Coherent sea level variation in and around the Sea of Okhotsk

Takuya Nakanowatari *, Kay I. Ohshima

Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan

* Corresponding author address.

Institute of Low Temperature Science, Hokkaido University

Kita-19, Nishi-8, Sapporo, 060-0819 Japan

Tel.:+81-11-706-5497 ; fax:+81-11-706-5497

E-mail address: nakano@lowtem.hokudai.ac.jp (T. Nakanowatari).
ABSTRACT

We investigated the seasonal and interannual variations of the sea level in and around the Sea of Okhotsk and their causes, based on tide gauge and satellite altimeter data. The sea level all along the coastal region of the Sea of Okhotsk is found to be dominated by the seasonal variation with a maximum in winter and a minimum in summer, which cannot be explained by the annual cycle of atmospheric heat flux and pressure. This sea level variation appears to reflect ocean current variations. Both the Arrested Topographic Waves (ATWs) caused by alongshore wind stress and the Sverdrup transport by wind stress curl show corresponding seasonal variations. Seasonal amplitude of the sea level is relatively large along Sakhalin Island with a tendency of a larger amplitude toward the south. This meridional dependence is consistent with the ATWs, but not with the Sverdrup transport in the Sea of Okhotsk. Seasonal variation of the geostrophic current velocity expected from the sea level variation is comparable to that of the observed nearshore current and is consistent with the theoretical ATW transport. It is also revealed that, on an interannual timescale, the wintertime sea level fluctuates quite coherently all around the Sea of Okhotsk and further along the East Kamchatka and Oyashio coasts in the North Pacific. The altimeter data clearly show that this coherent sea level variation is trapped over the coastal and continental shelf regions with depths shallower than 1000 m. The wintertime sea levels have a higher correlation with the ATW transport than with the Sverdrup transport in the Sea of Okhotsk and the upstream East Kamchatka coast. All these suggest that the interannual sea level variation along the coastal and shelf regions in winter, as well as the seasonal variation, is mainly caused by the ATWs (coastal trapped current forced by the alongshore wind stress). The wintertime
Sverdrup transport, raised by the previous studies, is the secondary contributor to these variations.
1. Introduction

The Sea of Okhotsk is a marginal sea located on the northwest rim of the Pacific Ocean, connected through the Kuril Straits (Fig. 1). The surface ocean circulation is mainly characterized by a cyclonic circulation with a western boundary current along the east Sakhalin, which is called the East Sakhalin Current (ESC) (Leonov, 1960; and also reviewed by Talley and Nagata, 1995). The ESC has two velocity cores: one exists near the coast and the other over the shelf slope (Ohshima et al., 2002). The annual mean volume transport of the ESC is estimated as ~7.0 Sv with a large seasonal variation ranging from a maximum of ~12 Sv in winter to a minimum of ~2 Sv in summer (Mizuta et al., 2003). The ESC has an important role in southward transport of cold dense shelf water, which is a source water of the North Pacific Intermediate Water (Shcherbina et al., 2004), iron, which is an essential nutrient for phytoplankton (Nishioka et al., 2007), and sea ice (Fukamachi et al., 2009).

The driving mechanism of the ESC has been examined in term of the ocean current driven by the wind stress in the Sea of Okhotsk. Simizu and Ohshima (2002) conducted a numerical simulation based on a barotropic ocean model with realistic topography. Their simulation indicates that the nearshore core of the ESC is well explained by the Arrested Topographic Waves (ATWs), which is induced by wind
stress along the coast (Csanady, 1978). Ohshima et al. (2004) showed that the
Sverdrup balance approximately holds for the cyclonic gyre over the northern
half-basin of the Sea of Okhotsk (50°–53°N) and that a major part of the ESC can be
regarded as the western boundary current of this gyre. An Ocean General Circulation
Model (OGCM) simulation demonstrates that the two velocity cores of the ESC can
be reproduced by the wind stress within the Sea of Okhotsk and quantitatively
explained by the ATW and Sverdrup transport (Simizu and Ohshima, 2006).

Recent studies have suggested that ocean currents in the Sea of Okhotsk are also
affected by the subarctic gyre in the North Pacific. Ohshima et al. (2010) showed that
the water exchange between the Sea of Okhotsk and the North Pacific predominantly
occurs during winter, with inflow through the northern straits and outflow through the
southern straits. These features are qualitatively consistent with the Island Rule
(Godfrey, 1989). Thus, it is likely that a part of the western boundary current of the
subarctic gyre intrudes into the Sea of Okhotsk (Andreev and Shevchenko, 2008;
Ohshima et al., 2010). Katsumata and Yasuda (2010) estimated the exchange transport
based on the outputs from the OGCM for Earth Simulator (Masumoto et al., 2004)
and hydrography in combination, and suggested that the water exchange reaches ~10
Sv in winter.
The ocean circulation in the Sea of Okhotsk has been also investigated based on sea level variability. Satellite altimeter data have revealed the velocity core structure of the ESC (Ebuchi, 2006) and the annual cycle related to the strength of the anticyclonic circulation in the Kuril Basin (Uchimoto et al., 2008). Itoh and Ohshima (2000) showed that the tide gauge sea level along the northern coast of Hokkaido Island has remarkable seasonal variation, with a peak in winter. They suggested that the wintertime sea level increase is caused by the advent of fresh and cold ESC water. Such a seasonal variation has also been found on the North Pacific side of Hokkaido Island, and the effect of the ESC on the seasonal variation of the Coastal Oyashio was discussed (Isoda et al., 2003; Sakamoto et al., 2013).

Along the coast of Hokkaido Island, warm and saline water flows through the shallow Soya Strait as the Soya Warm Current. The Soya Warm Current is a part of the Tsushima Warm Current System in the Sea of Japan and driven by the sea level difference between the Sea of Okhotsk and the Sea of Japan (Aota, 1975; Ohshima, 1994; Matsuyama et al., 2006). Therefore, there is a possibility that the sea level fluctuation in the Sea of Okhotsk is related to the strength of the Soya Warm Current and further the Tsushima Warm Current. Tsujino et al. (2008) proposed that the seasonal variability of the Tsushima Warm Current as well as the Soya Warm Current...
is controlled by the sea level set up by the ATWs along the coast of the Sea of Okhotsk, based on an OGCM simulation and analytical model.

In the subarctic North Pacific, it is known that sea level variability along the western coast is well explained by the barotropic response of wind-driven gyre circulation on seasonal to interannual timescales (Isoguchi et al., 1997; Ito et al., 2004; Isoguchi and Kawamura, 2006). Isoguchi and Kawamura (2006) showed that the coastal sea level rises in winter and lowers in summer in accordance with the strength of the East Kamchatka Current (EKC), based on tide gauge and satellite altimeter data. Ito et al. (2004) evaluated the interannual variability of the Oyashio transport by comparing satellite altimeter data with repeated hydrography and mooring observations and found that it is partly explained by the Sverdrup transport.

