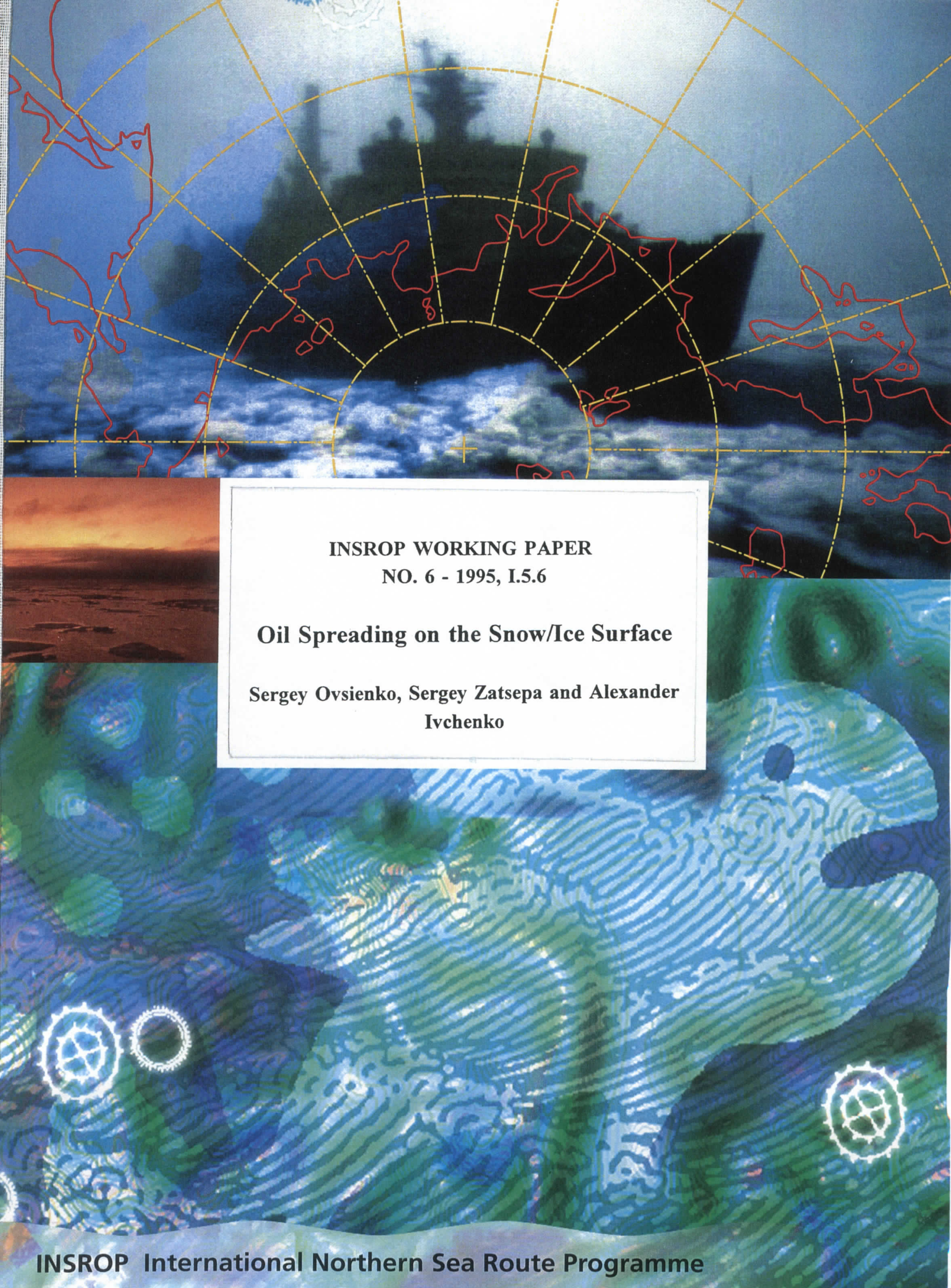

INSROP WORKING PAPER
NO. 6 - 1995, I.5.6

Oil Spreading on the Snow/Ice Surface

Sergey Ovsienko, Sergey Zatsepa and Alexander Ivchenko

INSROP International Northern Sea Route Programme

Central Marine Research & Design Institute, Russia

The Fridtjof Nansen Institute, Norway

Ship and Ocean Foundation, Japan

International Northern Sea Route Programme (INSROP)

