Influence of Amur River discharge on hydrological conditions of the Amurskiy Liman and Sakhalin Bay of the Sea of Okhotsk during a spring–summer flood

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Introduction

The Amur River is one of the largest rivers of the world. Its length is 4350 km and its total discharge is about 390 km^3 from a river basin of 1,855,000 km^2. The regime of the Amur River is distinguished by the spring–summer flood, summer low water, summer–fall flood, and winter low water. The spring flood is caused by melting snow and the summer–fall flood is caused by monsoon rains in the river basin. About 87% of the annual discharge falls during the warm part of year (May–October).

The Amur River flows into the Amurskiy Liman which is a narrow and shallow strait connecting the Sea of Japan and the Sea of Okhotsk. The Amurskiy Liman can also be considered as an estuary of the Amur River within which are several navigation channels. The Sakhalin and the Southern navigation channels connect the Sea of Okhotsk and the Sea of Japan, and from the Amur River mouth the Nevelskoy (Northern), the Southern and the East navigation channels (Petrov, 1959) exit. The Nevelskoy Strait connects the Amurskiy Liman to the Tatar Strait (Sea of Japan).

The dynamic conditions of the Amurskiy Liman are formed under the influence of the Amur River discharge, the ratio of background sea levels between the Sea of Japan and the Sea of Okhotsk, strong tidal currents and mixing. As a result of the monsoon character of the atmospheric circulation, southern winds prevail over the Amurskiy Liman in the summer and northern ones in the winter.

On the northern border of the Amurskiy Liman in the summer, the background level of water falls, and in the winter it rises; on the southern border of the Liman the sea level fluctuations occur in the opposite manner. Thus, during the warm period of the year (May–October), the difference in background levels between the Sea of Japan and the Sea of Okhotsk is positive (northward inclination). Due to this difference in sea levels, estuarine circulation is formed, and in the summer, the mean current is directed to the north. The data on sea level changes during the winter period are inconsistent. Some researchers (Lobanova, 1987) state that the difference in the levels during the winter period becomes negative (southward inclination) and the current is directed mainly to the south (into the Sea of Japan). Other data (Chao and Boicourt, 1986) suggest that the difference of the background levels is close to zero in the winter which should lead to the uniform distribution of the Amur River discharge between the Sea of Japan and the Sea of Okhotsk. Considering the available data on seasonal changes of the difference in the background sea levels and the variability of the Amur River discharge (Glukhovskiy *et al.*, 1998), it is possible to roughly estimate the volume of freshwater inflow into the Okhotsk Sea and the Sea of Japan during a year under average conditions. During the period from May till October, all river discharge is directed towards the Sea of Okhotsk. During this period the average discharge is equal to 331 km^3. If, during the cold period of the year (November–April), the discharge is uniformly distributed between the seas, about 6.5% of the Amur River annual discharge (31.5 km^3) is directed towards the Sea of Japan. Thus, on average, the Sea of Okhotsk receives 362.5 km^3 of fresh water within a year.

In the Amurskiy Liman two structural zones divided by a front have been determined (Lobanova, 1987; Zhabin *et al.*, 2007). The northern zone is associated with the mouth of the Amur River, the Sakhalin channel and the Nevelskoy channel, and the southern zone with the Southern channel and the Nevelskoy Strait. The northern part of the estuary is stratified under the influence of the river discharge. The southern zone is characterized by a homogeneous vertical distribution of oceanographic parameters. In the warm part of the year the waters of low salinity flow from the Amurskiy Liman to the Sakhalin Bay (the Sea of Okhotsk) and form the Amur River plume

(Rostov and Zhabin, 1991; Zhabin *et al.*, 2005; Zhabin *et al.*, 2007).

A study of the Amur River mouth ecosystem was carried out during a cruise of the R/V *Professor Gagarinskiy* in June, 2007. Oceanographic measurements were conducted with the CTD-probe SBE 19plus. The location of hydrological stations for this study is shown in Figure 1.

