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Oil spill scenario modelling for Sakhalin shelf

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Abstract

Development of Sakhalin shelf for oil and gas brings about the danger of oil spills. The paper provides the technique of oil spill impact assesment used in modelling for four potentially endangered areas of Sakhalin shelf in 1995-1999. The methods and models consist of hydrometeorological environmental models, scenario preparation technique, trajectory models of oil spill transport, and models of physical-chemical processes in a film. Testing of modelling calculations is described. The examples of modelling results for one area are given. They include local transport diagrams, potential impact zones, shoreline impact probabilies and physical-chemical characteristics of oil.

1 Introduction

Operation of oil and gas on Sakhalin shelf is potentially dangerous by the accidents that may produce oil spills in risky zones. Those are appraisal wells drilled during the period of navigation, operation of shelf oil fields since 1999, oil terminals, oil shipments, and subsea pipelines (Fig. 1) [1].

The measures of oil spill risk minimization, as well as the contingency plans, must be developed for each potential source. They are based on the assessment of potential spill behavior that includes oil spill modelling over probabilistic scenarios. Modelling comprises such phases as: preparation of the initial information about potential spill sources and their technical characteristics, analysis and preparation of the initial hydrometeorological information for meteorological and oceanographic fields construction, development of hydrometeorological scenarios, modelling over the developed scenarios using

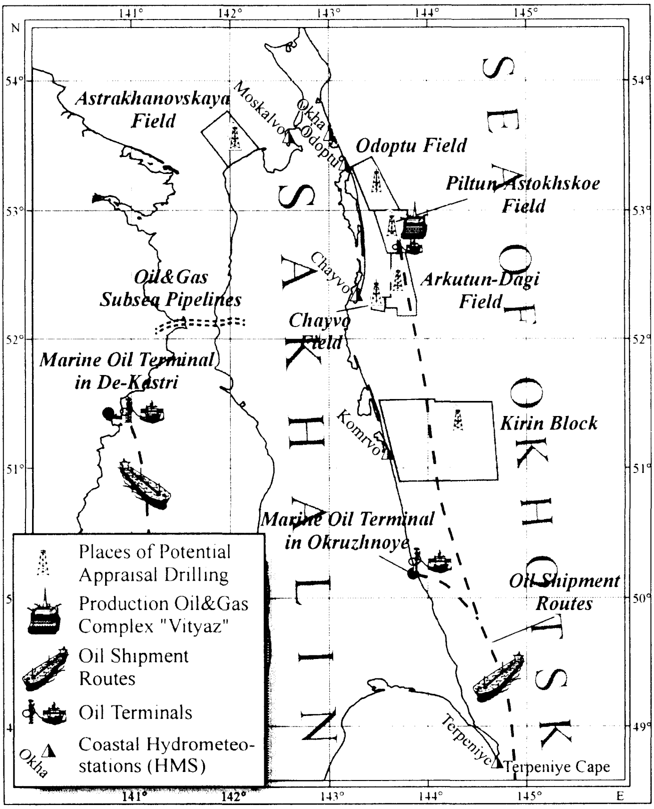

Figure 1: The scheme of potentially dangerous objects of Sakhalin shelf oil and gas operation and the major coastal hydrometeorological stations.

trajectory and physical-chemical models, and statistical processing of results. This approach is well illustrated by the modelling of potential summer and autumn oil spills on the Piltun-Astokhskoe oil field (PA) [2].

For the projects of Sakhalin shelf oil exploration in 1995-2000 FERHRI together with the experts from other organizations fulfilled oil spill modelling over the scenarios for four areas: PA, Kirin, Astrakhanovskaya, and an area near the Terpenye Cape (Fig. 1). The modelling applied various initial data, models, and methods [3].

Below given are generalized modelling results, description of the initial information, models and methods, tests of the models applied, and examples of the results.

2 Description of the initial information

The initial information used in oil spill modelling is subdivided into technical characteristics of potential oil spill sources, physical-chemical properties of oil hydrocarbons inclusive, and hydrometeorological data used to construct the environmental model over a set of calculated scenarios.