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Title: Oil Spreading on the Snow/Ice Surface

Sub-programme I: Natural Conditions and Ice Navigation

Project I.5.6: Pilot Study of Behaviour and Spreading of Oil in Ice

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INSROP is split into four main projects: 1) Natural Conditions and Ice Navigation; 2) Environmental Factors; 3) Trade and Commercial Shipping Aspects of the NSR; and 4) Political, Legal and Strategic Factors. The aim of INSROP is to build up a knowledge base adequate to provide a foundation for long-term planning and decision-making by state agencies as well as private companies etc., for purposes of promoting rational decisionmaking concerning the use of the Northern Sea Route for transit and regional development.

INSROP is a direct result of the normalization of the international situation and the Murmansk initiatives of the former Soviet Union in 1987, when the readiness of the USSR to open the NSR for international shipping was officially declared. The Murmansk Initiatives enabled the continuation, expansion and intensification of traditional collaboration between the states in the Arctic, including safety and efficiency of shipping. Russia, being the successor state to the USSR, supports the Murmansk Initiatives. The initiatives stimulated contact and cooperation between CNIIMF and FNI in 1988 and resulted in a pilot study of the NSR in 1991. In 1992 SOF entered INSROP as a third partner on an equal basis with CNIIMF and FNI.

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Oil spreading on the snow/ice surface.

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Abstract

This paper describes oil spreading on ice or snow surface. Description of the physical basis, mathematical formalization and original numerical technique for oil spreading simulation is represented. Shallow-water-like equations for viscous liquid are used for oil spill spreading on the ice or snow surface. Oil penetration into ice or snow is reduced to a one-dimensional process equation. The boundary of oiled area is considered to be unknown, and is determined in the process of solution. The particles-in-cell technique on quasi-Eulerian adaptive grids is used. The numerical solution results are compared with known analytical solutions. The question of the model tuning is discussed.

Introduction

The study of oil spill behavior in sea ice is made as a logical continuation of the oil spill spreading investigations carried out over the last few years. During this period, the Oil Spill Accident forecasting system (OSA) has been developed. The main part of the system describes the oil spill spreading and transport on a water surface. It is possible to use a similar numerical technique for modeling of oil spreading on and under the ice or snow cover.

Traditionally oil spreading is described by self-similarity solutions, and elements of filtration theory are used for oil penetration into ice or snow. Other processes, such as evaporation, weathering, etc. are usually described by semi-empirical parametrizations.

A modern computational model use can help us understand the main features of the process. An understandable physical basis is used to formalize the mathematical task in the main processes description. Such approach can be proposed as a complement to experimental studies, as well as for experiments planning and practical forecasting purposes.

Model description

Behavior of oil in ice conditions depends on the physical properties of oil and ice as well as hydro-meteorological conditions. The basic processes, traditionally under consideration, are oil spreading on the smooth or rough ice surface, oil penetration into substratum media, oil evaporation, physical and chemical properties transformation.

The processes mentioned above have varying physical properties, various time and spatial scales and, therefore, different possibilities for modeling. The balance of the gravity force with inertia and viscous tension forces is traditionally used in various simple analytic solutions of the spreading process. Such approximations lead to estimate of the oil slick radius as a function of time about order of magnitude.

Advanced numerical technique can be employed to investigate the spreading phenomena in detail and analyze the role of separate processes and parameters.

The first assumption in the mathematical formulation of the spreading process is (*I*) that thickness **H** of spreading liquid is much less than horizontal process scale **B**, and their ratio $\varepsilon \equiv \mathbf{H/B} \ll 1$ may be chosen as an expansion procedure parameter to simplify the original Navier-Stokes equations used for viscous liquid currents description. The next useful simplification, which follows from the first one, is (*II*) that surface tension effects are negligible because of the small surface curvature. Also we assume that (*III*) the local surface effects at the point of three media contact (oil-ice-air) are negligible.