On the other hand, most of the sea surface in the Sea of Okhotsk is covered by sea ice in winter. Therefore, examination of the sea level variability has been limited to seasons with no ice (Ebuchi, 2006) or the southern area (Uchimoto et al., 2008). Examination of the sea level variability over a whole year has been limited to the tide gauge data collected along Hokkaido Island (Konishi et al., 1986; Itoh and Ohshima, 2000; Isoda et al., 2003; Andreev and Shevchenko, 2008) and Kuril Islands (Sedaeva and Shevchenko, 2001). Shevchenko and Romanov (2005) analyzed the
Topex/Poseidon satellite altimetry data to investigate seasonal changes in the circulation of the Sea of Okhotsk. However, the cause of seasonal and interannual variations of sea level has not yet been fully examined.

In this study, we examine tide gauge data mainly provided by the Far Eastern Regional Hydrometeorological Research Institute (FERHRI) and satellite altimeter data to clarify seasonal and interannual variations of the sea level in and around the Sea of Okhotsk. As will be shown, the sea level all along the coastal region of the Sea of Okhotsk shows similar seasonal variation and the coherent variation in winter. This coherent variation extends further into the surrounding coastal areas in the North Pacific. These results imply that the sea level variation in and around the Sea of Okhotsk is related to the ocean current change.

The paper is organized in the following manner. Data and methods are described in Section 2. In Section 3, seasonal and interannual variations of the sea level in and around the Sea of Okhotsk are examined based on tide gauge data and satellite altimeter data. The cause of the sea level variation is explored with a focus on the ocean currents related to wind stress change. The relationship between the sea level variation and atmospheric circulation changes is described in Section 4. In Section 5, we discuss the effect of the ocean current change related to the sea level variation on
the interannual variability of the sea ice extent in the Sea of Okhotsk. The summary
and discussion are presented in Section 6.

2. Data and method

Tide gauge data were provided by the FERHRI, and the Permanent Service for
Mean Sea Level (PSMSL) hosted by the Proudman Oceanographic Laboratory
(Woodworth, 1991). These data sets consist of monthly mean sea level records for 15
stations in and around the Sea of Okhotsk (Fig. 1 and Table 1). Most of the tide gauge
data are available from the 1950s to 1990s. To exclude the effect of the land
deformation by the earthquake in the Kuril Straits in 1994 (Lockridge, 1995), we used
the tide gauge data before 1993. In the tide gauge data from the FERHRI, there seem
to be no significant trends or abrupt changes caused by subsidence and earthquakes.
On the other hand, a remarkable increasing trend is found in the tide gauge data for
Kushiro provided by the PSMSL. Therefore, we removed this linear trend from the
time series for this station. The corrections for the inverse barometer effect caused by
changing atmospheric pressure were applied using sea level pressure data from the
NCEP/NCAR reanalysis data.
Altimeter data used in the present study were derived from the merged products
of monthly mean sea surface height anomaly (SSHA) from Topex/Poseidon, Jason-1, and European Research Satellite altimeter observations from 1993 to 2009. The sea level anomalies are produced by the French Archiving, Validation, and Interpolation of Satellite Oceanographic Data (AVISO) project using the mapping method of Ducet et al. (2000). It is known that there is a possibility that the European Research Satellite altimeter observations have an aliasing at the period of one year (Schlax and Chelton, 1994). However, the effect of this aliasing problem is expected to be small in and around the Sea of Okhotsk (Uchimoto et al., 2008). The aliased tidal errors in the AVISO altimetry data are relatively large for marginal seas such as the Sea of Okhotsk (e.g., Morimoto, 2009). Significant tidal errors are considered to occur in the northwestern shelf, the Shelikhov Gulf, and the Kuril Straits. For the northwestern shelf and Shelikhov Gulf, we mask out the altimeter data, because sea ice covers these areas in winter. For the Kuril Straits, we do not discuss the results based on the altimeter data.

To examine the sea level response to wind forcing, we used ERA-40 data from 1958 to 2001 (Uppala et al., 2005). For the Sea of Okhotsk, the high-resolution version with a spatial resolution of $1.125°$ in latitude and longitude was used. The monthly mean wind stress $\tau = (\tau_x, \tau_y)$ is calculated from 6 hourly wind data based on a
bulk formula as follows:

\[ \vec{\tau} = \rho C_D \vec{v} \vec{v} \]  

(1)

where \( \rho \) is the surface air density, \( C_D \) is the drag coefficient, and \( \vec{v} \) is the wind vector. For \( C_D \), we adopt a stability-independent drag coefficient of Large and Pond (1981) as follows:

\[
\begin{align*}
C_D &= 1.2 \times 10^{-3} \quad \text{for } |\vec{v}| \leq 11.0 \text{ m} \cdot \text{s}^{-1}, \\
C_D &= (0.49 + 0.065 |\vec{v}|) \times 10^{-3} \quad \text{for } |\vec{v}| \geq 11.0 \text{ m} \cdot \text{s}^{-1}.
\end{align*}
\]

(2)

For the North Pacific, we used the monthly mean wind stress data with a resolution of 2.5° in latitude and longitude from ERA-40.

In general, the drag coefficient for sea ice is somewhat larger than that for the ocean surface (Lepparanta, 2005). However, it is difficult to evaluate the effect of sea ice on wind stress applied to the ocean, because the ice–water drag coefficient and internal stress in ice cover are also related to the determination of the wind stress. Ohshima and Simizu (2008) showed that a general ocean circulation model with no ice reproduces the velocity field over the east Sakhalin shelf region very well. This result implies that the wind stress applied to the ocean does not change significantly regardless of the presence or absence of sea ice. In this paper, we calculated the wind stress based on a bulk formula for the open ocean without sea ice, even in winter. To assess our results, we also used the monthly mean wind stress data derived from the
NCEP/NCAR reanalysis data, in which the roughness of sea ice area is accounted for (Kanamitsu, 1989).

In mid- and low-latitude oceans, the sea level variations are dominated by the thermosteric signal caused by seasonal density variations (Gill and Niiler, 1973).

Based on previous studies (Gill and Niiler, 1973; Vivier et al., 1999; Qiu, 2002), we evaluated the thermosteric signal caused by local atmospheric heat flux. The thermosteric signal was calculated from net surface heat flux data as follows:

\[
\frac{\partial \eta'(t)}{\partial t} = -\frac{\alpha}{\rho_0 c_p} \{Q(t) - \bar{Q}(t)\}
\]

where \(\rho_0\) is the reference density, \(c_p\) is the specific heat of sea water, and \(\alpha\) is the thermal expansion coefficient. The thermal expansion coefficient was calculated from the temperature and salinity averaged over the mixed layer based on the World Ocean Atlas 2005 (WOA05) (Antonov et al., 2006; Locarnini et al., 2006). As the mixed layer depth, we adopted a constant value of 50 m depth which corresponds to the typical seasonal thermocline depth in the Sea of Okhotsk (Ohshima et al., 2005). \(Q(t)\) is the net surface heat flux derived from the climatological monthly means of the NCEP/NCAR reanalysis data during 1979 to 2008. The overbar denotes the annual average of the climatological monthly means from January to December. The estimated thermosteric values nearest to the tide gauge stations and satellite altimeter
gridded point were used for evaluation of the thermosteric component for the corresponding sea level data.