Technical characteristics of the potential oil spill sources were determined over the risk statistics of certain operations [4] or expert assessments. 1995-1997 modelling used oil composition over the fractions meeting the Russian State Standard (GOST) 11011-85. Starting from 1998 oil composition is subdivided into 8 classes of hydrocarbons: paraffin, cycloparaffin, aromatic, naphtenoaromatic, and residual [5].

The initial hydrometeorological data used in modelling include meteoconditions (wind and temperature are the most important), currents and hydrological conditions, and waves. The choice of data describing these or those environmental conditions depends on the tasks to be solved through modelling.

Meteorological fields were constructed using on-route data observed by vessels and rigs, and coastal hydrometeorological stations Komrvo, Chayvo, Odoptu, Okha, Terpeniye, and Moskalvo (Fig. 1) in 1960-1999. Statistical characteristics of the NorthEast Sakhalin meteorological regime, constructed on the basis of the above information are available in the paper of Dashko *et al.* [6].

Current schemes were constructed using two approaches. In the first case the probability characteristics of currents and corresponding wind were used for the assessment of oil spill behavior during the first hours in the local zone (within several tens kilometers away from the spill site). Synchronous instrumental observations of winds and currents were used. In the second case nontidal current fields were calculated for typical wind characteristics and hydrological conditions, tidal currents were calculated for the assumed moment of a spill. Hydrological characteristics of the region were constructed using the data stored at the FERHRI's Regional Center of Oceanographic Data observed in 1930-1998 [7]. The nontidal currents for typical meteofields were calculated over the three-dimensional diagnostic model of the Ekman type with approximations traditional for such models [8]. Current regime characteristics and fields received for the East Sakhalin shelf are described in the paper [9]. To verify the current model the series of instrumental observations were used. Tidal currents were calculated using the harmonic constants of main waves obtained from the instrumental data. Then the tidal current harmonics were interpolated into a spatial grid, with the results being tested over the hydrodynamic model [10].

3 Methods and models

3.1 Technique of local transport diagram construction

Statistical characteristics of oil transport velocity and direction at a potential spill site are analyzed by means of local transport diagrams or transport probability tables [3]. The series of synchronous instrumental current and wind observations or the tables of current and wind frequency of occurence are used as the initial information.

Oil spill transport vector ($\vec{\tilde{V}}^{i,j}$) is determined for each wind/current combination over the following formula:

$$\begin{aligned} \vec{\tilde{V}}^{i,j} &= \vec{\tilde{V}}^{i,j}\{\tilde{V}_x^{i,j};\tilde{V}_y^{i,j}\}, \\ \tilde{V}_x^{i,j} &= V_x^{k,l} + kW_x^{m,n}, \\ \tilde{V}_y^{i,j} &= V_y^{k,l} + kW_y^{m,n}. \end{aligned} \tag{1}$$

Where: $V_x^{k,l}, V_y^{k,l}$ - zonal and meridional projections of surface current velocities from the current frequency of occurence table with *KxL* dimensions; $W_x^{m,n}, W_y^{m,n}$ - projections of wind velocities from the wind frequency of occurence table with *MxN* dimensions; *k* - wind drift coefficient.

When synchronous instrumental data series are used the local transport probability tables is constructed over transport vectors for each concrete period of observation, eqns (1). When the current frequency of occurence tables are used the values of vector transport probability with the given gradation of dimensions *IxJ* is determined as the product of multiplied wind and current probabilities for each combination, with eqns (1) being taken into account.

$$\begin{aligned} \tilde{P}_{i,j}[v_i - v_{i-1};\varphi_j - \varphi_{j-1}] &= \sum_{k,l,m,n=1}^{K,L,M,N} P_{k,l}P_{m,n}Y(\vec{\tilde{V}}^{i,j}), \\ Y(\vec{\tilde{V}}^{i,j}) &= \begin{cases} 1, \Rightarrow v_{j-1} \le \left|\vec{\tilde{V}}^{i,j}\right| < v_j,\ u\ \ \varphi_{j-1} \le \angle\vec{\tilde{V}}^{i,j} < \varphi_j \\ \hline 0, \Rightarrow \mathit{other\ cases} \end{cases}. \end{aligned} \tag{2}$$

Where: *P* - probability values from the corresponding frequency of occurence tables; v_i, φ_j - gradations of velocity and direction from the table of oil spill transport probability, from line *i* and column *j* correspondingly .