We will limit ourselves to the case when oil penetration into ice or snow obeys Darcy's law.

Assumptions (I)-(III) allow the description of the oil spreading on ice or snow surface by a two-dimensional system of equations. The complete expansion procedure for these equations is quite traditional and therefore can be omitted there.

Thus the governing equations for oil spreading in two-dimensional area $\Omega(t,\mathbf{x})$, $\mathbf{x}=(x,y)$ are as follows :

$$\mathbf{U}_t+\mathbf{U}\nabla\mathbf{U}=-g\nabla H-3\nu\mathbf{U}/H^2 \qquad (1)$$

Ω:

$$H_t+\nabla.(H\mathbf{U})=-(k_e+k_f-Q)/\rho \qquad (2)$$

where

ρ - oil density,

U - oil velocity,

H - oil thickness,

ν - oil kinematic viscosity,

k_e - mass flux due to evaporation,

k_f - mass flux due to filtration;

Q - oil flux at the ice surface from spill source,

$\nabla.$ - horizontal divergence operator,

∇ - horizontal gradient operator.

If the boundary of $\Omega(t,x,y)$ is $L(t,x,y)$ and $L=L_1(t,x,y)\cup L_2(x,y)$, where L_1 is a free boundary and L_2 is contact (solid) boundary, it is necessary to use the following boundary conditions:

$$L_1: \quad \mathbf{R}_t+\mathbf{U}\nabla\mathbf{R}-1/\rho(k_e+k_f)(|\nabla H|\nabla\mathbf{R}/(\nabla H\nabla\mathbf{R}))=0 \quad (3)$$

(kinematic condition),

where $R(t,x,y)=0$ is the equation of free boundary;

and

$$L_1: \quad H=0 \quad (4)$$

(dynamic condition)

The first two terms of equation (3) describe the movement of free boundary due to movement of liquid particles inside the boundary. The last term describes the movement of free boundary due to evaporation and filtration processes.

At fixed (contact) boundary L_2 (if any) must be

$$L_2: \quad U_n=0 \tag{5}$$

where U_n is normal to L_2 component of **U**.

The system (1)-(5) must be combined with the following initial conditions:

$\Omega(x,y,0)=\Omega_O(x,y)$;

$$H(x,y,0)=H_O(x,y),\ \mathbf{U}(x,y,0)=0,\quad x,y \in \Omega_O, \tag{6}$$

where Ω_O - area covered by oil at t=0.

It is necessary to determine H,**U**,Ω for $t \geq 0$.

The system (1)-(6) is open because of unknown mass fluxes due to evaporation and filtration processes.

The filtration flux depends on spreading process in $\Omega(t,x,y)$ and filtration process in $\Omega_f(t,x,y,z)$, where Ω_f is a volume with boundary $L^F_1 \cup L^F_2$ by oil in ice or snow. While $\Omega(t,x,y)$ exists, $\Omega(t,x,y) \equiv \Omega_f(t,x,y,0)$. Here L^F_1 is free boundary of filtration area , L^F_2 is surface of ice or snow.

For slow, laminar Darcy's filtration in Ω_f, the following equations for homogeneous media can be written as:

$$-1/\rho \nabla P + \mathbf{X} - \mathbf{X}_R = 0 \tag{7}$$

Ω_f:

$$\nabla . \mathbf{u}_f = 0 \tag{8}$$

where for resistance force $\mathbf{X}_R$ hypothesis of Jukovski

$$\mathbf{X}_R = \mu \mathbf{u}_f / k_p \rho \tag{9}$$

can be used. Here k_p is ice, snow permeability;

X=(0,0,*g*) is a gravitational force.