3. Results

We begin by showing the time series of raw monthly mean data from the tide gauges averaged over the Sakhalin coast (Fig. 2). We found a seasonal cycle with a clear maximum in winter and a minimum in summer. The timing of this seasonal cycle is out of phase with that of the altimeter SSH over the Kuril Basin (Uchimoto et al., 2008) and the North Pacific (e.g., Stammer, 1997). The interannual variability also has a large fraction on the sea level variability. For example, the wintertime peak of 22 cm in 1973/1974 season is about twice larger than that of 1972/1973 season. Below, we will examine the seasonal and interannual sea level variations individually.

3.1. Seasonal variation

To examine the seasonal variation of the sea level, the climatological monthly mean was calculated for each tide gauge. Figure 3a shows the annual cycle of the sea level at each tide gauge. The most remarkable feature is the peak in December or
January. This annual cycle is still evident after the thermosteric signal and inverse barometer effect is removed from each tide gauge data (Fig. 3b). In addition to the wintertime peak, the sea level along the northern coast of Hokkaido Island (K–O) and the northern shelf of the Sea of Okhotsk (B, C) have a secondary peak in September (Fig. 3a). The secondary peak for the northern coast of Hokkaido Island is explained by the seasonal variation of the Soya Warm Current (Itoh and Ohshima, 2000). On the other hand, the secondary peak for the northern shelf might be related to the halosteric component, because a relatively large river discharge occurs in summer near these tide gauges (M, N) (e.g., Dai and Trenberth, 2002). Hereafter, the thermosteric and inverse barometer effects are subtracted from the tide gauge data.

Next, we examined the spatial distribution of the seasonal amplitude with the winter peak, using both the tide gauge and satellite altimeter data. Considering that most of the tide gauge data show maximum peaks from December to January and minimum peaks from April to May (Fig. 3b), and that satellite altimeter data cannot be used in the sea-ice covered season, the sea level difference between December and May is adopted as a measure of the seasonal amplitude. The tide gauge data (Fig. 4a) show that the seasonal amplitude is relatively large along Sakhalin Island (E, G, H, I, J), with the difference value larger than 10 cm. This result is consistent with the
satellite altimeter data (Fig. 4b). On the other hand, the seasonal amplitude is much
smaller in the basin with depths greater than 1,000 m (see the depth contours in Fig.
1), indicating that the seasonal variation is confined to the coastal and shelf regions.

Since the seasonal variation of sea level in and around the Sea of Okhotsk is not
explained by the thermosteric height signal at all (Fig. 3b), the variation is suggested
to be related to dynamic response of the ocean current systems. Considering that the
high sea level season (winter) corresponds to the strong wind season and that the
seasonal amplitude is relatively large along the western boundary current region off
Sakhalin Island, the seasonal variation is likely caused by near-barotropically quick
responses through the ATWs and/or the western boundary current through the
Sverdrup transport (e.g., Ebuchi, 2006; Simizu and Ohshima, 2006). In winter,
northwesterly and northeasterly winds prevail over the western part of the Sea of
Okhotsk and the eastern part of the East Kamchatka Peninsula, respectively (Fig. 5a).
This wind pattern is favorable for the pile up of the Ekman transport to set up the
ATWs and the sea level rise along these coastal regions. In the western subarctic gyre
of the North Pacific, it has been suggested that the sea level along the western coast
increases in winter by intensification of the southward western boundary current
through the time-varying Sverdrup balance (Isoguchi and Kawamura, 2006). Similarly,
the southward ESC in the Sea of Okhotsk also intensifies in winter (Mizuta et al., 2003; Simizu and Ohshima, 2006). These results imply that the coastal sea level along Sakhalin Island also may be affected by the compensation of the sea level change in the offshore through the Sverdrup balance (Fig. 5b).

Therefore, we here examine the effects of ATW and Sverdrup transport on seasonal sea level variations along Sakhalin Island. According to Csanady (1978), the alongshore volume transport of the ATWs that occurs in a steady manner, \( V_{ATW} \), is determined by:

\[
V_{ATW} = \int_{l_1}^{l_2} \frac{\tau_l}{\rho f} \, dl,
\]

where a right-handed coordinate system is used with the \( l \) axis along the coastline. \( \tau_l \) is the alongshore component of the wind stress, \( \rho \) is the density of water, and \( f \) is the Coriolis parameter. On timescales larger than a month, the volume transport of the coastally trapped flow is determined by Eq. (4), which can be derived from the linear momentum equation (or vorticity equation) in a stationary state. This steady flow is called the Arrested Topographic Waves (ATWs) by Csanady [1978]. A similar equation was also used to examine the coastal sea level along the Alaska/Canada coast (Qiu, 2002). This equation implies that the alongshore transport at \( l_1 \) is the sum of the Ekman transport to or from the coast over the integral route from the starting point of
The integral route of the Ekman transport depends on several factors, such as the shape of the coastline, shelf width, shelf slope, and bottom friction, which are difficult to identify (Csanady, 1978). The OGCM simulation of the Sea of Okhotsk indicates that the starting point of the integral route suitable for the ATW calculation is the west of the Shelikhov Gulf (Fig. 1) (Simizu and Ohshima, 2002). However, the effect of wind stress variability in the North Pacific was not included in their model simulation. Since similar seasonal variations of the sea level are also found along the northern coast of the Sea of Okhotsk and the eastern coast of the Kamchatka Peninsula (Fig. 4), there is a possibility that the ATWs along Sakhalin Island is also affected by wind stress over further upstream regions. Thus, we examine two additional integral routes (routes 2 and 3, Fig. 5c) as well as the one (route 1) proposed by Simizu and Ohshima (2002).

The Sverdrup transport in the Sea of Okhotsk ($V_s$) is estimated based on the following equation:

$$V_s = -\frac{1}{\beta \rho} \int_{x_1}^{x_s} \text{curl}\vec{\tau}dx,$$

(5)

where the right-handed Cartesian coordinate system is adopted with $x$ and $y$ axes in the eastward and northward directions, respectively. $\beta$ is the $y$ derivative of the Coriolis parameter and $\vec{\tau}$ is a wind stress vector. The integral route is taken along
latitudinal lines from the eastern boundary ($x_2$) to the western boundary ($x_1$), where the eastern boundary is defined as the west coast of the Kamchatka Peninsula and the Kuril Islands (Fig. 5b). Northward Sverdrup transport is defined as positive. Several studies imply that a part of the EKC intrudes into the Sea of Okhotsk through the northern part of the Kuril Straits and that the inflow is significantly correlated with the Sverdrup transport in the North Pacific (Andreev and Shevchenko, 2008; Ohshima et al., 2010). To evaluate the variability of the inflowing water from the Pacific, we also examined the Sverdrup transport over the North Pacific, integrated from the eastern boundary of the North Pacific. The Sverdrup transport in each basin is meridionally averaged over 46°–50°N.