3.2 Construction of hydrometeorological scenarios

The term "hydrometeorological scenario" defines a set of typical hydrometeorological situations, successively replacing one another during the modelled period. Typical hydrometeorological situations define a set of the averaged interrelated meteorological and hydrological fields characterized by statistically significant frequencies of occurence, duration, and probability of transition from one type into another. These interrelated fields are the averaged wind fields characterized by a certain probability of ocurrence and corresponding to them current and wave fields , as well as atmospheric and surface seawater temperatures.

Durable hydrometeorological scenarios must be representative and observing statistical dependencies of real hydrometeorological parameters. Representativeness is achieved by sufficient amount of scenarios that realistically describe spatial tendencies of oil spill transport. Statistical dependencies of the developed scenarios are required to correspond to real conditions, that means to observe frequency of occurence characteristics of transport direction and velocity, statistics of meteosituation duration, and probabilistic coefficients of the transit between meteosituations [2,11].

Detailed technique of hydrometeorological scenario construction includes:

- construction of the meteosituation frequency of occurence table using the database of meteo observations;
- determination of typical meteosituations;
- calculation of near-water wind fields corresponding to the chosen meteosituations;
- calculation of duration criteria for the chosen meteosituations and distribution of meteosituations over time intervals;
- construction of probabilistic matrix of meteosituation transition;
- calculation of tidal currents over harmonic constants;
- approximate calculation of wind wave amplitudes at the grid nodes;
- construction of typical fields of density, boundary conditions and wind fields necessary for realization of hydrodynamic model of nontidal currents;
- calculation of nontidal current fields for the whole set of the typical hydrometeorological situations;
- optimized selection of situations to fill the time interval of multi-day scenarios with conservation of meteosituation frequency of occurence and duration statistics and transition probability coefficients;
- construction of multi-day scenarios from the selected situations with optimization of scenarios over probability criteria;
- accounting of the delay effect on the current and wind fields due to changed meteosituation and smoothing of transits between situations.

3.3 Oil spill transport and physical-chemical models

The model calculating the environmental spill-impacted parameters consists of two blocks [2]. Trajectory model describes oil spill drift under the given hydrometeorological situations, it includes the methods of spill square area calculation. Physical-chemical model describes the within-spill processes, evaporation, dispersion, emulsification, loss in drops, etc.

Trajectory model represents an oil spill as a number of oil slicks, each spreading independently. An oil slick consists of a finite number of markers representing the shape and oil distribution within a slick. The below equations describe the trajectories of markers conditioned by the determinate (currents, wind, spreading mechanisms) and stochastic (turbulent pulsation) processes:

$$\frac{dx_i}{dt} = u(x_i, y_i, t) + u'(x_i, y_i, t) + kw_u(x_i, y_i, t) + f_u(x_i, y_i, t),$$
$$\frac{dy_i}{dt} = v(x_i, y_i, t) + v'(x_i, y_i, t) + kw_v(x_i, y_i, t) + f_v(x_i, y_i, t). \tag{3}$$

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Where: x_i , y_i - coordinates of i marker; u, v - liquid velocity components (currents); u', v' - components of turbulent pulsation rate; w_u, w_v - zonal and meridional components of near-water wind; k - wind drift coefficient ranging from 0.015 to 0.04 and depending on the wind effect upon surface currents; f_u, f_v - rate components of oil spill spreading.

Thus, the motion of markers in eqns (3) accounts 4 mechanisms of oil spill spreading. Rate component f contains the first three spreading phases, inertia, gravitation, and surface tension, described in accordance with [12]. The fourth diffusion phase is described by u', v' rates of turbulent pulsations using the "Monte-Carlo" method and spatial-temporal scales of turbulence, according to [13].