The data obtained during the cruise and from remote sensing (Terra and Aqua satellites, radiometer MODIS) allow us to investigate the structure and dynamics of the waters near the Amur River mouth during the spring–summer flood.

Oceanographic structure near the Amur River mouth

At the mouth of the Amur River, the mixing of seawater and river water occurs. The area around the mouth includes the Amurskiy Liman and the adjoining parts of Sakhalin Bay and the Tatar Strait.

Looking at the section through the Amurskiy Liman (Fig. 2), bounded by the Southern and the Sakhalin channels, there are two distinguished structural zones – a mixed zone and a stratified one. The southern zone has a typical homogeneous vertical distribution of hydrographical characteristics with high salinity; the northern one has a two-layered structure with water of very low salinity in the surface layer. The stratification in the northern part of the estuary is supported both by the flow into the near-bottom layer of the Sea of Okhotsk (a salt wedge on the northern outlet of the Liman), and by the near-bottom advection of saltier waters from the Sea of Japan (the stratified regime near the river mouth). The stratification in the northern part of the estuary is essentially weakened in the zone that is under direct influence of the river discharge.

The southern part of the Amurskiy Liman is filled by the waters flowing from the Sea of Japan. Intensive tidal and wind mixing in this zone leads to a homogeneous vertical distribution of oceanographical characteristics. The influence of the river discharge on this part of the Amurskiy Liman is insignificant. The salinity in the mixed zone increases in the direction to the southern outlet from the estuary. The distribution of temperature and salinity in the section across the Amur River plume in Sakhalin Bay is shown in Figure 3.

Low salinity and warm waters flow from the Amurskiy Liman to Sakhalin Bay through the northern outlet of the Liman. The plume is about 7 m thick, the salinity in the plume ranges from 7 to 15 psu, and temperature ranges from 7 to 12°C. A sharp pycnocline separates the plume from very cold (< –1.5°C) and salty (> 32 psu) bottom shelf waters of the Sea of Okhotsk. Higher values of temperature and smaller values of salinity are observed in the discharge current.

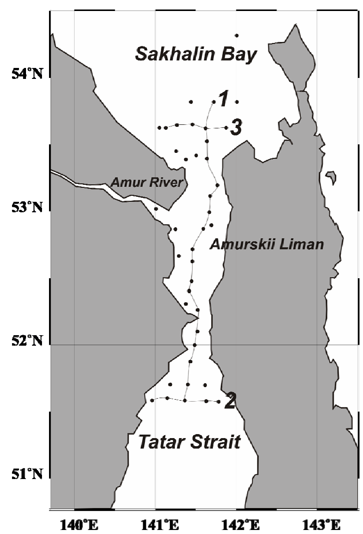

Fig. 1 Hydrographic sections occupied during the cruise of the R/V *Prof. Gagarinskiy* in June 2007. Closed circles show the station locations.

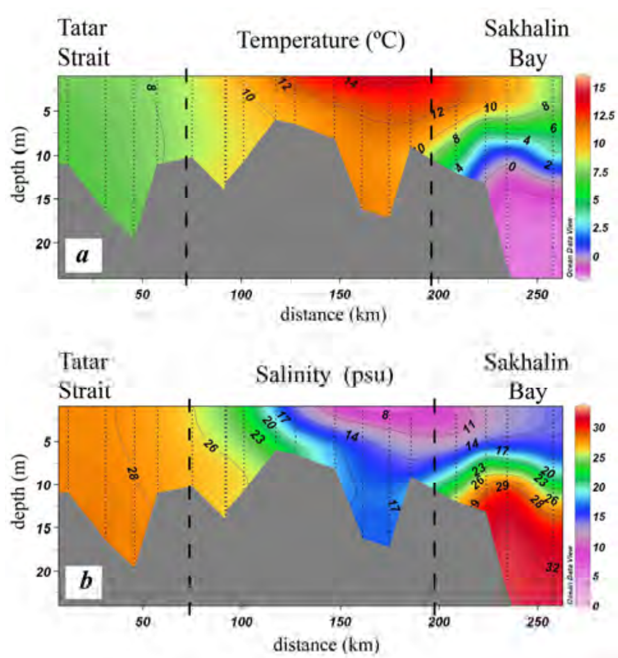

Fig. 2 Vertical distributions of (a) temperature and (b) salinity along section 1, June 2007.