Figure 6 compares the seasonal variation of the sea level along Sakhalin Island with that of the ATW transport and Sverdrup transport. As the representative for the sea level, we show the climatological monthly values averaged over 6 tide gauge stations (D–J) (Fig. 6a). For the ATW, the climatological values from 1979 to 2008 for routes 1, 2, and 3 are shown (Fig. 6b). For the Sverdrup transport, the climatological values for both the Sea of Okhotsk and the North Pacific are shown (Fig. 6c). Both the ATW transport and Sverdrup transport show a maximum from December to January and a minimum from June to August, although the absolute value of the volume
transport is rather different among these transports. These seasonal variations are also similar to those of the sea level along Sakhalin Island. Similar results are obtained using the NCEP/NCAR reanalysis data, although the seasonal amplitude of the ATW transport calculated using the NCEP/NCAR reanalysis data is somewhat larger than that using the ERA-40 data (not shown).

Next, we compare the latitudinal dependence of the seasonal sea level variation from 46° to 52°N with those of the corresponding ATW transport and Sverdrup transport. The ATW transport at each latitude is calculated based on the wind stress along route 1. The seasonal amplitude is evaluated from the difference of the climatological value between December and May. The seasonal amplitude of the sea level tends to be larger in lower latitudes (Fig. 7a). This latitudinal dependence is consistent with that of the ATW (Fig. 7b). The larger seasonal variation of the ATW in the southern areas is caused by the prevailing southward wind along Sakhalin Island in winter (Fig. 5a). On the other hand, the latitudinal dependence of the Sverdrup transport in the Sea of Okhotsk is contrary to that of the sea level. The latitudinal dependence of the seasonal sea level variation is not qualitatively explained by the Sverdrup transport.

The above analyses suggest that the seasonal variation of the sea level along
Sakhalin Island is dominated by the ATWs. To quantify this suggestion, we evaluated the geostrophic current from the sea level data and compare it with the current velocity data obtained from mooring measurements (Mizuta et al., 2004) and the theoretical ATW transport. Assuming that the seasonal current variation is barotropic, the seasonal amplitude of the geostrophic current speed $\Delta v$ is calculated as follows:

$$\Delta v = \frac{g \Delta (\eta_c - \eta_o)}{f \Delta x}$$  \hspace{1cm} (6)

where $\Delta x$ is the width of the ATW, $g$ is gravity acceleration (9.8 m s$^{-2}$), $f$ is the Coriolis parameter ($1.2 \times 10^{-4}$ s$^{-1}$), and $\Delta (\eta_c - \eta_o)$ is the seasonal amplitude of the sea level difference between the coast and the offshore, where the offshore sea level is assumed to be constant.

Based on the observed current structure from the surface drifters (Ohshima et al., 2002) and the simulated result of the nearshore branch of the ESC using an OGCM (Simizu and Ohshima, 2006), the width of the ATW $\Delta x$ is assumed to be $\sim$70 km. Since the difference between the monthly mean sea levels along Sakhalin Island in January and April is about 14 cm (Fig. 6a), the seasonal amplitude of the surface velocity $\Delta v$ would be $\sim$16 cm s$^{-1}$ according to the geostrophic balance (Eq. 6). Since the monthly mean velocity obtained from the mooring measurement at 53°N showed that the difference between the southward current velocity near the coast in January
and April is \(\sim 20 \text{ cm s}^{-1}\) (Fig. 6 of Mizuta et al., 2003), the seasonal amplitude of the estimated value is comparable to the observed value.

When the thickness \(H\) of the ATW is assumed to be 100 m, which is the mean water depth over the width of the ATW (from the coast to 70 km offshore in latitudes of \(46^\circ\text{–}52^\circ\text{N}\)), the seasonal variation of the volume transport \((\Delta v \times H \times \Delta x)\) is estimated to be \(\sim 1.3 \text{ Sv}\) using the velocity difference \((\Delta v = 20 \text{ cm s}^{-1})\) measured from the moorings. The seasonal variation of the theoretical ATW transport calculated using the wind stress along routes 1, 2, and 3 is 0.95 (1.6), 0.85 (1.2), and 2.5 (3.0) Sv, respectively (The brackets show the theoretical ATW transport for the same routes calculated using the NCEP/NCAR reanalysis data). Hence, the orders of the theoretical values are comparable to the estimated values.

We also evaluate the contribution of the offshore (western boundary current) component of the ESC to the seasonal sea level variation. From the vertical cross sections of the monthly mean velocity field obtained from the mooring measurement (Mizuta et al., 2003), the southward current speed of the offshore component at the surface is \(\sim 25 \text{ cm s}^{-1}\) and \(\sim 15 \text{ cm s}^{-1}\) in January and April, respectively. Since the zonal width of the offshore ESC component is \(\sim 50 \text{ km}\) (Mizuta et al., 2003), the sea level rise toward the coast by this current is estimated to be \(\sim 15 \text{ cm}\) and \(\sim 9 \text{ cm}\) in
January and April, respectively. Since the difference between the estimated sea level in January and April (6 cm) is smaller than that of the observed sea level difference (14 cm), the seasonal variation of the sea level is insufficiently explained by the Sverdrup transport. As well as the latitudinal dependence of the seasonal amplitude, these comparisons on the basis of the geostrophic balance imply that the ATWs are the primary contributor to the seasonal sea level variation and that the Sverdrup transport is the secondary.

3.2. Interannual variation

In this section, we examine the interannual variability of the sea level, compared to those of ATW and Sverdrup transports. For the examination of the interannual variation, the climatological seasonal variation was removed from the tide gauge and satellite altimeter data. The standard deviations of the monthly sea level anomalies in winter (December to February) are considerably larger than those in the other seasons (not shown). Wind speed and its interannual variability, a likely cause of the sea level variation, are also large in winter. Thus, we mainly focus on the interannual variability in winter. In this paper, the year of the wintertime from December 1969 to February 1970 is defined as 1970, and similarly for the other years. Figure 8 shows the time
series of the wintertime tide gauge sea level anomalies from the East Kamchatka coast (A), then all around the Okhotsk coast (B–N), and finally to the Oyashio coast (O).

We found that the wintertime sea levels fluctuate quite coherently all around the Sea of Okhotsk (B–N) with a remarkable year-to-year variability: positive anomalies in 1970, 1974, 1981, and 1984 and negative anomalies in 1972, 1979, and 1982. It should be noted that these coherent variations partly extend upstream to the East Kamchatka coast (A) and downstream to the Oyashio coast (O).

To extract dominant modes for the interannual variability of tide gauge sea levels in and around the Sea of Okhotsk, Empirical Orthogonal Function (EOF) analysis based on a covariance matrix was applied to sea level data from 11 stations (A, B, E, G, H, I, J, L, M, N, and O) at which continuous data were obtained from 1965 to 1988. The first EOF mode for the wintertime sea level anomalies explains 61% of the total variance, indicating that this mode is by far the dominant mode. The temporal coefficient of the first EOF mode (PC-1) is shown at the bottom of Fig. 8. The spatial structure of the first EOF mode shows all positive values with large values along Sakhalin Island (Fig. 9a).

