Modeling of oil spills for the shelf conditions of northeastern Sakhalin

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Introduction

Shelf oil and gas fields of northeastern Sakhalin to be developed in the near future bring forth the risk of oil spills which may occur in the course of oil production and transportation. Oil field behavior modeling has been carried out for potential sources located in the area of the Piltun-Astokhskoye oil field and Terpeniye Cape along the route of oil transportation. Statistical regularities of oil spill migration have been studied on the basis of 158 ten-day hydrometeorological scenarios modeled for summer and autumn seasons.

Methods and models

Various models and methods have been used to develop scenarios of ecological situations in the case of accidental oil spills, as well as their migration and evolution. The most important and complex models used to determine the dynamics and physical–chemical characteristics of an oil spill are as follows:

> The model is used to construct the scheme of currents to determine the basic environmental parameters for spatial dynamics of oil spill migration under various hydrometeorological situations. The technology of current scheme estimation includes the model of non-tidal currents (Budaeva, 1997) and the technology of tidal current estimation over calculated harmonics;
>
> the trajectory model of oil spill dynamics (describes oil spill migration under set hydrometeorological situations) (Harlow, 1964; Zatsepa, 1992);
>
> the oil evolution model (describes physical–chemical processes taking place in a spill, such as evaporation, dispersion, emulsification, etc.) (Kuipers, 1981; Michoukov, 1997; Zatsepa. 1992).

Besides the above mentioned, the following models and methods were also used in calculations:

> Statistical, correlation and interpolation methods for estimation of meteorological fields (re water, wind);
>
> correlation methods to reconstruct and analyze interacting hydrometeorological elements were used to verify the methods and models (wind components and surface currents in particular);
>
> estimation for ten-day scenarios based on typical hydrometeorological situations, accounting for reoccurrence and duration characteristics. The succession of events was determined with the help of the generator of random numbers and weighting coefficients from the transit correlation matrix.

Trajectory evolution model of oil spill dynamics

An oil spill is assumed to consist of a number of independent little oil spills. A little oil spill is made up of a finite number of markers representing the shape and distribution of oil within this spill. The behavior of an oil spill is divided into four phases: time lag; gravitational–viscous; phase of surface tension; migration and spreading due to the influence of wind and advective-turbulent processes.

The basic equations describing the trajectories of marker motion are represented as follows:

$$\frac{dx}{dt} = u(x_i, y_i, t) + u'(x_i, y_i, t) + w_u(x_i, y_i, t),$$
$$\frac{dy}{dt} = v(x_i, y_i, t) + v'(x_i, y_i, t) + w_v(x_i, y_i, t), \quad (1)$$

where,

x_i , y_i	– current coordinates of the *i*-marker;
u, v	– liquid (currents) velocity components;
u , v	– turbulent pulsation rate components;
w_u, w_v	– wind components.

$$w_u(x, y, t) = k \times W_u(x, y, t),$$
$$w_v(x, y, t) = k \times W_v(x, y, t), \quad (2)$$

where,

W_u, W_v	– zonal and meridional components of the near water coefficient;
k	– wind transport coefficient (in this particular case it is assumed equal to 0.017).

The given equations below were developed from the assumption that the basic dispersion value is conditioned by the current, with wind correction added:

$$s_x = (\sqrt{2 + 0.196 v_x^2 + 0.076 v_y^2}) * K$$

$$s_y = (\sqrt{2 + 0.196 v_y^2 + 0.076 v_x^2}) * K, \quad (3)$$

where,

v_x, v_y	– liquid current velocity in cm/s,
K	– wind addition parameter.

