On wind and tide induced sea-ice drift on the northeastern shelf of Sakhalin Island (analysis of radar data)

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Introduction: Radar measurements of sea ice drift

Severe ice conditions are typical for the northeastern shelf of Sakhalin Island. Sea-ice fields in this region are large, heavy and fast moving (Pokrasenko et al., 1987). Examination of these motions is interesting from the scientific point of view and has significant applied importance. In the present work we investigate the velocities of ice drift induced by tides and wind. The main purpose of the study is to estimate their nature, main parameters, and maximum values.

The properties of the Okhotsk Sea ice cover are determined by the sea circulation, winter winds, and tides (Martin et al., 1998). To examine the sea-ice drift in the region of oil and natural gas fields the Hydrometeorology Division of the Far Eastern Marine Engineering and Geology Expedition (now the Environmental Company of Sakhalin) installed three radar transceivers on the northeastern coast of Sakhalin Island. Temporary meteorological stations, measuring wind, atmospheric pressure, air temperature, precipitation, and visibility, were also established in the vicinity of these installations whose coordinates were as follows: 54.1°N, 142.9°E (Cape Levensterna, 1992–1995), 53.5°N, 143.1°E (Odoptu, 1985–1996), and 51.1°N, 143.6°E (Komrvo, 1991–1993). The location of these radar stations and current-meter recorders deployed on the shelf of Sakhalin Island are presented in Figure 1.

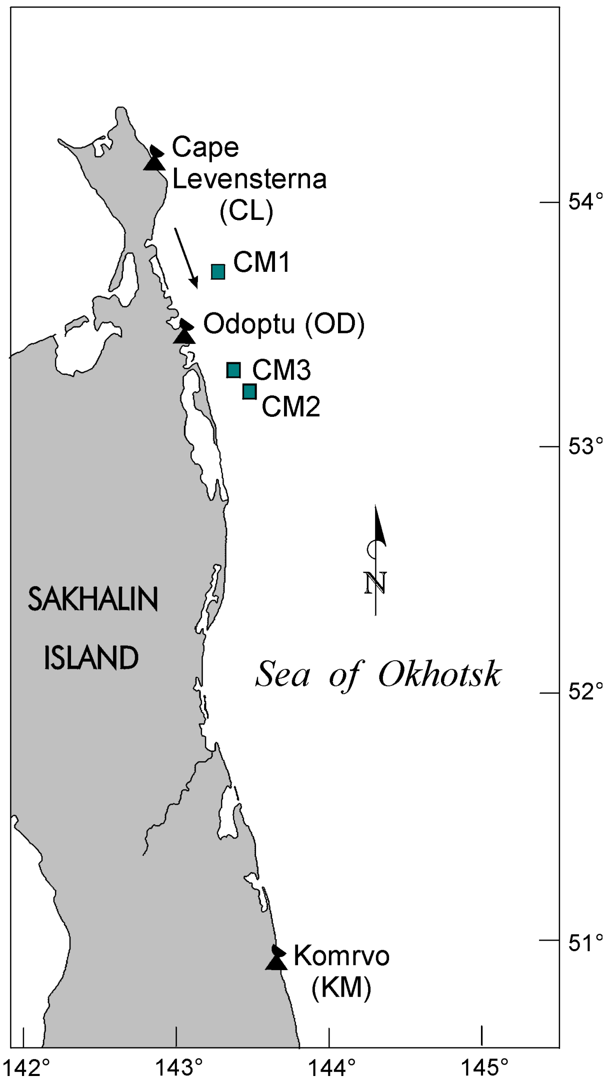

Fig. 1 Location of radar stations Cape Levensterna (CL), Odoptu (OD), and Komrvo (KM), meteorological station and tide gauge Nabil, and current meter stations CM1 (Hanhuzinsk area) and CM2, CM3 (Odoptinsk area) on the northeastern shelf of Sakhalin Island. The arrow indicates direction of propagation of tidal shelf waves.

