of the numerical model is the simple sea ice model which does not include the processes of formation and melting of ice. The next important step is to incorporate a sophisticated sea ice model in the ocean circulation model for the simulation of the Okhotsk Sea circulation.

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