The interannual variability of the wintertime sea level is further examined using satellite altimeter data. We used the SSHA averaged in December, because the
altimeter data are not fully available for the sea ice seasons from January to February. Figure 9b shows the regression map of the SSHAs onto the time series of the normalized SSHAs for the Sakhalin coast (48°–49°N, 143°–144°E). The significant positive correlations are found all over the shelf region with the water depths shallower than 1,000 m in the Sea of Okhotsk (Fig. 1). The significant correlations are also found further to the eastern shelf of the Kamchatka Peninsula and the Oyashio coast in the North Pacific. The absolute values of the regression coefficients in these regions are comparable to those for the tide gauge data.

To explore the mechanism giving rise to the coherent sea level variation, we compared the interannual variability of the wintertime sea level along Sakhalin Island with those of the ATW and Sverdrup transports. As an index of the sea level along Sakhalin Island, we used the tide gauge data averaged over stations E, G, H, I, and J, which is found to be quite similar to the PC-1 (the correlation between them is 0.98). Table 2 summarizes the correlation coefficients between the sea level along Sakhalin Island and the related volume transports. The wintertime sea level is significantly correlated with both the ATW and Sverdrup transports in the Sea of Okhotsk, and the former is larger than the latter. The result that the sea level has a higher correlation with the ATW1 (ATW for route 1) than the ATW2, supports that the integral route
proposed by Simizu and Ohshima (2002) is reasonable. Figure 10 shows the time series of the sea level anomalies and the ATW anomalies for route 1, demonstrating their good correspondence all through the analyzed period. It is noteworthy that the correlation between the sea level and ATWs for route 3 is also high (Table 2). The wind stress far from the east of Kamchatka and the Bering Sea may also contribute to the ATWs in the Sea of Okhotsk to some extent. Similar results are obtained using the NCEP/NCAR reanalysis data (Table 2).

Finally, we examine the relationship between the sea level and the ATWs all through the seasons. In Fig. 2, the time series of the monthly mean ATW transport for route 1 is superimposed on the sea level data. The timing and strength of the peaks of the ATW transport corresponds to those of the sea level anomalies. The correlation coefficients between the monthly mean of the sea level and the ATWs for routes 1 and 3 are 0.60 and 0.56 (significant at 95% confidence level), respectively. The correlations between the sea level and ATWs from spring to autumn are quite small and insignificant (Table 3). Since the variance of the wind stress in these seasons is smaller than that in winter, it is likely that the contributions of other factors rather than the ATWs are relatively large from spring to autumn, when compared to the winter case.
3.3. The sea level variation in the North Pacific and its relation to the ATWs

For the North Pacific, Isoguchi and Kawamura (2006) examined the relationship between the coastal sea level along the Kamchatka Peninsula and the Sverdrup transport over the North Pacific and found the significant correlation between them on seasonal to interannual timescales. Ito et al. (2004) also indicated that year-to-year variability of the Oyashio transport is partly explained by the time-varying Sverdrup transport. The present study suggests that the coherent sea level variation in the Sea of Okhotsk extends to the coastal regions in the upstream EKC and the downstream Oyashio on seasonal (Fig. 4) to interannual timescales (Fig. 10). Thus, we here examine the effect of the ATWs on the sea level variability in these western boundary current regions of the North Pacific.

As for the sea level data at the EKC and Oyashio regions, we use the tide gauge sea level data at Petropavlovsk–Kamchatsky (PK) and Kushiro (Fig. 1) from 1958 to 2001. The integral routes for the ATWs to PK and Kushiro are determined as the paths from starting points 3 and 1 to the locations of the tide gauges, respectively (Fig. 5c). We conducted a correlation analysis between the sea level in winter and the ATWs and compare it with that for the Sverdrup transport in the North Pacific.
The correlation coefficients among the sea levels and the transports are summarized in Table 4. The sea level at PK is highly correlated with the corresponding ATWs ($r = 0.65$) rather than the Sverdrup transport ($r = 0.59$), suggesting that the ATWs primarily contributes to the sea level variation. For Kushiro, the sea level is significantly correlated with both the ATW transport ($r = 0.59$) and Sverdrup transport ($r = 0.56$) and their correlation coefficients are comparable. It is noted that there is no significant correlation between the ATW transport and Sverdrup transport ($r = 0.15$), suggesting that the sea level is affected by both transports. When we built a statistical regression model for the sea level at Kushiro based on both the ATW and Sverdrup transports, the multiple correlation coefficient between the observed and predicted sea level becomes a significantly high value of 0.76.

4. Atmospheric circulation variability

To understand the wintertime atmospheric circulation pattern related to the coherent sea level variation, we performed regression analyses of wind stress, wind stress curl, and sea level pressure onto the PC-1 of the tide gauge sea level in winter (December to February). Monthly sea level pressure and wind stress data in the northern hemisphere were used from the NCEP/NCAR reanalysis data. Figure 11a
shows the regression map of the wind stress over the North Pacific onto the PC-1. The northeasterly wind anomalies are found over the Sea of Okhotsk and the Bering Sea. These wind stress anomalies induce Ekman transport anomalies over the coastal region to pile up the sea level along Sakhalin Island and the east coast of the Kamchatka Peninsula to generate the ATWs. The PC-1 is also significantly correlated with the wind stress curl over the Sea of Okhotsk (Fig. 11b). This result indicates that the northeasterly wind anomalies lead to the increase in both the ATW transport and Sverdrup transport in the Sea of Okhotsk.

From the regression map of the sea level pressure, the northeasterly wind anomalies related to the PC-1 are also found to be related to the dipole pattern of the high pressure over the Eurasian continent and the low pressure over the subtropics (Fig. 11c). This anomalous sea level pressure pattern resembles the negative phase of the Western Pacific (WP) pattern dominated over the northern hemisphere (Horel and Wallace, 1981) and the strengthened Aleutian low.

We thus calculated the correlations between the PC-1 and the WP index of the Climate Prediction Center (Barnston and Livezey, 1987) as well as the North Pacific Index (NPI). The NPI is an index of Aleutian low strength and is defined as the sea level pressure averaged over a region from 30°–60°N and 160°E–140°W (Trenberth
and Hurrell, 1994). The significant negative correlation between the PC-1 and the WP
index is obtained \((r = -0.46)\) at 90\% confidence level, when we use the WP index in
January. The PC-1 has a significant correlation with the NPI in December \((r = -0.60)\)
at 95\% confidence level. Thus, when the WP pattern is in the negative phase and the
Aleutian low is strengthened, the sea level in and around the Sea of Okhotsk is piled
up coherently, mainly associated with strengthened ATWs.

5. Relation to sea ice extent variability

It is known that the southward transport of the ESC has a role on the southward
transport of the sea ice extent within the Sea of Okhotsk (Fukamachi et al., 2009). The
current along Sakhalin Island associated with the coherent sea level pile-up may lead
to the southward extension of the sea ice. Conversely, the current along the
Kamchatka Peninsula associated with the sea level pile-up may suppress the sea ice
extent through the inflow of warmer water from the Pacific. The importance of the
ocean thermal condition in the East Kamchatka Current on the interannual variability
of the sea ice extent in February to March has been suggested (Nakanowatari et al.,
2010).