These radar stations recorded sea-ice drift at the distances of approximately 4, 8, 12 and 18 km (the latter only by the Odoptu radar). Hourly drift vectors were estimated by the differences in the ice field positions. The positions were fixed three times per hour: at 10 to the hour, at the hour and 10 min after the hour. We interpolated and averaged the data and get several hourly vector series for each installation. In this work we analyze only the drift series measured at the most distant points (12 and 18 km).

Preliminary data analysis

The best quality data were obtained in 1993: 100–day series (March 1–June 8) at Cape Levensterna (CL), 73 days at Odoptu (OD), and 85 days at Komrvo (KM). We paid the most attention to the examination of just these series.

The velocity components of the ice drift were estimated in the eastward (*u*) and northward (*v*) directions, i.e. in the offshore and longshore directions relative to Sakhalin Island (Fig. 2). The offshore velocities were relatively small, of about 10–30 cm/s for all stations. In contrast, the longshore velocities were strong, approximately 100 cm/s. Preliminary analysis showed the dominant role of diurnal tides in the longshore drift motions (at least for the area of stations CL and OD).

The calculated spectra of *u* and *v* components for the radar stations CL, OD, and KM are presented in Figure 3. The northward components dominate at all frequencies, however, whereas for the low-frequency band the difference between the energy of two components is significant, for the high-frequency band it is relatively small. There are two noticeable low-frequency peaks at periods of about 12 and 5 days, apparently related to the

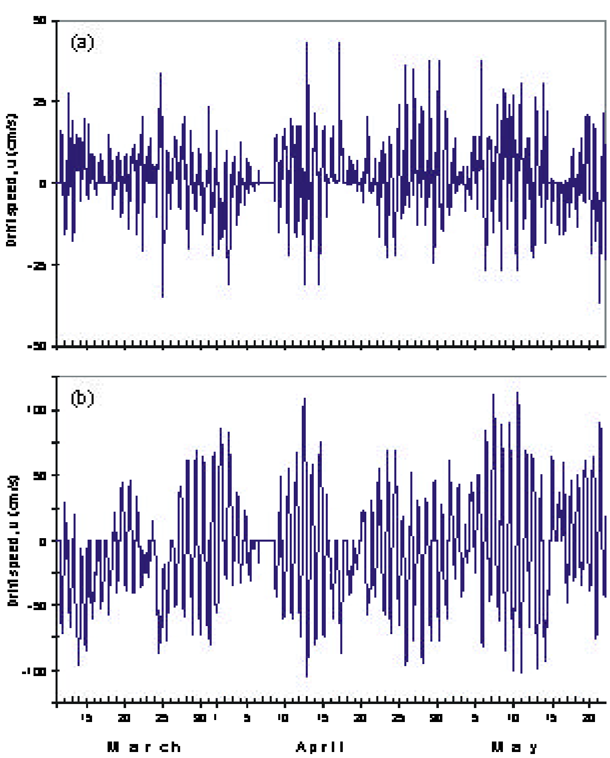

Fig. 2 Eastward (*u*) and northward (*v*) components of sea ice drift measured by radar at station OD in 1993.

atmospheric activity. The low-pass filtered data show also existence of the oscillations with a period of about 21 days. The corresponding peak is not seen in Figure 3, but we could detect it based on high-resolution spectral analysis. The same peaks were detected in wind spectra (not shown). Based on results of rotary spectral analysis (see Gonella, (1972)) we found that the angle between the wind and ice-drift vectors at the periods of the spectral peaks is about 20–30°.

The diurnal spectral peak is dominant at stations CL and OD, but is insignificant at station KM; the semidiurnal oscillations of the sea-ice are small at all stations (Fig. 3). These results are in agreement with the results of Rabinovich and Zhukov (1984) and Popudribko et al. (1998), who showed that semidiurnal tidal currents are negligible in this region, in comparison with diurnal currents.

Based on the results of the spectral analysis, we defined three "natural" frequency bands associated with different types of external forcing: The low frequency (LF) band, with frequencies less than 0.8 cpd; the tidal (TD), with frequencies between 0.8 and 2.2 cpd; and the high-frequency (HF), with frequencies greater than 2.2 cpd. In the text that follows, these three frequency bands are analyzed separately.