Initial conditions set up the coordinates of oil spill markers and corresponding time of release. Each series of markers released by a source has the "main" marker. Migration equation contains no stochastic members for the "main" marker. An oil spill, according to mechanisms of [12,13], spreads around this "main" marker. The square area covered by an oil spill is numerically calculated. Calculation accounts distribution of the field of markers, with the required film thickness of 0.1 μm, not less, being critically observed.

For the first time the physical-chemical model was described in [14]. Practical results of calculations are stated in [2]. To calculate physical-chemical processes in a spill the oil composition is divided into several classes or individual compounds [5]. To calculate evaporation the film is assumed well mixed, evaporation from a square area unit proportional to the average pressure of vapor in an individual compound at the temperature of film being equal to the temperature of underlying water. Evaporation is also assumed inhibited in course of formation of water-in-oil emulsion, with evaporation rate being proportional to nonemulsified oil in the total oil volume and dependent upon an oil slick square area. The rate of water-in-oil emulsification is assumed proportional to the wind effect (wave height) and oil volume on the sea surface. The rate of oil dispersion into water is proportional to the wave height and volume of nonemulsified oil on the sea surface.

In general the results of modelling are represented by the following balance relations:

$$\begin{aligned} V_s(t) &= V_0 - V_{ev}(t) - V_{dis}(t) - V_{lost}(t), \\ V_w(t) &= c_{wo} V_{em}(t), \\ V_t(t) &= V_s(t) + V_w(t). \end{aligned} \tag{4}$$

Where: $V_s(t)$ - oil volume on the sea surface t time after the spill event; V_0 - total volume of the oil spilt; $V_{ev}(t)$ - evaporated oil; $V_{dis}(t)$ - dispersion of oil into water; $V_{lost}(t)$ - oil losses caused by different factors (loss in drops, oil reached the shoreline, collected oil, etc.); $V_w(t)$ - water volume in the water-in-oil emulsion; c_{wo} - water-in-oil emulsification coefficient; $V_{em}(t)$ - oil volume in water-in-oil emulsion; $V_t(t)$ - total volume of oil and emulsion.

4 Testing of models

Sustaining of statistic dependencies in the scenarial nontidal fields at the sites supported by instrumental observations was the main method used for nontidal current model verification. The ensemble of nontidal current fields is represented as a set of typical "summer" or "autumn" situations for the period of 2400 hours accounting statistic characteristics of corresponding wind fields. The constructed data series were added with calculated tidal currents. For the summary data series the probability characteristics of surface velocity and direction were constructed. Analogous probability characteristics were determined over instrumental data series. Instrumental data series were subdivided into two periods, "summer" - before 15 September, and "autumn" - after 15 September, and united into test data series. Comparative analysis revealed good correlation, especially for autumn characterized by more stable currents, *e.g.* see [11].

To verify the tidal current fields they were also compared with the existing instrumental observations. The calculated data series of tidal currents revealed high correlation with the observed ones (0.95-0.98).

To test the scenario construction technique, as well as statistic significance of scenarios, comparison with real characteristics of winds velocity and direction, duration of meteosituations, and transit probability coefficients was carried out. The requirement to sustain statistic characteristics defined the amount of scenarios for modelling.

Trajectory model was tested over the observed local spills. Comparison of the calculated and observed trajectories of the oil spill (2 barrels) occurred in autumn 1999 is shown in Fig. 2. The observed trajectory was constructed using the