Equations of oil spreading:

$$\frac{d^2R}{dt^2} = -\frac{3}{2}\frac{\ddot{A}V_0 g}{\eth R^3} + \frac{3\eth\eth R^t}{\tilde{n}_0^t V_t} + \frac{1}{R}\left(\frac{dR}{dt}\right)^2 - \frac{2.175\tilde{n}_w \acute{\imath}_w^{1/2} R^{3/2}}{\tilde{n}_0^t V_t}\left(\frac{dR}{dt}\right)^{3/2} - \frac{3}{2}\frac{\acute{\imath}_0^t}{R^2}\frac{dR}{dt} \quad (4)$$

$$\frac{dR}{dt} = U = \int_0^t \left(\frac{d^2R}{dt^2}\right) dt \quad (5)$$

$$R = \int_0^t \left(\frac{dR}{dt}\right) dt \quad (6)$$

$$R_{max} = \left(\frac{V_0}{p} * 10^5\right)^{1/2} \quad (7)$$

where,

t	– time passed from the moment oil began to spread [s];
R	– spill radius at time t [m];
$D = (r_w - r_0^t)/r_w$	
V_0, V_t	– initial oil volume and volume of oil spread on the sea surface at time *t*;
g = 9.8 [m/s²];	
s^t, r_o^t, n^t	– pressure of the spreading oil [n/m], density [kg/m³], kinematic viscosity [m²/s] of oil at moment t;
r_w, n_w	– density [kg/m³] and kinmatic viscosity [m²/s] of water;
R_{max}	– maximal radius of oil spill [m].

The time lag phase is characterized by sufficiently intensive spreading of oil over the sea surface under gravity. For the round oil spill with radius *R* and thickness *h*, we can write the following equation:

$$R \approx k_1 \cdot (\ddot{A} \cdot g \cdot V_t)^{\frac{1}{4}} \cdot t^{\frac{1}{2}}, \quad (8)$$

where, k_1 - unity order constant;

In the gravitational-viscous phase of oil spreading one shall account viscous friction in an oil film.

$$R \approx k_2 \left(\ddot{A} \cdot g \cdot V_t \cdot \acute{\imath}_w^{-\frac{-1}{2}}\right)^{\frac{1}{6}} \cdot t^{\frac{1}{4}}, \quad (9)$$

where, k_2 – unity order constant.

The equation of oil spreading at the phase of surface tension is as follows:

$$R \approx k_3 \cdot \left(\frac{\text{ó}_w{}^2 \cdot t^3}{\text{ñ}_w{}^2 \cdot \text{í}_w} \right)^{\frac{1}{4}}, \qquad (10)$$

where, k_3 – unity order coefficient.

The total volume of the oil evaporated from an oil spill is proportional to the spill square area. The expression for calculations is

$$\frac{d\,m_i}{dt} = \frac{U_*}{15.2}\left(\frac{D_i}{n_a}\right)^{0,61} \frac{x_i P_i}{R_a T_w}\left(p\,R^2\right)\left(\frac{V_n}{V_s}\right) \qquad (11)$$

$$U_* = 0.04 U_{10} \qquad (12)$$

where, for *i*-group or an individual compound,

$m_i, x_i, P_i, D_i, r_i, M_i$ – number of moles, mole share, vapor pressure [Pa], coefficient of molecular diffusion in the atmosphere [m^2/s], density [kg/m^3], molecular weight [kg/mole] at water temperature (T_w , [K]) by atmospheric pressure;

n_a – kinematic air viscosity, [m^2/s];

R_a – gas constant;

U_*, U_{10} –dynamic wind velocity [m/s] and wind velocity 10 m above the surface [m/s].

The total oil volume evaporated is calculated by the following equation:

$$V_{ev} = -\sum_{i=1}^{n} \frac{M_i}{r_i} \int_0^t \left(\frac{d\,m_i}{dt}\right) dt \qquad (13)$$

The rate of oil emulsification into water was assumed equal the wave height (H_w, [M]) and the volume of oil in the surface layer.

$$\frac{d\,V_{em}}{dt} = C_7 V_s H_w \qquad (14)$$

where, C_7 – emulsification constant.

For a shallow sea with depth less than 40 m,

$$H_w = 0.07 \frac{U_{10}^2}{g} \left(\frac{g H_s}{U_{10}^2} \right)^{3/5} \qquad (15)$$

where, H_s is the depth of the sea.