Low-frequency wind induced drift

The low-frequency ice motions, obtained by low-pass filtering of the residual (non-tidal) series with 25-h sliding window, were highly correlated with wind. Figure 4 presents the meridional (alongshore) components of the ice-drift and wind at station Odoptu (OD). We have not found any phase shift between the wind and ice drift. Estimation of the correlation function for all three stations showed that the sea-ice field responds to wind forcing almost immediately. These results are in contrast to the results of Pokrasenko et al. (1987) who pointed out that there is 8-h time shift between these processes.

The typical seasonal variations of longshore wind and low-frequency ice-drift motions are shown in Figure 4. Northerly and northwesterly winds with speeds of about 5–8 m/s normally prevail in January to March on the northeastern coast of Sakhalin Island. These winds are induced by a steady "winter monsoon" determining winter weather in this region (see Shevchenko and Saveliev in this

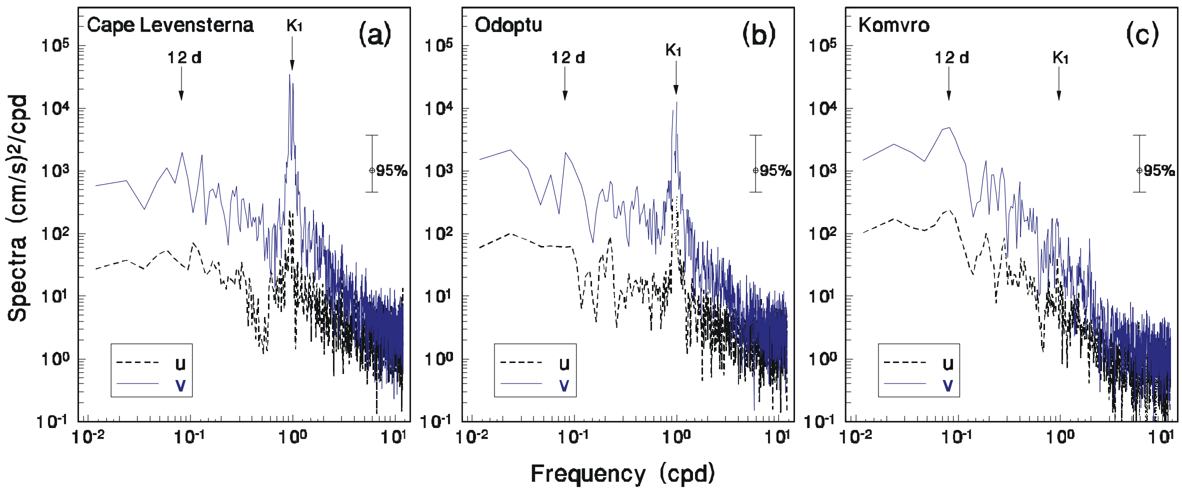

Fig. 3 Spectra of *u* and *v* components of sea ice drift at stations CL (a), OD (b), and KM (c). Spectra are computed for degree of freedom, DoF = 8.