We now examine the relationship between the sea ice extent variability and the
PC-1 of the sea level in winter, assuming that the ocean current affects the sea ice extent. We use the sea ice concentration data from 1971 to 2006 provided from the Japan Meteorological Agency (JMA). These data are a merged product from various sources of observations, including visual and aircraft observations as well as satellite observations of infrared, visible, and microwave radiometers.

Based on the correlation analysis between the monthly sea ice extent averaged over the Sea of Okhotsk and the PC-1 (sea level during December to February) from 1971 to 1988, the PC-1 has by far the highest negative correlation with the sea ice extent in January ($r = -0.67$, significant at 95% confidence level based on the Monte Carlo simulation). As also shown in the time series (Fig. 12), less ice extent corresponds well with larger PC-1 implying stronger currents. The PC-1 based on the sea level data from December to January is still significantly correlated with the sea ice extent in January ($r = -0.69$). Conversely, the correlations between the PC-1 and the sea ice extent in December and February are only -0.01 and -0.32, respectively.

In December, the sea ice extent variability has been reported to be mostly determined by the local heat flux over the northwestern area in the preceding autumn (October–November) (Ohshima et al., 2006; Sasaki et al., 2007). In February to March, the ocean thermal condition inflowing from the Pacific is also a determinant
factor for the sea ice extent as well (Nakanowatari et al., 2010). Our result implies that for January, the warmer coastal current from the Pacific, associated with the sea level pile-up, suppresses the sea ice extent dynamically and/or thermodynamically.

6. Summary and discussion

The cause of the sea level variability in the Sea of Okhotsk had previously been investigated mostly in terms of the relation to wind-driven ocean circulation (Ebuchi, 2006; Andreev and Shevchenko, 2008). Using satellite altimeter data, Ebuchi (2006) indicated that the seasonal to interannual variability of the ESC is related to both the ATWs caused by alongshore wind stress and the Sverdrup transport by wind stress curl. However, these previous studies were based on altimeter data in no sea ice seasons or tide gauge data only in the southern part of the Sea of Okhotsk. The sea level variability over the entire Sea of Okhotsk for the full annual cycle had not yet been examined. In this study, using tide gauge data in and around the Sea of Okhotsk and satellite altimeter data, we examined the seasonal and interannual variations of the sea level and their causes in terms of both the thermosteric signal and wind-driven ocean circulation.
In and around the Sea of Okhotsk, the sea level along the coastal region is found to be dominated by the seasonal variation with a maximum in winter and a minimum in summer. Since this seasonal variation is not explained by the annual heat flux cycle and inverse barometer effect caused by changing atmospheric pressure, the cause for the seasonal variation is explored in terms of the ATW and Sverdrup transports. We found that both transports show the corresponding seasonal variation. The seasonal amplitude of the sea level is relatively large along Sakhalin Island with a tendency of larger amplitudes toward the south. This meridional dependence of the seasonal variation is consistent with the ATWs but not with the Sverdrup transport in the Sea of Okhotsk. The seasonal amplitudes of the geostrophic current speed of the nearshore ESC and the associated volume transport estimated from the observed sea level data are \(~16\) cm s\(^{-1}\) and \(~1.3\) Sv, respectively. These values are quantitatively comparable to the observed amplitude of the current speed (\(~20\) cm s\(^{-1}\)) and the theoretical ATW transport (\(~1\) Sv). While the Sverdrup transport partly explains the seasonal sea level variation, its contribution is smaller than that of the ATWs.

On an interannual timescale, it is also revealed that the wintertime sea levels fluctuate quite coherently along the coastal and shelf regions in the Sea of Okhotsk and further along the East Kamchatka and Oyashio coasts in the North Pacific. The
first EOF mode of the wintertime sea level explains 61% of the total variance with a
dlarge amplitude along Sakhalin Island. Satellite altimeter data support these results
and clearly reveal that the coherent sea level variation is trapped over the continental
shelf (Fig. 9b). Wintertime sea level along Sakhalin Island has a higher correlation
with the ATW transport than with the Sverdrup transport. On the other hand, the
significant correlation between the sea level along Sakhalin Island and the ATWs is
not found from spring to autumn. These findings imply that the interannual sea level
variation along the coastal and shelf regions in the Sea of Okhotsk in winter, as well
as the seasonal variation, is mainly caused by the ATWs (coastal trapped currents
forced by alongshore wind stress). The wintertime Sverdrup transport, raised by the
previous studies, seems to be a secondary factor.

The present study also showed that the sea levels along the upstream East
Kamchatka coast and the downstream Oyashio coast coherently vary with the sea
level around the Sea of Okhotsk on seasonal to interannual timescales and that these
variations have higher correlation with the ATWs than with the Sverdrup transports.
The importance of the wind stress along the coast on the sea level variability was
pointed out only by a numerical study (Tatebe and Yasuda, 2005). The present study
raises the caution about the previous studies that the coastal sea level variability is
determined by the Sverdrup transport.

It is known that the ESC transport and its variability is mainly governed by the Sverdrup transport (Ohshima et al., 2004; Simizu and Ohshima, 2006). Conversely, this study suggests that the coastal sea level variability is primarily explained by the ATWs. The ATWs have a shallow structure and are trapped over the nearshore region, while the western boundary current exists offshore with a deeper structure. Therefore, the coastal sea level can be largely governed by the ATWs, despite that the ATW transport is one order less than the Sverdrup transport. Our results are consistent with the previous numerical study (Shimada et al., 2005), which showed that the shelf region has a role of an obstacle on the intrusion of the barotropic response in the central basin. Since the northeasterly wind stress anomaly (Fig. 11a) is accompanied by the strengthened wind stress curl in the Sea of Okhotsk, a part of the correlation between the sea level and Sverdrup transport might be an apparent one.

Using an OGCM and analytical models, Tsujino et al. (2008) proposed that the ATWs are responsible for the seasonal variations of the throughflow transport of the Japan Sea. Wintertime wind stress along the coastal region of the Sea of Okhotsk yields the positive SSHAs and the following SSH rise weakens the Tsushima Warm Current as well as the Soya Warm Current in winter. Our result that the seasonal sea
level variation in the Sea of Okhotsk is dominated by the ATWs supports their study.

We also found that the interannual variation of the coastal sea level in winter is well explained by the ATWs. According to Ebuchi et al. (2009) and Fukamachi et al. (2010), the Soya Warm Current exhibits interannual variability even in winter, although the average transport is small in winter. Therefore, we would like to propose that the ATWs (i.e., alongshore wind stress) partly control these throughflow transports on an interannual timescale as well as seasonal timescale.

In this study, the ATWs are assumed to be barotropic for simplicity, on the basis of Csanady (1978). Even if the effect of stratification is taken into account, our results would not be essentially changed. Since the ATWs could have a partially baroclinic structure analogous to the coastally trapped waves (CTWs) that have a hybrid structure of barotropic shelf waves and internal Kelvin waves, it is likely that the ATWs are somewhat accompanied by the dynamical displacement of isopycnals.