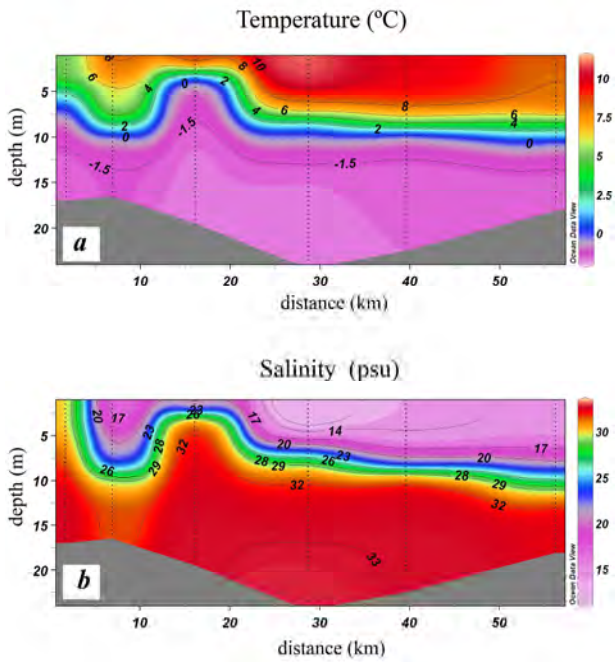

Fig. 3 Vertical distributions of (a) temperature and (b) salinity along section 3, June 2007.

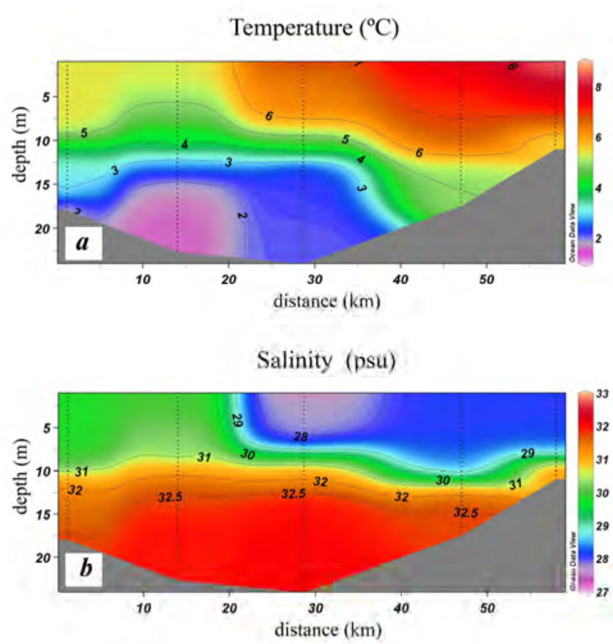

Fig. 4 Vertical distributions of (a) temperature and (b) salinity along section 2, June 2007.

Two cross-sections were obtained for the Tatar Strait. On the southern section a two-layer vertical structure of waters was observed (Fig. 4).

The upper layer was about 10 m thick and was separated from the bottom water layers by a sharp thermohalocline. The surface layer near the coast of the continent was characterized by low values of temperature (about 5°C) and high values of salinity (> 30). In the middle part of the Tatar Strait and near Sakhalin Island, waters with lower salinity (< 28.5) and higher surface temperatures (6–8°C) were observed. The origin of this zone of low salinity could have been caused by the discharge of the waters from the southern part of the Amurskiy Liman through the Nevelskoy Strait in the period preceding the observation.