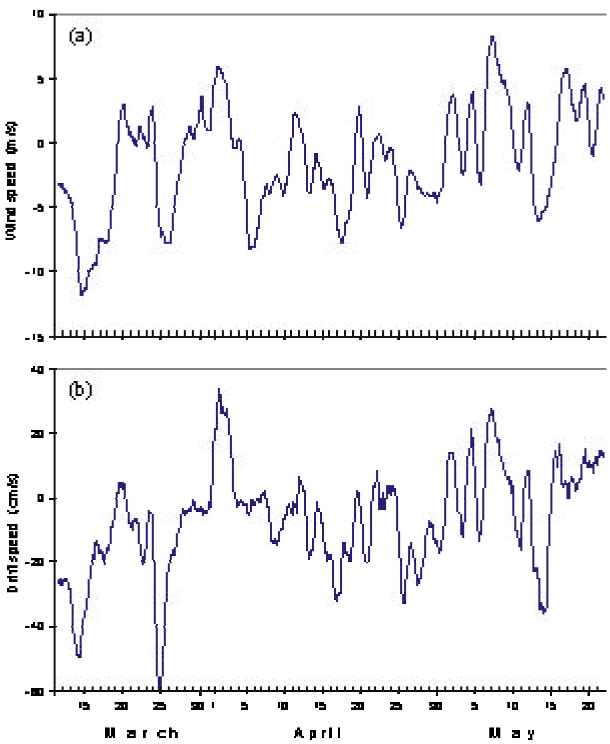

Fig. 4 Northward (longshore) components of (a) wind and (b) low-frequency ice drift at station OD, March 11 to May 23, 1993.

volume). Respectively, wind-induced ice-drift motions have southern and southeastern directions. The distribution of wind directions is less stable in April than in wintertime. In May southeasterly winds of about 3–5 m/s ('summer monsoon') dominate in the area. The general southward propagation of sea ice in May and June is probably associated with the Eastern Sakhalin Current.

Strong winds with velocities of about 15–25 m/s are related to continental cyclones frequently occurring in this region during the ice-covered period. For cyclones crossing Sakhalin Island, wind directions change very fast and these winds do not produce significant currents and associated ice-drifts. In contrast, for cyclones staying in the Sea of Okhotsk, steady northerly and northwesterly winds are rather typical. Specifically, these winds produce maximum velocities of residual (non-tidal) ice-drift of about 1 m/s traveling in southern and southeastern directions.

The high correlation of low-frequency ice motions and wind is clearly seen in Figure 5. We used a linear regression model to estimate, *R*, the "wind coefficient of the ice-drift". We made computations for longshore and cross-shore components independently and obtained the following values: $R_v = 4.0$ (cm/s)/(m/s) (Fig. 5), and $R_u = 2.0$ (cm/s)/(m/s), respectively. That means that a longshore wind of 10 m/s induces ice-drift moving with a speed of about 40 cm/s, and a cross-shore wind of the same speed produces ice-drift of about 20 cm/s. These regressional coefficients, R_v and R_u, can be used for short- and long-term forecasts of ice-drift on the northeastern shelf of Sakhalin Island.

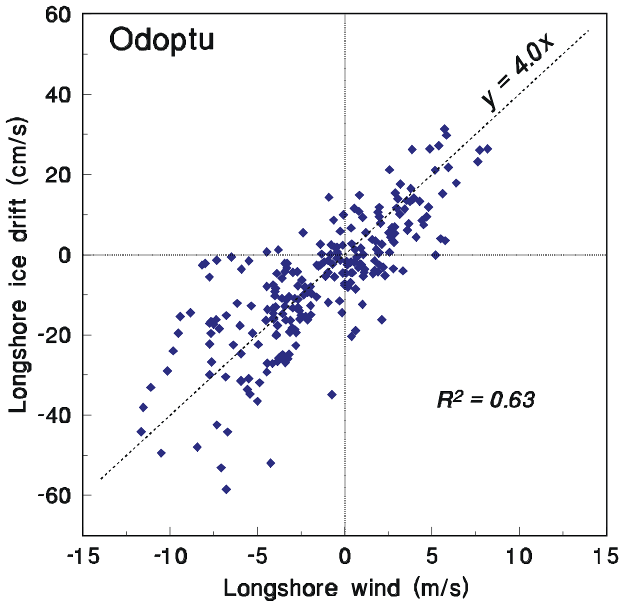

Fig. 5 Correlation (R^2) between longshore components of wind and low-frequency ice-drift. The solid straight line corresponds to "wind coefficient of ice drift" (cm/s)/(m/s) estimated using a linear regression model.