We assumed the rate of oil dispersion into water to be proportional to the wave height and volume of non-emulsified oil on the sea surface (V_{nem}, [M^3]):

$$\frac{d\,V_{dis}}{dt} = k_{em} V_{nem} H_w \qquad (16)$$

where, k_{em} – emulsification coefficient.

In the course of modeling, we controlled the changes in:

$$\begin{aligned} V_s &= V_0 - V_{ev} - V_{dis} - V_{lost} \\ V_{nem} &= V_0 - V_{ev} - V_{em} - V_{dis} - V_{lost} \\ V_W &= C_{wo} V_{em} \\ V_t &= V_s + V_w \end{aligned} \qquad (17)$$

where,

V_0 – volume [m^3] of oil discharged;

V_s – volume of oil [m^3] on the sea surface at time *t*;

V_{nem} – volume of non-emulsified oil [m^3];

V_w – volume of water [m^3] in water-in-oil emulsion;

V_{lost} – volume of lost oil [m^3] for other reasons;

V_t – total volume of oil and emulsion [m^3];

C_{wo} – coefficient of maximal emulsification of water into oil.

Estimation technique for hydrometeorological scenarios

The estimation technique for hydrometeorological scenarios consists of the following stages:

Development of a table of reoccurring meteorological situations over the data base of on-route ship observations and a corresponding reoccurrence table of the nearest on-land hydrometeorology stations;

selection of typical seasonal meteorological situations from the reoccurrence table;

calculation of spatial fields of near water wind corresponding to the calendar of the selected meteorological situations;

Determination of duration criteria for the selected meteorology and their over the duration factor, construction of correlation matrix;

calculation of generalized harmonic constants for the basic modes of the regional tidal currents supported by instrumental observations and construction of tidal current harmonics at the nodes of a spatial grid (in accordance with shallow water theory);

approximate calculation of wind–wave amplitude at the grid nodes;

construction of climatic density fields and boundary conditions for the model of non-tidal currents;

construction of non-tidal current fields for the selected meteorological situations;

filling the time interval of 15–18 ten-day scenarios for two seasons by typical meteorological situations according to the required statistics of reoccurrence and duration of situations;

construction of ten-day scenarios for selected situations using the transit correlation matrix, optimization of scenarios over the probability criterion;

preparation of the fields of total currents, wind, and waves for hydrometeorological situations and construction of calculated fields at the nodes of a grid for each 1-h interval of ten-day scenarios, taking into account the condition of smooth transits;

visual control of oil spill migration within the studied scenarios with preliminary modeling over the trajectory model (when necessary, correction of the developed scenarios and/or removal of surplus information);

final preparation of hydrometeorological data for scenarios in the format required for modeling.

Modeling of the worst meteorological situations conditioning the quickest migration of an oil spill to a shoreline was made separately.

Modeling results of oil spills on the Sakhalin shelf

Some examples of modeling for real scenarios are illustrated in Figures 1–6. Figures 1 and 3 demonstrate the calculated trajectories of oil spills for 18 and 15 ten-day scenarios, developed for the northeastern shelf of the Piltun-Astokhskoye oil field and the eastern shelf of Terpeniye Cape. Figures. 2 and 4 show the zones of potential impact for the calculated trajectories (Figs. 1 and 3). Figure 5 illustrates the evolution of oil spill characteristics (evaporation, dispersion, emulsification, etc.) 3 days after a “light-oil” spill in the area of the Piltun-Astokhskoye oil field. Figure 6 shows the dynamics of the oil spill square area modeled over 18 ten-day scenarios.