Actually, Mizuta et al. (2004) showed that the alongshore component of wind stress is essential for the interannual variability of the isopycnals in the southern part of the Sea of Okhotsk in winter. Considering that the subinertial variability of velocity in the ESC over the continental shelf is dominated by CTWs and its vertical structure is fairly barotropic (Mizuta et al., 2005), it is expected that the vertical structure of the
ATWs in the Sea of Okhotsk is also fairly barotropic, while that the coherent sea level variation is partly or slightly accompanied by the displacement of isopycnals. Previous studies suggest that wintertime increases in the sea level along the Okhotsk coast of Hokkaido (Itoh and Ohshima, 2000) and the Oyashio coast (Isoda et al., 2003) are related to the advent of lighter ESC water from the upstream region. In fact, sea surface salinity reductions are observed along Sakhalin Island (~50° N) in autumn (Shevchenko and Chastikov, 2008). From the current velocity data of the ESC, the Amur River discharge in May is estimated to arrive at the coast of Sakhalin Island (~50° N) by October (Mizuta et al., 2003). When we carefully see Fig. 3b, it seems that the tide gauge sea level near the Amur River (D) begin to rise in September to October (Fig. 3b). Thus, a portion of the sea level rise along Sakhalin Island in autumn–winter may be related to advection of low-salinity water from the Amur River.

With respect to the interannual variability, we also examine the effect of the advent of lighter ESC water from the upstream region on the sea level fluctuation using the tide gauge data. The wintertime peak is commonly found in December along Sakhalin Island (Fig. 6a) and the Okhotsk coast of Hokkaido (L, Fig. 3b). While, the timing of the peak along the Oyashio coast in January is one month behind that along...
Sakhalin Island in December. Thus, we calculated the lead-lag correlations between the monthly sea level anomalies among all these tide gauges during winter (from November to March). Significant correlations are obtained only for no time lag, and we could not find any significant correlations when the sea level along Sakhalin Island leads those at the downstream stations by one or two months. Thus, the effect of the advent of cold and fresh water is considered to be smaller than that of the dynamical displacement in the southern part of the Sea of Okhotsk on the interannual timescale.

Acknowledgments

Tide gauge data around the Sea of Okhotsk were provided by the Far Eastern Regional Hydrometeorological Research Institute. Some figures were produced with the GrADS package developed by B. Doty. The altimeter products were produced by SSALTO/DUACS and distributed by AVISO with support from CNES. We wish to thank N. Ebuchi for his constructive discussion and anonymous reviewers for their constructive comments. This work was supported by a fund from Core Research for Evolution Science and Technology (CREST), Japan Science and Technology
Corporation (JST), Grant-in-Aid for Scientific Research (20221001, 22221001).
References


mixed layer and its yearly variability under sea ice in the southwestern part of the Sea of Okhotsk. Continental Shelf Research, 24, 643-657.


Ohshima, K.I., Simizu, D., Itoh, M., Mizuta, G, Fukamachi, Y., Riser, S.C.,


Sasaki Y.N., Katagiri, Y., Minobe, S., Rigor, I.G., 2007. Autumn atmospheric
preconditioning for interannual variability of wintertime sea-ice in the Okhotsk

northwestern shelf of the Okhotsk Sea: 2. Quantifying the transports. Journal of

Shevchenko, G., Romanov, A., 2005. Seasonal variations of surface circulation in the
Okhotsk Sea from Topex/Poseidon satellite altimetry data. Proceedings of the
20th international symposium on Okhotsk Sea and Sea Ice, Okhotsk Sea and cold

Shevchenko, G. V., Chastikov, V. N., 2008. Seasonal variations of oceanic conditions
near the southeastern coast of Sakhalin Island. Russian Meteorology and
Hydrology, 33, 514-524 (in English).


on the annual mean transport of the East Sakhalin Current: A simple model.
Journal of Oceanography, 61, 913-920.


Simizu, D., Ohshima, K.I., 2006. A model simulation on the circulation in the Sea of
Okhotsk and the East Sakhalin Current. Journal of Geophysical Research, 111,

Stammer, D., 1997. Steric and wind-induced changes in TOPEX/POSEIDON
large-scale sea surface topography observations. Journal of Geophysical
Research, 102, C9, 20,987-21,009.


**Figure captions**

**Fig. 1.** Bathymetry map of the Sea of Okhotsk with the positions of the tide gauge stations used in this study. Filled and open circles indicate the tide gauge stations at which the available data length before 1994 is longer and shorter than 25 years, respectively. The station names from A to O are listed in Table 1. The bathymetry data are derived from the ETOPO5. The contour levels are 100-, 500-, 1000-, and 2000-m depths.

**Fig. 2.** Time series of monthly sea level (black line) averaged over the tide gauge stations along Sakhalin Island (E, G, H, I, J; see Fig. 1 for locations of the tide gauges) and ATW transport (gray line) for route 1 (see Fig. 5c for the route) from 1965 to 1975. The sea level and ATW transport are shown by the anomalies from the averages for the whole period.

**Fig. 3.** (a) Monthly mean climatologies of the sea level from the tide gauge data (see Fig. 1 for the locations of the tide gauges). (b) Same as (a), but the thermosteric components related to surface heat flux and the inverse barometer effect caused by atmospheric pressure are removed. Black, red, and blue lines indicate the tide gauge data for the northern part of the Sea of Okhotsk including the Kamchatka Peninsula, Sakhalin Island, and the coastal region of Hokkaido Island, respectively.

**Fig. 4.** Climatological sea level difference (cm) between December and May for (a) the tide gauge data (see Fig. 1 for the locations of the tide gauges) and (b) the satellite altimeter data. In (b), regions in which the sea ice concentration is larger than 10% are
Fig. 5. (a) Wind stress (vectors; N/m$^2$) and sea level pressure (contours; hPa) from ERA-40 data for the period 1958–2001 in winter (December to February). The contour interval is 5 hPa. The scale for the vectors is indicated at the bottom. (b) The Sverdrup transport streamfunction in winter. The Sverdrup transport in the Sea of Okhotsk and the North Pacific are calculated independently. The assumed eastern boundary for the Sea of Okhotsk is shown as a bold line. The contour intervals are 2 Sv and 10 Sv in the Sea of Okhotsk and the North Pacific, respectively. (c) The integral routes for the ATW transport. In (c), the integral routes 1, 2, and 3 are defined as the line from the corresponding starting points to the end point each marked with an open circle. The label of S, P, K indicates the Sakhalin, Petropavlovsk–Kamchatsky, and Kushiro stations, respectively.

Fig. 6. (a) The monthly mean climatologies of the tide gauge sea level averaged along Sakhalin Island (D–J). (b) The monthly mean climatologies of the ATW transport integrated over routes 1 (circle), 2 (triangle), and 3 (cross). The scale of the ATW transport for route 1 and 2 (3) is indicated on the left (right) axis. (c) The monthly mean climatologies of the Sverdrup transport over the Sea of Okhotsk (circle) and North Pacific (triangle). The scale for the Sverdrup transport in the Sea of Okhotsk (North Pacific) is indicated on the left (right) axis.