Tide-induced sea ice drift

The tide-induced drift motions of sea-ice were estimated using the least square method. The maximum values of the longshore tidal drift velocities were found to be of about 100–110 cm/s at CL, 90–100 cm/s at OD, and 15–25 cm/s at KM radar stations. These large tidal currents were related mainly to K_1 and O_1 diurnal tidal harmonics. As was shown first by Rabinovich and Zhukov (1984), and later by other authors (Suzuki and Kanari, 1986; Kowalik and Polyakov, 1998), strong diurnal currents on the northeastern shelf of Sakhalin Island are produced by tidally generated trapped shelf waves (a similar effect is well known for the Pacific coast of Vancouver Island (cf. Crawford and Thomson (1984); Foreman and Thomson (1997)).

Normally, for the areas with dominant diurnal tides, the extreme yearly tidal values have a prominent 19-year cycle. According to the computations made by Shevchenko et al. (1990), extreme tides for the northeastern shelf of Sakhalin Island were observed in 1968–1969, 1987–1988, etc. The year 1993 was the time when diurnal tides were approximately 20–30% weaker. So, the maximum tidal drift velocities can probably reach 120–140 cm/s.

It follows from the results of spectral analysis (Fig. 3), and from direct estimations of tidal currents by the least square method, that diurnal tides play a dominant role in the ice-drift motions at stations OD and CL, but are insignificant at KM. According to numerical modeling of tides on the northeastern shelf of Sakhalin Island (Suzuki and Kanari, 1986; Kowalik and Polyakov, 1998), diurnal tidal currents are very strong near the northern end of the island (the probable generation area of shelf waves), and then decrease in the southward direction. A similar picture of strong diurnal tidal currents decreasing with distance from the generation area of diurnal shelf waves (Juan de Fuca Strait) was described by Foreman and Thomson (1997) for the Pacific shelf of Vancouver Island. The main reason of this effect is dissipation of diurnal shelf waves (Rabinovich and Shevchenko, 1984). It is known that tidal shelf waves are normally accompanied by strong currents in nearshore zone (see the review article by Clarke (1991)), but bottom friction causes their fast dissipation. So, we may assume that weakening of diurnal currents and associated ice motions in the area of Komrvo is related to the decreasing (because of dissipation) of shelf waves propagating southward along the northeastern coast of Sakhalin Island. The other possibility is the presence of local amphidromic points for diurnal tides near to Sakhalin Island as was supposed by Rabinovich and Zhukov (1984). Existence of such local amphidromic points for diurnal tides near to the shore is also related to the influence of shelf waves (cf. Cartwright et al. (1980)).

We constructed ellipses of the tidal ice-drift for major diurnal constituents K_1 and O_1. At stations CL and OD these ellipses are very similar: They have approximately the same magnitude, same direction of rotation (clockwise) and are strongly extended alongshore. The only significant difference between CL and OD ellipses is the phase shift. These ice-drift ellipses are in very good agreement with the respective ellipses of tidal currents measured at nearby current-meter stations CM1 and CM2 (Fig. 6), as well as with other measurements of tidal currents made on the northeastern shelf of Sakhalin Island (cf. Rabinovich and Zhukov (1984); Popudribko et al. (1998)). Maximum currents at these stations were about 40–50 cm/s for K_1 and 35–40 cm/s for O_1.

So stable results and good agreement of ice-drift and current observations made at different years