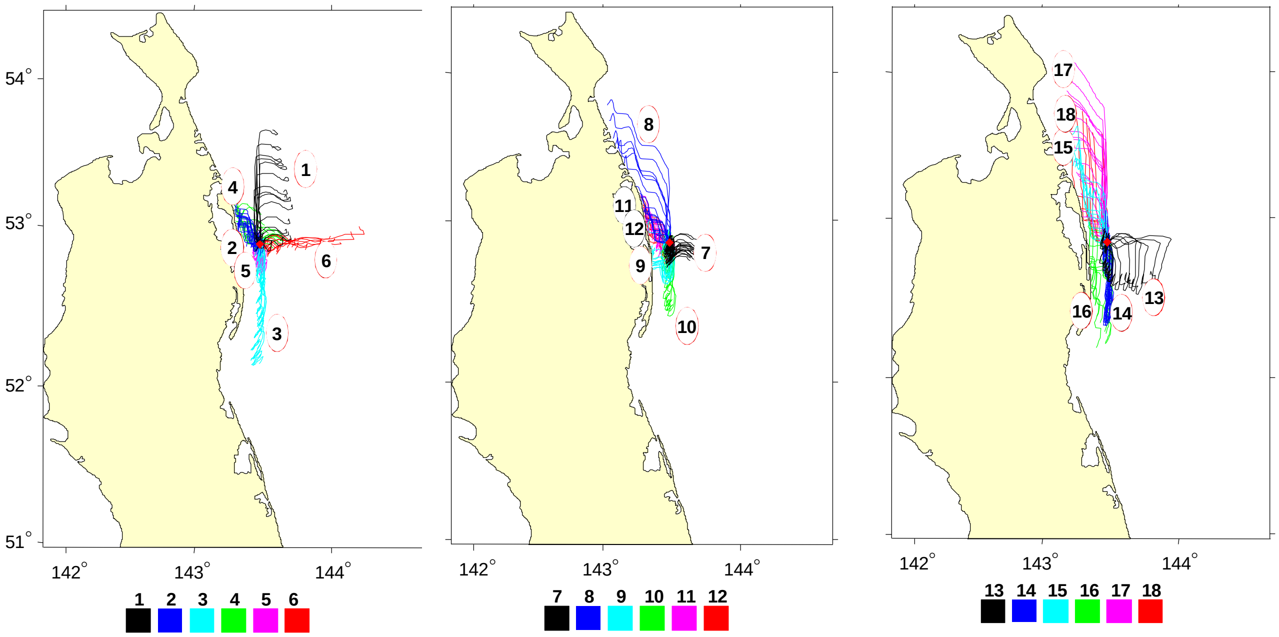

Fig. 1 Oil spill trajectory for 18 hydrometeorological scenarios, summer season, 3 days after the event. The source is in the area of the Piltun-Astokhskoye oil field, Sakhalin shelf.