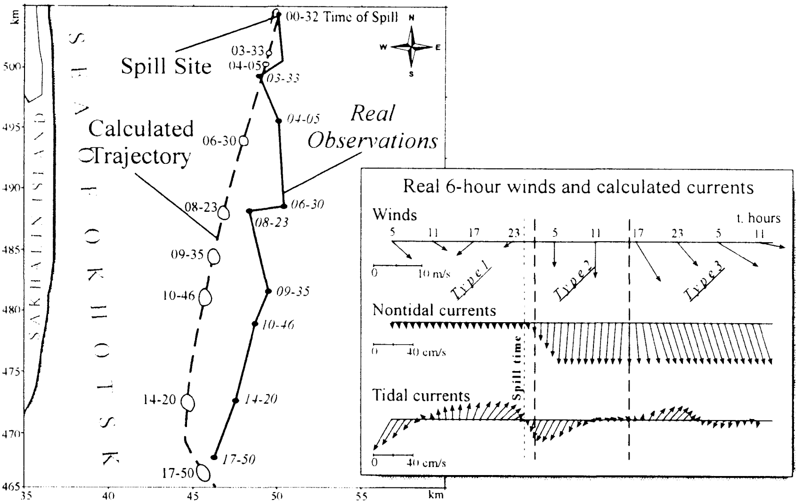

Figure 2: Calculated and observed trajectories of the real 2 barrels oil spill in the northeast area of Sakhalin shelf. Incut shows real wind vectors and calculated nontidal and tidal current vectors used in test modelling.

ship-and-helicopter collected data. The calculated trajectory is based on the wind data series with 6-hour discretion typified into three types (Fig. 2, incut). Nontidal current fields were calculated for typical wind situations and tidal currents were calculated over the period of spill observation (Fig. 2, incut). Local time shown on trajectories indicates the spill at the moments it was observed from ships and a helicopter. Comparison revealed high precision of model calculations using very limited hydrometeorological information.

Correctness of the physical-chemical model of oil spill behavior was confirmed by the real data observed during the full-scale field experiment with the oil spilt on the Sakhalin shelf [15]. Calculation technique of chemical processes in oil was also tested by comparison with the real data [16]. Test calculations revealed good comparability of models over such parameters as density, viscosity, evaporation, and water content in the water-in-oil emulsion.

5 Modelling results and discussion

Modelling of oil spill scenarios was carried out for 4 areas of Sakhalin shelf. The below calculation results describe the most developing Piltun-Astokhskoe oil field (Fig.1).

Navigation period of intensive drilling in this area lasts from late June to late October. Analysis of hydrometeorological data revealed for this period two characteristic types of weather conditions, "summer" - July, August, and first half of September, and "autumn" - second part of September, October. Characteristics of potential oil spill zones 1 and 3 days after the spill event constructed using the summary analyses of 1152 trajectories of calculated hydrometeoscenarios for point sources and the local transport diagrams constructed are shown in Fig. 3 for two types of hydrometeorological regime.

In this area the relatively weak southern and southeastern winds are predominant in "summer". The most probable direction of oil film migration is slightly northward, however, south-directed drift is also possible. The diagram shown in Fig. 3a demonstrates that at the potential spill site the most statistically probable is the northward drift with 40-80 cm/sec velocity. In ten-day hydrometeoscenarios an oil spill may migrate over 200 km to the north and 150 km to the south from the spill site. In "autumn" winds intensify and change for the northwestern. This results in intensification of surface water transport to the south. Correspondingly oil films start drifting south- and southeastward. As follows from the local transport diagram shown in Fig. 3b, initial transport of oil spills to the southeast makes 40-80 cm/sec and over 100 cm/sec to the south. Ten-day hydrometeoscenarios may make south- and southeast drift of oil spill to about 400-500 km.

Among the most dangerous impacts oil spills may produce is shoreline contamination. Probability of such impacts and length of the impacted zones are individual for each source. It depends on source position, distance from a shoreline, and hydrometeorological conditions during the spill life-peroid. The situation when a calculated marker enters the depth less than 1.5 m, that is the inshore zone, is considered as a shoreline contamination.