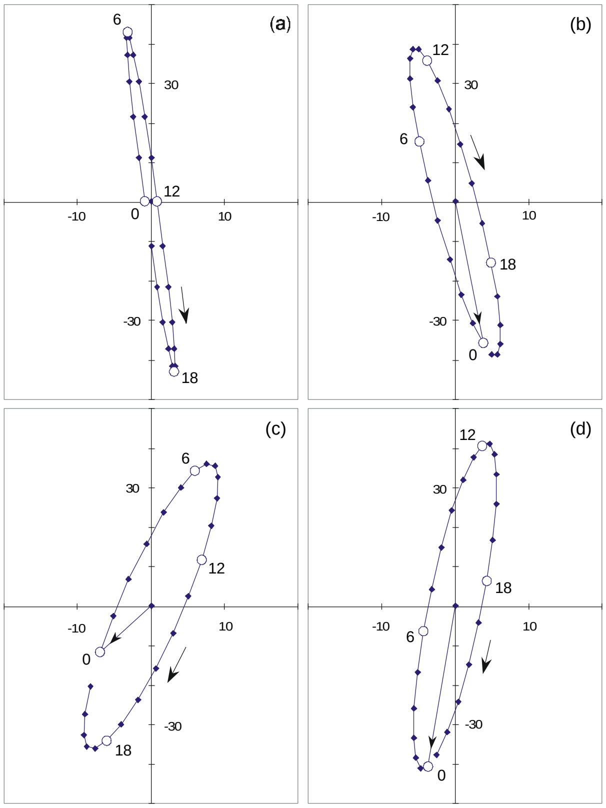

Fig. 6 Tidal ellipses for the main diurnal constituent K_1 for the ice drift measured by radar at stations (a) CL and (b) OD, and for the sea currents recorded at stations (c) CM1 and (d) CM2. Note that the scales of vertical (northward) and horizontal (eastward) axes are different.

and different seasons demonstrate that for the prediction of tidally induced sea-ice drift on the northeastern shelf of Sakhalin Island, we can apparently use the results of tidal analysis of currents formerly measured in this area. The other possibility is to use recent results of numerical modeling of tides and tidal currents in the Sea of Okhotsk (cf. Kowalik and Polyakov (1998)). Both approaches could be important for short- and long-term forecasts of sea ice drift in the vicinity of northeastern Sakhalin Island.

The phase shifts of tidal ellipses between CL and OD stations (both for K_1 and O_1 constituents), corresponding to time shifts of about 6–7 h, show that tidal waves propagate along the northeastern coast of Sakhalin Island from north to south (Fig. 1), i.e. in the direction coinciding with the theoretical direction of shelf waves (cf. Rabinovich and Zhukov (1984); Kowalik and Polyakov (1998)). If the same tendency remains southward from Odoptu station (at the Piltun-Astokhsk, Chaivinsk or Arkutun-Daginsk oil and gas-bearing areas), then tidal sea-ice drifts in the vicinity of Cape Levensterna and at these areas have *opposite directions*. The southward tidal drift at CL station corresponds to the northward drift at the southern areas, and vice versa.

Following Rabinovich and Zhukov (1984), we estimated phase speeds of K_1 and O_1 diurnal tidal waves using the observed phases of longshore (v) component of ice-drift at stations CL and OD, and currents at stations CM1, CM2, and CM3 (Fig. 5). Least-square fit showed that the phases of diurnal waves increase southward per 1 degree of latitude on 117° (for K_1) and 101° (for O_1). The corresponding phase speeds are: $c = 14.3 \pm 1.6$ km/h (K_1) and $c = 15.8 \pm 1.8$ km/h (O_1). Evident dispersion of diurnal waves is interesting. This result as well as phase speed magnitudes themselves are in good agreement with theoretical estimates of phase speed of diurnal shelf waves made for this region by Rabinovich and Zhukov (1984): 13.9 km/h (for K_1) and 15.3 km/h (for O_1).

Results of tidal analysis show that the diurnal shelf waves play a key role in ice-drift motions on the northeastern shelf of Sakhalin Island. The main properties of shelf waves are well established (cf.

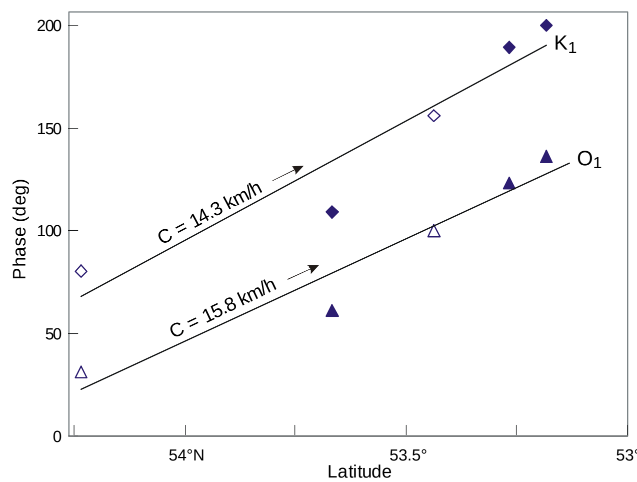

Fig. 7 The K_1 (diamonds) and O_1 (triangles) observed phases of the longshore component of sea ice drift (empty symbols) and sea currents (solid symbols) as functions of the latitude. The straight lines show phase speeds of diurnal shelf waves estimated by a linear regression model from the data.