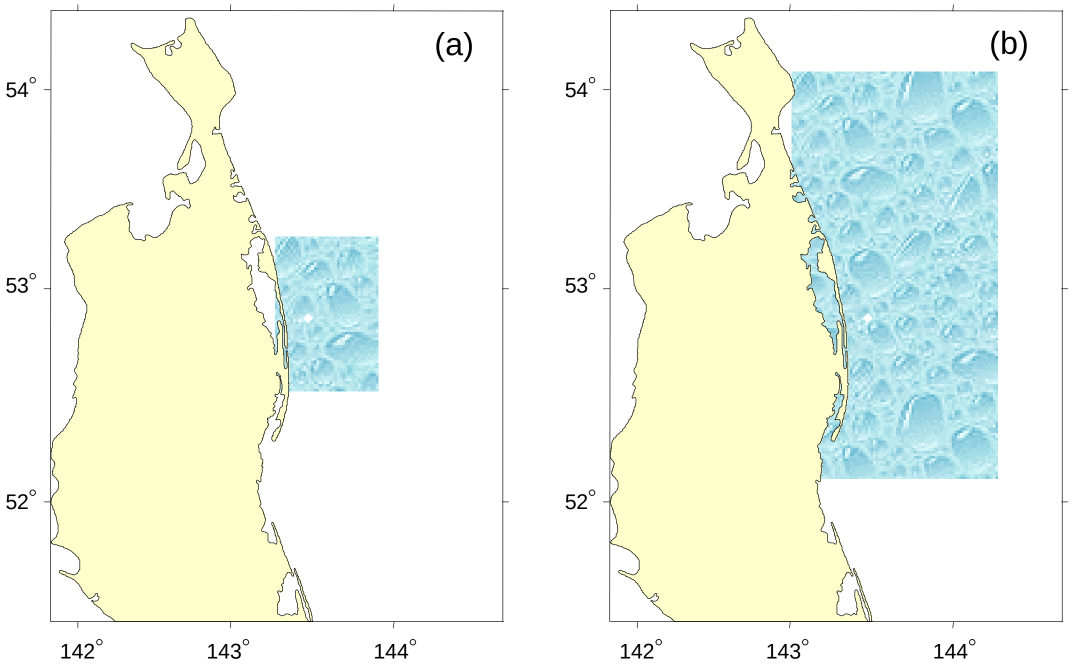

Fig. 2 Zone of potential impact for source located in the area of the Piltun-Astokhskoye oil field, Sakhalin shelf: (a) 1 day after the event and (b) 3 days after the event.

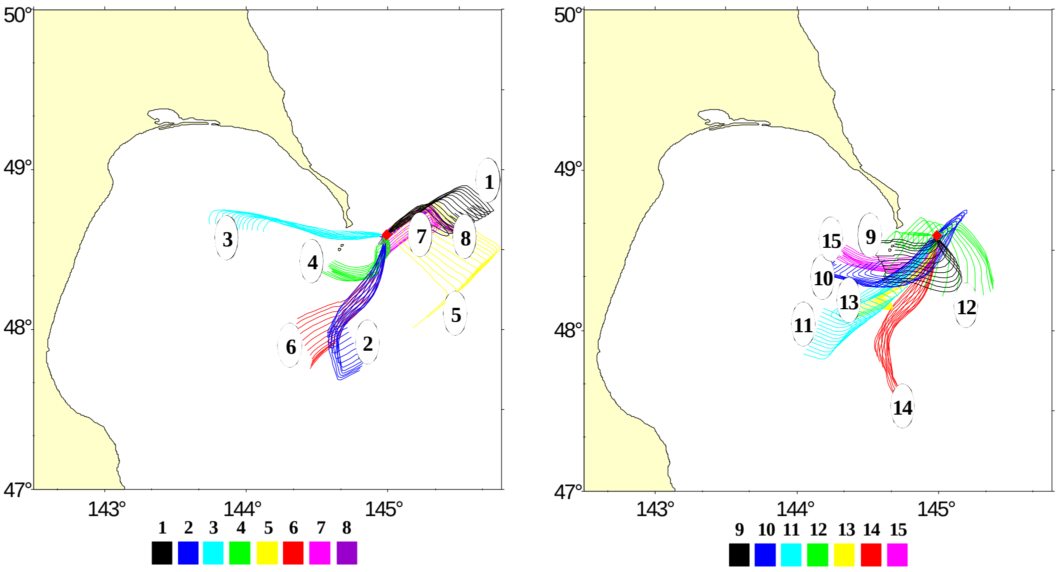

Fig. 3 Migration trajectories of an oil spill for 15 hydrometeorological scenarios, autumn, 3 days after the event. Source is in the area of Terpeniye Cape, eastern Sakhalin shelf.