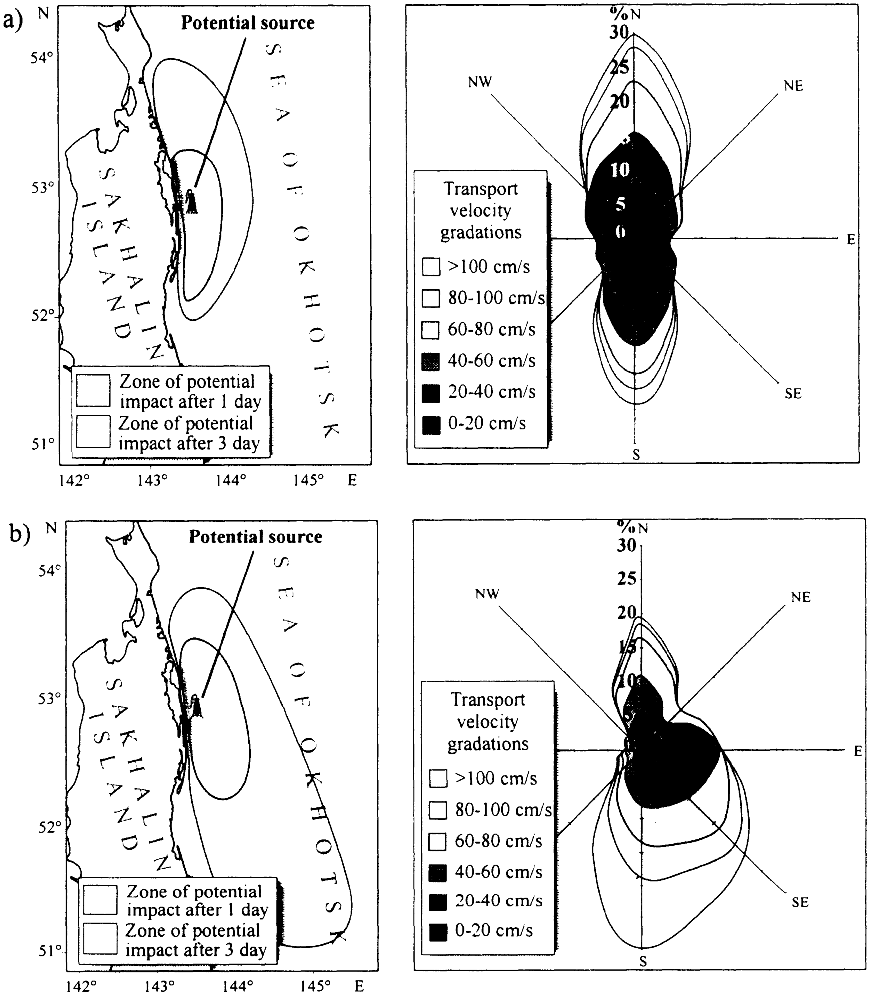

Figure 3: Zones of potential oil spill impact for 1 and 3 days for a potential source in the PA field and local transport diagrams at the site of a spill for a) "summer", and b) "autumn" hydrometeorological conditions.

Fig. 4 shows percent characteristics of shoreline contamination as functions of time after the spill event and distribution of oil contamination probability along the shoreline 3, 6, and 10 days after the spill event. Characteristics of shoreline contamination (Fig. 4) were constructed using the results of point source spill modelling over 1152 scenarios for both seasons. Fig. 4 shows that the probability of a shoreline impact in "summer" is more than twice higher than the one in "autumn". The obtained results are well comparable with the averaged probabilities of a shoreline impact calculated for various sources on Sakhalin shelf (34% for "summer" and 27% for "autumn" correspondingly) [3].