A second cross-section of the observation (Fig. 1) was executed near the southern inlet of the Nevelskoy Strait. The vertical thermohaline structure in this section differed from the structure of waters of the northern part of the Tatar Strait. At the inlet to the strait a more homogeneous vertical distribution of hydrological characteristics was observed. The temperature monotonically decreased and the salinity increased with depth. The waters in the central part of the section were completely mixed from the surface to the bottom. The salinity of the surface layer did not exceed 28.5 and the temperature changed within the range of 7–9°C. The waters of low salinity at the outlet from the Amurskiy Liman demonstrate the influence of the Amur discharge in the northern part of the Tatar Strait during the spring–summer flood.

The Amur River discharge from satellite observations

The Amur River discharge contains a significant amount of sediments. This allows us to see contrasts in turbidity from remote sensing in order to study the Amur River discharge distribution in the shelf zone of the Sea of Okhotsk. Figure 5 shows a visible satellite image of Sakhalin Bay, acquired during the survey period (June 7, 2007). It can be seen that turbid waters fill the northern part of the Amurskiy Liman and through the northern outlet outflow to Sakhalin Bay. Two structural elements are distinguished: a discharge lens with a jet current (bulge) and the coastal Amur current. The discharge lens is filled by the inflow of more turbidity (warm and low salinity) waters. The coastal Amur current is observed near the Sakhalin coast of Sakhalin Bay.

A map of current vector speeds, calculated by the displacement of markers (drifting ice floes and other characteristic points), is superimposed on a pair of images taken from the Aqua and Terra satellites on June, 7, 2007 with a 100-min time difference (Fig. 5).

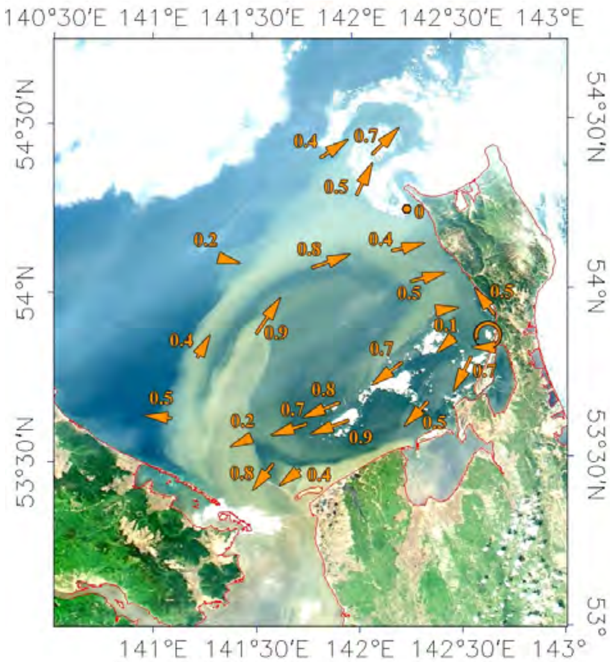

Fig. 5 Color image from the Aqua satellite, (June 7, 2007) illustrating the plume bulge formation as the Amur River plume exits the estuary. The overlaid current vectors identify the recirculation zone within the bulge.

The images show that the Amur River discharge, while leaving the estuary, forms an anticyclonic circulation on the periphery of the plume. The recirculation provides the inflow of low salinity waters to the internal field of the plume. The current speeds in the discharge current leaving the estuary reach 1 km/s. The speed ranges between 0.4 to 1.5 km/s in the jet current passing along the periphery of the lens.

Dynamics of the Amur River discharge

The river discharge in the shelf zone forms bulge and coastal density currents. Garvin (1995) offers a dynamical system for classifying buoyant discharges. The key parameter of this classification is the Kelvin number which is defined as the relation of the coastal current scale L to the baroclinic Rossby deformation radius L_D. The deformation radius is $L_D = c/f = (g'h)$ 0.5/f, where f is the Coriolis parameter, c is the phase velocity of long interfacial waves, h is the plume thickness, $g' = g(\rho_2 - \rho_1)/\rho_2$, is the reduced gravity (g is gravitational acceleration, ρ_1 and ρ_2 are densities of the upper and the lower layers, respectively). One more important parameter used in this classification is the non-dimensional densimetric Froude number $F = U/c$, where U is a characteristic velocity within the coastal current. It is known that at $F > 1$ the current will be "rough" (supercritical regime), and at $F < 1$ it will be quiet (a subcritical regime). At the transition from a supercritical movement regime to a subcritical one ($F = 1$, critical Froude number) an internal hydraulic jump is observed which is accompanied by energy dissipation and mixing.