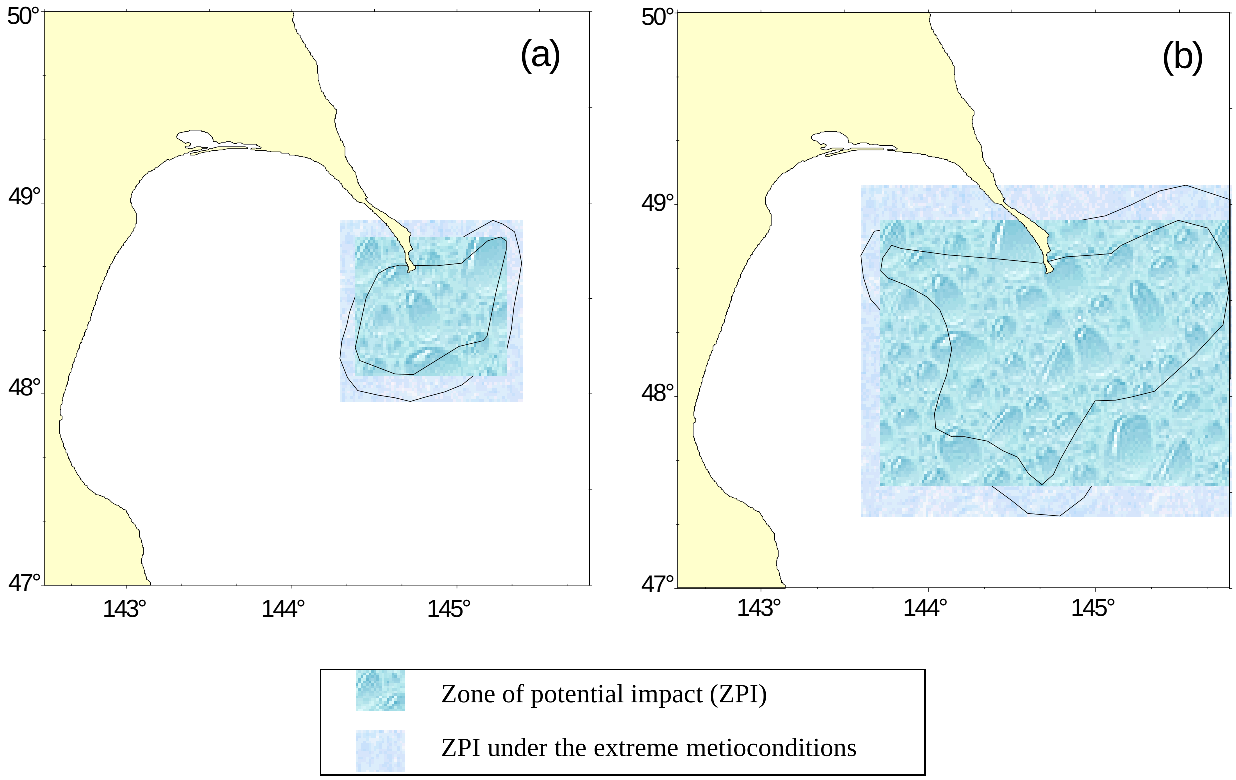

Fig. 4 Zone of potential impact of an oil spill (a) 1 day and (b) 3 days after the event. Source is in the area of the Terpeniye Cape, eastern Sakhalin shelf in the autumn.