Fig. 7. Longitudinal dependence of the differences in the sea level, ATW transport, and Sverdrup transport between December and May. (a) Tide gauge data along the
Sakhalin coast (station labels are indicated at the top). (b) ATW transport integrated from the starting point of route 1 to the corresponding latitude at the Sakhalin coast. (c) Sverdrup transport integrated over the Sea of Okhotsk (circle) and the North Pacific (triangle). In (c), the scale for the Sverdrup transport in the Sea of Okhotsk (North Pacific) is indicated on the left (right) axis.

Fig. 8. Time series of the sea level anomalies (cm) at the tide gauge stations in winter (December to February) (see Fig. 1 for the locations of the tide gauges) and the temporal coefficients of the first EOF mode from the 11 tide gauge data in winter. Note that the sea level anomalies for each station are successively offset by 15 cm.

Fig. 9. (a) Regression maps (colors) of the sea level anomalies onto the PC1 of the tide gauge sea levels in winter (December–February). (b) Regression maps (colors) of the December SSHAs onto the normalized SSHAs averaged over the area offshore of Sakhalin Island (48°–49°N, 143°–144°E; indicated as green square). Contours indicate the areas where the correlation exceeds the 95% confidence level. The regions in which the sea ice concentration is larger than 10% are masked out by white.

Fig. 10. Time series of the wintertime (December to February) sea level anomalies (solid line) averaged along Sakhalin Island (E, G, H, I, J) (see Fig. 1 for the locations) and the ATW transport anomalies (dashed line) for route 1 (see Fig. 5c for the route location).

Fig. 11. Regression maps of (a) the wind stress, (b) wind stress curl, and (c) sea level
pressure onto the PC-1 of the sea levels in winter (December to February). In (a), the
standard vector length of 0.03 N/m² is shown at the bottom. The contour intervals in
(b) and (c) are 0.2 N/m³ and 0.5 hPa, respectively. Light (heavy) shading indicates the
region in which the positive (negative) correlation is significant at the 95% confidence
level.

**Fig. 12.** The time series of the PC-1 (solid line) of the wintertime (December to
February) sea levels and the sea ice extent anomalies in January (dashed line).
Table 1
Locations of the tide gauge stations and the available data period

<table>
<thead>
<tr>
<th>Station Label</th>
<th>Station Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Data Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Nagaev</td>
<td>59°33’N</td>
<td>150°43’E</td>
<td>1957–1993</td>
</tr>
<tr>
<td>C</td>
<td>Okhotsk</td>
<td>59°22’N</td>
<td>143°12’E</td>
<td>1972–1993</td>
</tr>
<tr>
<td>D</td>
<td>Nabil</td>
<td>51°44’N</td>
<td>143°18’E</td>
<td>1960–1964</td>
</tr>
<tr>
<td>E</td>
<td>Poronaisk</td>
<td>49°14’N</td>
<td>143°08’E</td>
<td>1950–1993</td>
</tr>
<tr>
<td>F</td>
<td>Vostochniy</td>
<td>48°17’N</td>
<td>142°35’E</td>
<td>1948–1957</td>
</tr>
<tr>
<td>G</td>
<td>Vzmorie</td>
<td>47°52’N</td>
<td>142°29’E</td>
<td>1950–1988</td>
</tr>
<tr>
<td>H</td>
<td>Starodubskoe</td>
<td>47°25’N</td>
<td>142°49’E</td>
<td>1950–1993</td>
</tr>
<tr>
<td>I</td>
<td>Korsakov</td>
<td>46°39’N</td>
<td>142°45’E</td>
<td>1948–1992</td>
</tr>
<tr>
<td>J</td>
<td>Krilion</td>
<td>45°54’N</td>
<td>142°05’E</td>
<td>1961–1988</td>
</tr>
<tr>
<td>K</td>
<td>Wakkanai</td>
<td>45°24’N</td>
<td>141°41’E</td>
<td>1975–2009</td>
</tr>
<tr>
<td>L</td>
<td>Monbetsu</td>
<td>44°21’N</td>
<td>143°22’E</td>
<td>1956–2008</td>
</tr>
<tr>
<td>M</td>
<td>Abashiria</td>
<td>44°01’N</td>
<td>144°17’E</td>
<td>1965–2009</td>
</tr>
<tr>
<td>N</td>
<td>Kurilsk</td>
<td>45°16’N</td>
<td>147°53’E</td>
<td>1951–1993</td>
</tr>
<tr>
<td>O</td>
<td>Kushiroa</td>
<td>42°58’N</td>
<td>144°22’E</td>
<td>1947–2009</td>
</tr>
</tbody>
</table>

aData from the PSMSL.
Table 2

Correlation coefficients between the sea level along Sakhalin Island and the Sverdrup transport integrated over the Sea of Okhotsk (OK) and North Pacific (NP) and the ATW transport integrated along routes 1, 2, and 3 (ATW-1, -2, and -3), calculated using ERA-40 and NCEP/NCAR reanalysis data in winter (December to February)

<table>
<thead>
<tr>
<th></th>
<th>OK</th>
<th>NP</th>
<th>ATW-1</th>
<th>ATW-2</th>
<th>ATW-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERA40</td>
<td>0.64</td>
<td>0.37</td>
<td>0.66</td>
<td>0.53</td>
<td>0.62</td>
</tr>
<tr>
<td>NCEP-NCAR</td>
<td>0.71</td>
<td>0.34</td>
<td>0.71</td>
<td>0.68</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Bold numbers indicate correlations exceeding the 95% confidence level based on the Monte Carlo simulation, using a phase randomization technique generating 1,000 surrogate time series (Kaplan and Glass, 1995).
Table 3

Correlation coefficients between the sea level along Sakhalin Island and ATW transport for routes 1 and 3 in winter (December to February), spring (March to May), summer (June to August), and autumn (September to November)

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATW-1</td>
<td><strong>0.66</strong></td>
<td>0.25</td>
<td>-0.07</td>
<td>0.42</td>
</tr>
<tr>
<td>ATW-3</td>
<td><strong>0.62</strong></td>
<td>0.03</td>
<td>-0.17</td>
<td>-0.01</td>
</tr>
</tbody>
</table>

Bold numbers indicate the correlation exceeding the 95% confidence level.
**Table 4**

Correlation coefficients between the tide gauge sea level anomalies at Petropavlovsk–Kamchatsky (PK) and Kushiro and the corresponding ATW transport and Sverdrup transport in the North Pacific in winter (December to February).

<table>
<thead>
<tr>
<th></th>
<th>ATW</th>
<th>Sverdrup transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>PK</td>
<td>0.65</td>
<td>0.59 (at 51°N)</td>
</tr>
<tr>
<td>Kushiro</td>
<td>0.59</td>
<td>0.56 (at 42°N)</td>
</tr>
</tbody>
</table>

Bold numbers indicate the correlations exceeding the 95% confidence level.
Figure 1.
Figure 2.
Figure 3.
Figure 4.
Figure 5.
Figure 6.
Figure 7.
Figure 8.
Figure 9.
Figure 10.
Figure 11.
Figure 12.