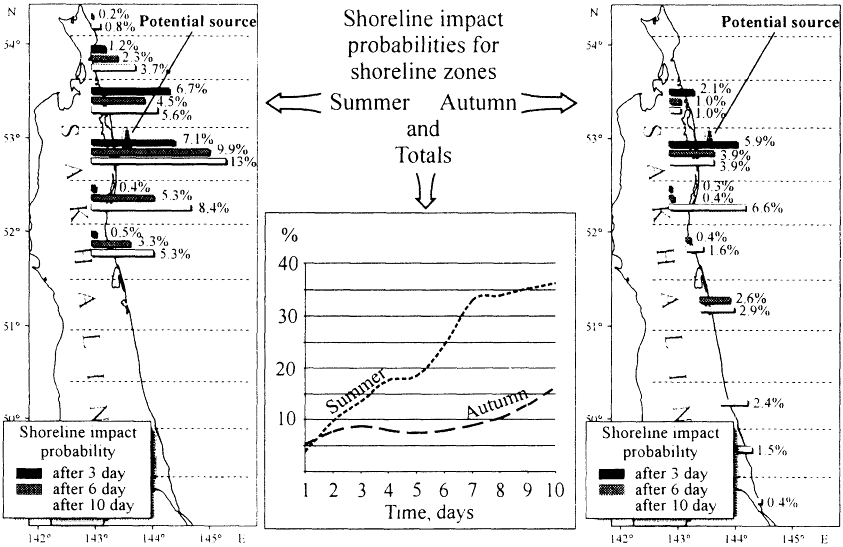

Figure 4: Probability characteristics of a shoreline impact and their along-shoreline distribution for "summer" and "autumn" hydro-meteorological conditions.

The modelling results show that oil evaporation, dispersion into water, and emulsification depend on oil composition, with process intensity being conditioned by hydrometeorological parameters. Fig. 5 demonstrates the characteristics of physical-chemical processes taking place in a summer 30-minute spill of 20 m^3 of light oil. When oil interacts with marine environment its composition (Fig. 5a), as well as physical characteristics, such as density, viscosity, and surface tension, change. Characteristics of phase composition of oil (volume of oil on the sea surface, evaporation, emulsification, dispersion, and loss in drops) are shown in Fig. 5b. During the first 10 hours after the event oil is spreading over the sea surface with accompanied increase of oil density and viscosity and complete loss of light hydrocarbons. Due to evaporation during the first hours the volume of oil on the sea surface decreased approximately by 60%, while the total volume of water-in-oil emulsion increased up to 27-35 m^3.

The full-scale field experiment [15], as well as calculation results showed that most changing of oil composition and characteristics occurred during the first hours. The oil of Sakhalin shelf contains 40-70% of light oil hydrocarbons (up to C_{12}). Nearly all of them evaporate during the first hours. Thus, the consequent oil characteristics depend mostly on the formation of water-in-oil emulsion accompanied by increasing oil density and viscosity.

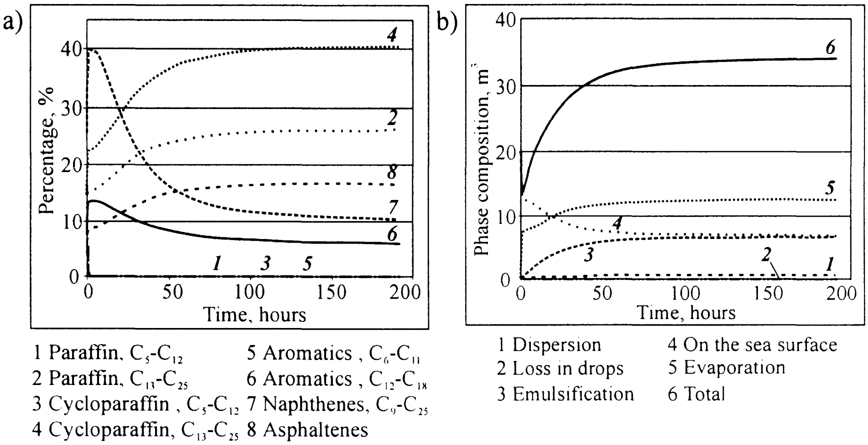

Figure 5: Calculated characteristics of a carbon class percentage and phase composition of the summer 20 m^3 and 30-minute oil spill (averaged over the scenarios causing no shoreline impact).

6 Conclusions

The described results demonstrate the possibilities of engineering modelling over scenarios for the purpose of practical analysis of oil spill transport characteristics and impact assessment the sea and shoreline areas of Sakhalin suffered under various hydrometeorological conditions. The calculated characteristics of the impacted area, oil balance in a spill, and its physical properties can be used in contingency planning. Further development of the described models and methods depends on realization of additional verification experiments and development of the methods to forecast oil spill drift trajectories in the real time.

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