LeBlond and Mysak (1978)). So, we can use these known properties to describe and predict essential features of ice motions in this area.

It is worthwhile to emphasize another aspect of the problem. A significant influence of shelf waves on various dynamical processes on the shelf is well known. In particular, they play an important role in sedimentation, meandering of boundary currents, coastal upwelling, shelf circulation, formation of storm surges, etc. (LeBlond and Mysak, 1978). However, this is one of the first demonstrations of direct influence of shelf waves on ice-drift. It is interesting to ask, is it a local phenomenon observed only in the northern part of the northeastern shelf of Sakhalin Island or it has a more general character and shelf waves affect the behavior of ice motions over the whole region of the Okhotsk Sea shelf of Sakhalin?. We plan to use the data from Piltun-Astokh, Arcutun-Daginsk, and Lunsk marine oil and natural gas-bearing areas to study this question in the future.

High-frequency drift

The difference between *u* and *v* components decreases at periods less than diurnal, and became negligible at periods of a few hours. There are no noticeable spectral peaks at high frequencies of ice-drift motions (Fig. 3). However, these high-frequency motions are quite significant (typical mean currents are of about 7–10 cm/s, maximum currents are 20–30 cm/s both for *u* and *v* components). Probably, the main source of these energetic motions is the turbulence induced by the bottom friction. Due to strong tidal currents in the shallow nearshore zone, there is a crucial effect of bottom friction on dynamical processes on the shelf of Sakhalin Island. Stronger high-frequency oscillations at CL and OD stations are associated with stronger tidal currents in this region, so we can assume that we see cascade transfer of tidal energy into high frequencies. As Figure 3 shows, in contrast to tidal and low-frequency bands, the difference between longshore and offshore components of ice-drift at high frequencies is very small, and they look like the spectra of the Gaussian stochastic process. A similar picture is observed for high frequency current oscillations, there is almost no difference between *u* and *v* components and between surface and near-bottom layers (Popudribko et al., 1998).

Conclusions

Coastal radar stations can be used effectively to measure sea ice drift over the shelf. Three radar stations established on the coast of Sakhalin Island recorded high quality data, which gave us the opportunity to examine ice motions on the northeastern shelf of the island in a wide frequency range.

Spectral analysis of ice-drift observations revealed three major types of ice motions: (1) Low-frequency, (2) diurnal, and (3) high-frequency. These three types of motions are related to three different generation sources: (1) Atmospheric activity, (2) tides, and (3) turbulence.

Low frequency drift motions are highly correlated with wind. A linear regression model showed that ‘wind coefficients of drift’ are 4.0 (cm/s)/(m/s) for longshore component and 2.0 (cm/s)/(m/s) for cross-shore component. Strong north winds in this region can induce ice motions with velocities more than 1 m/s. The computed ‘wind coefficients’ may be used for long-term and short term forecast of ice drift on the northeastern shelf of Sakhalin Island.

Diurnal tides play the major role in the sea-ice motions in the northern part of the northeastern shelf of Sakhalin. These diurnal tidal motions have velocities more than 1 m/s. Computed tidal ellipses of ice-drift are in good agreement with the respective ellipses of sea currents measured in this region. Computed tidal constituents of currents, as well as the results of numerical modeling of tidal motions, may be used for the prediction of ice-motions in the oil and gas-bearing areas of the Okhotsk Sea shelf of Sakhalin Island.