The Kelvin number can be used to compare the contributions of inertial and rotary effects in the dynamics of the discharge current near the outlet from the Liman. In the limiting case when $K << 1$, the influence of the Coriolis effect on the distribution of river discharge waters is insignificant. In this case the dynamic regime near the mouth or the outlet from the Liman is determined by the advection of low salinity waters. At greater Kelvin numbers (>> 1) the dynamics of the current outflow from the Liman (mouth) is defined by rotation of the Earth.

The dynamic classification is diagnostic and requires preliminary data on the parameters and scales of the phenomenon, such as stratification, characteristic speed of the stream and the scale of current. Estimations of these parameters for the discharge of the Amur River to the Sea of Okhotsk are received through oceanographic and satellite observations. The discharge current is characterized by the difference in density of $\rho_2 - \rho_1 = 20$ kg/m^3, and the average thickness of the plume is 7 m. The scale of the current according to satellite data is equal to approximately 20 km. The scale of the current coincides with the width of the northern outlet from the Liman. The Coriolis parameter at the latitude of Sakhalin Bay is equal to 1.15×10^{-4} s^{-1}. At the observed values of the parameters, the baroclinic radius of deformation is 10 km which gives $K = 2$. This estimation shows that the dynamics of the Amur River discharge depends on the effects of rotation.

The estimation of the speed the outflow of low salinity waters from the Liman to the Sea of Okhotsk (the area of the section at the outlet is 105 m^2) can be determined by the average value of the Amur River discharge in June (166,000 m^3/s) (Glukhovskiy *et al.*, 1998). The salinity at the outlet from the Liman was 10 psu. Therefore, when making the calculations, it is supposed that the Amurskiy Liman river waters (salinity ~0) mix with the waters of the Sea of Japan (salinity 30 psu) in the ratio of 1:2. In this case, the average speed equals 0.5 km/s which gives $F = 0.4$. The estimation of the discharge current speed during the study can be determined with the help of satellite observations, using the method of sea markers. For this purpose, the displacement of characteristic points on consecutive images (time interval is 100 minutes), received on June 5, 7, 8 and 15, 2007 from the satellites Terra and Aqua were calculated. According to the satellite data, the average current speed at the outlet from the Liman is 0.85 km/s which gives F = 0.7. At such values of Froude numbers the regime of movement will be subcritical and the river discharge should extend as a superficial current above the layer of denser surrounding waters.

Thus, the calculation of nondimensional parameters shows that the contribution of the effect of the Earth's rotation to the dynamics of the discharge current of the Amur River exceeds the contribution of inertial effects. The numerical models of coastal circulation (James, 1997) show that at $K \sim 1$ near the river mouth two zones with various dynamics are formed – a bulge with an anticyclonic circulation and a density coastal current. The scale of this current is equal to the baroclinic Rossby deformation radius. A more complex dynamic regime with a steady anticyclonic circulation in the lens is formed in the bay which is under the influence of intensive river discharge.

Conclusion

In the estuary of the Amur River occurs mixing of river and sea waters which flow into the Amurskiy Liman from the Sea of Japan. The waters of low salinity flow into the Sea of Okhotsk in the form of a discharge current. Under the influence of the Earth's rotation the discharge current deviates to the right and forms an anticyclonic circulation in Sakhalin Bay. The mesoscale Amur River plume is formed and filled during a spring–summer flood. Further research on the dynamics, conditions of formation, and evolution of the plume is necessary.

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