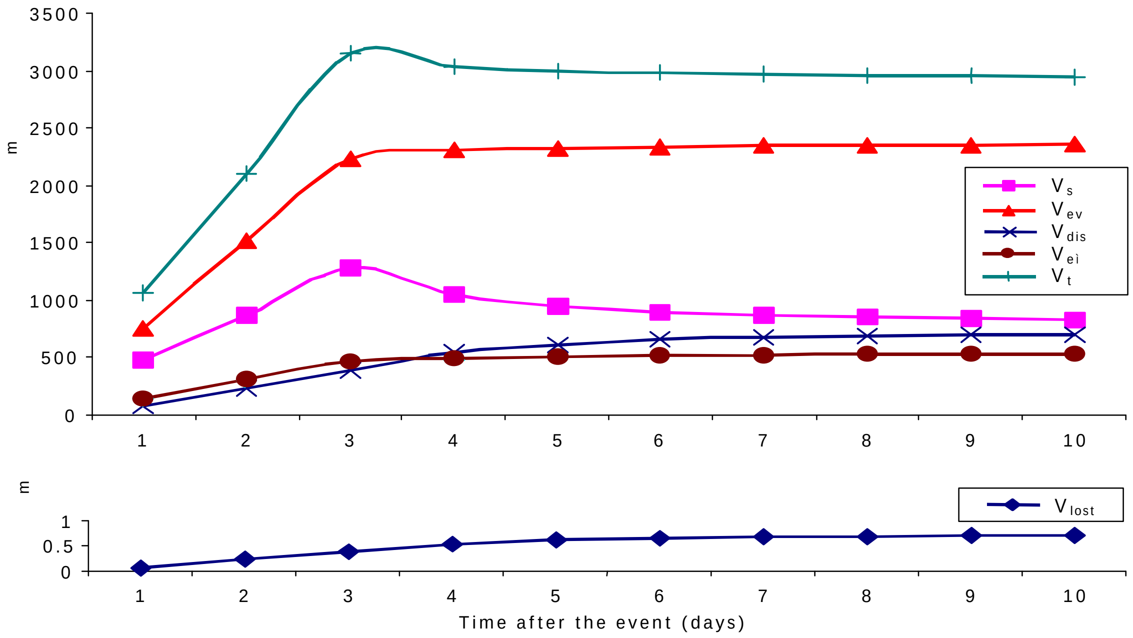

Fig. 5 Changing oil volumes 10 days after the event. Source is in the area of the Piltun-Astokhskoye oil field, Sakhalin shelf. Three days after the event, typical summer conditions: V_s is the oil volume on the sea surface, V_{ev} is the volume of the oil evaporated, V_{dis} is the dispersed oil volume, V_{em} is the emulsified oil volume, V_t is the total oil volume including water-in-oil emulsion, and V_{lost} is the oil volume lost in drops and other ways.

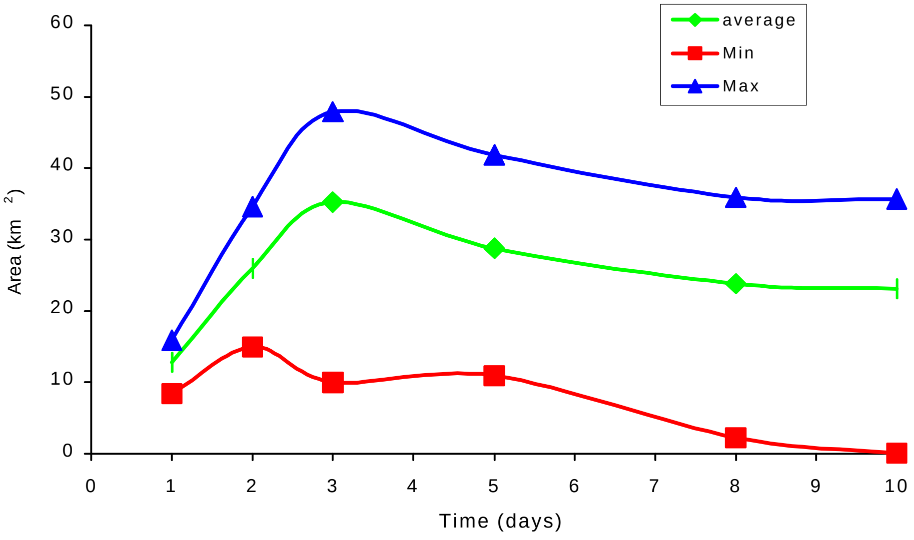

Fig. 6 Changing square area of an oil spill, ten-day evolution of the spill produced by the source located in the area of the Piltun-Astokhskoye oil field (3-day oil spill). Averaged, minimal, and maximal square areas were modeled for 18 ten-day summer scenarios.

Conclusions

1. The shelf of north-eastern Sakhalin is characterized by variable sea water dynamics: in summer oil films tend to migrate to the north, in autumn to the south, and in the area of Terpeniye Cape they mostly migrate to the south-east, south, and southwest.
2. Predominant hydrometeorological situations in the shelf area of northeastern Sakhalin for the sources are located closer to the shoreline (10–20 km) with conditions relatively equal for migration to the west and to the east both in summer and autumn, with distance from the shoreline (more than 20 km) where the eastward migration is better pronounced.
3. The probability of a spot spill migration to a shoreline within 10 days, for a source located 10–20 km away from a shoreline, is 35–55%, for a source located 20–30 km away from shore, it is 10–40%. The greatest probability of an oil spill reaching a shoreline in summer and autumn was observed on the third day.
4. In the worst hydrometeorological situations, the period during which an oil spill can reach a shoreline is estimated to be 8 h in summer and 11 h in autumn.
5. In accordance with oil characteristics, about 60% of the discharged oil will evaporate during the first several days; dispersion of oil into water for the modeled situations is not significant.

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