Strong diurnal tidal ice-motions on the northeastern shelf of Sakhalin Island are shown to be related to diurnal shelf waves. Phase shifts of K_1 and O_1 tidal ellipses estimated from ice-drift measurements and current-meter stations are in very good agreement with a theoretical model of diurnal shelf waves constructed by Rabinovich and Zhukov (1984) for this region. The observed phase speeds of K_1 and O_1 tidal harmonics are 14.3 and 15.8 km/h, in comparison with the theoretical values 13.9 and 15.3 km/h, respectively.

High frequency (0.1–0.5 cph) ice oscillations now and then exceed 20 cm/s in this area. In contrast to tidal and wind-induced motions, their spectra are almost isotropic. It was found that strong high-frequency ice-motions are normally associated with strong tidal motions. The probable reason of these oscillations is cascade transfer of tidal energy into higher frequencies due to turbulence and bottom friction in a shallow nearshore zone.

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References

Cartwright, D.E., Huthnance, J.M., Spencer, R. and Vassie, J.M. 1980. On the St. Kilda tidal regime. *Deep-Sea Res., 27A*, 61–70.

Clarke, A.J. 1991. The dynamics of barotropic tides over the continental shelf and slope (Review). In *Tidal Hydrodynamics*, B.B. Parker (ed.), J. Wiley, New York, 79–108.

Crawford, W.R. and Thomson, R.E. 1984. Diurnal-period continental shelf waves along Vancouver Island: A comparison of observations with theoretical models. *J. Phys. Oceanogr., 14*, 1629–1646.

Foreman, M.G.G., and Thomson, R.E. 1997. Three-dimensional model simulations of tides and buoyancy currents along the west coast of Vancouver Island. *J. Phys. Oceanogr., 27*(7), 1300–1325.

Gonella, J. 1972. A rotary-component method for analysing meteorological and oceanographic vector time series. *Deep-Sea Res., 19*, 833–846.

Kowalik, Z., and Polyakov, I. 1998. Tides in the Sea of Okhotsk. *J. Phys. Oceanogr., 28*(7), 1389–1409.

LeBlond, P.H. and Mysak, L.A. 1978. *Waves in the Ocean*. Elsevier, Amsterdam, 602 pp.

Martin, S., Drucker, R. and Yamashita, K. 1998. The production of ice and dense shelf water in the Okhotsk Sea polynyas. *J. Geophys. Res., 103*(C12), 27,771–27,782.

Pokrasenko S.A., Truskov, P.A. and Yakunin, L.P. 1987. Investigation of sea ice drift on the shelf of Sakhalin Island using the radar methods. *Proc. (Trudy) Far Eastern Research Inst. (DVNII), 36*, 49–52. (in Russian)

Popudribko, K.K., Putov, V.F. and Shevchenko, G.V. 1998. Estimation of sea currents characteristics for the Piltun-Astokh oil and gas-bearing area (northeastern shelf of Sakhalin Island). *Meteorology and Hydrology, 4*, 82–95. (in Russian)

Rabinovich, A.B. and Zhukov, A.E. 1984. Tidal oscillations on the shelf of Sakhalin Island. *Oceanology*, *24*(2), 184–189.

Rabinovich, A.B. and Shevchenko, G.V. 1984. Two-step mechanism for dissipation of tidal energy in the ocean. *Transact. (Doklady) USSR Acad. Sci., Earth Sci. Sec., 276*, 228–231.

Shevchenko, G.V. and Saveliev, V.Yu. 1999. Spatial variability of the wind field in the area of the Kuril Islands. pp. 49–53. In *Proc. of the Second Workshop on the Okhotsk Sea and Adjacent Areas, PICES Sci. Rep. No. 12*, Sidney, B.C. Canada.

Shevchenko, G.V., Fine, A.V., Rabinovich, A.B. and Mansurov, R.N. 1990. Estimation of extreme sea level oscillations in the mouth of the Tym River. In *Natural Hazards in the Far-Eastern Region*, USSR Academy of Sciences, Vladivostok, 253–276. (in Russian)

Suzuki, K. and Kanari, S. 1986. Tidal simulation of the Sea of Okhotsk. *Kaiyo Kagaku, 18*, 455–463. (in Japanese with English abstract)