From equation (8) equation (7) can be written as

$$\Omega_f: \quad \Delta P = 0 \tag{10}$$

with boundary conditions

$L^F{}_1$: $\mathbf{R}_t + u_f \nabla \mathbf{R} = 0$ (11)

$P = 0$ (12)

and

$L^F{}_2$: $P = \rho g h$ (13)

where h is the thickness of oil on ice or snow surface.

When the vertical scale of filtration h_F is sufficiently less than the horizontal length scale B_F ($h_F/B_F \ll 1$), it is possible to neglect the horizontal derivatives in first approximation and from equation (10) we obtain

$$P = \alpha_1 z + \alpha_2 \quad (14)$$

where α_1 and α_2 are determined from boundary conditions (12) and (13) at $z=0$ and $z=h_F$; where h_F is the depth of filtration. In this situation

$$u_F = (1 + h/h_F)\rho g k_p/\mu \quad (15)$$

and velocity of the boundary movement

$$\partial h_F/\partial t = u_F/E \quad (16)$$

where E is ice or snow porosity.

Mass flux due to evaporation may be represented as:

$$k_e = k\,(P_{ai} - P_i)/R_o T \quad (17)$$

where k is empirical coefficient, P_i is partial pressure of i-th fraction in oil mixture, P_{ai} is vapor pressure of i-th fraction in atmosphere, R_o is universal gas constant, T is snow, ice surface temperature.

Empirical coefficient may be chosen from a modified Mackay's relationship [Mackay et al., 1973]:

$$k = 0.005 \times (\mathbf{W}_{10})^{0.78}, \quad \text{if } \mathbf{W}_{10} > 0.5\text{m/s} \quad (18)$$

$$k = 0.005 \quad \text{if } \mathbf{W}_{10} < 0.5\text{m/s}$$

An additional parametrization is required for specific permeability of snow. We can take it, for example, from report prepared by Belore R.C. et al.(1988) with reference to Shimuzu (1969) as

$$k_p=7.7\times10^{-2} d_o \exp(-7.8\rho_s/\rho_i) \qquad (19)$$

where d_o is mean grain size of snow.

Parametrization (17) describes the fractional composition of oil mixture and its time variation and, therefore, oil density time variation. Unfortunately, oil viscosity variability due to fractional composition is not a simple question. There is no problem including temperature dependence of oil viscosity in equations (1) and (15), but we are uncertain about its concrete type, and we do not have enough experimental data to draw any conclusion about it.

For situations where snow properties are unknown the permeability can be estimated to within factor 2 by using $d_o = 0.5$ mm and $\rho_s = 400$ kg/m^3. It yields $k_p = 6\times10^{-10}$ m^2.

Numerical realization.

One of the most difficult problems in solving the system of equations (1)-(2) with additional conditions (15)- (17) and boundary conditions (3)-(5), is that the area where solution must be determined is unknown and must be calculated during the modeling process. A traditional Eulerian grid method use is inconvenient here , and it is preferable to work with a Eulerian-Lagrangian technique. Usually the similar method of calculation is called particles-in-cells technique (PIC), but in fact the technique described here differs from the original one developed by Harlow (1964) in many aspects. One of the features of this technology is the use of two types of media representation - Lagrangian and Eulerian.

The object of modeling (oil) may be represented as a set of particles with several inherent parameters, such as space coordinates (z_i), velocity (v_i) and mass (m_i). The initial situation is determined as:

$$\{x_i\}=\{x_i(x,y,0)\}\ ,\ \{v_i\}=\{v_i(x,y,0)\}\ ,\ \{m_i\}=\{m_i\}\quad ;\ \{x_i\}\in\Omega_o\ ; \qquad (20)$$

where Ω_0 - initial configuration of oil spill. The number of particles must be sufficient to describe the boundary of area Ω_0 and later $\Omega(t)$.

If coordinates of the particles are known, we superpose rectangular Eulerian grid on particles configuration in such way that it contains all particles. Then we can determine process characteristics U(x,y,t) and H(x,y,t) in grid representation . The most convenient grid type for equations (1)-(2) is shown on Fig.1.

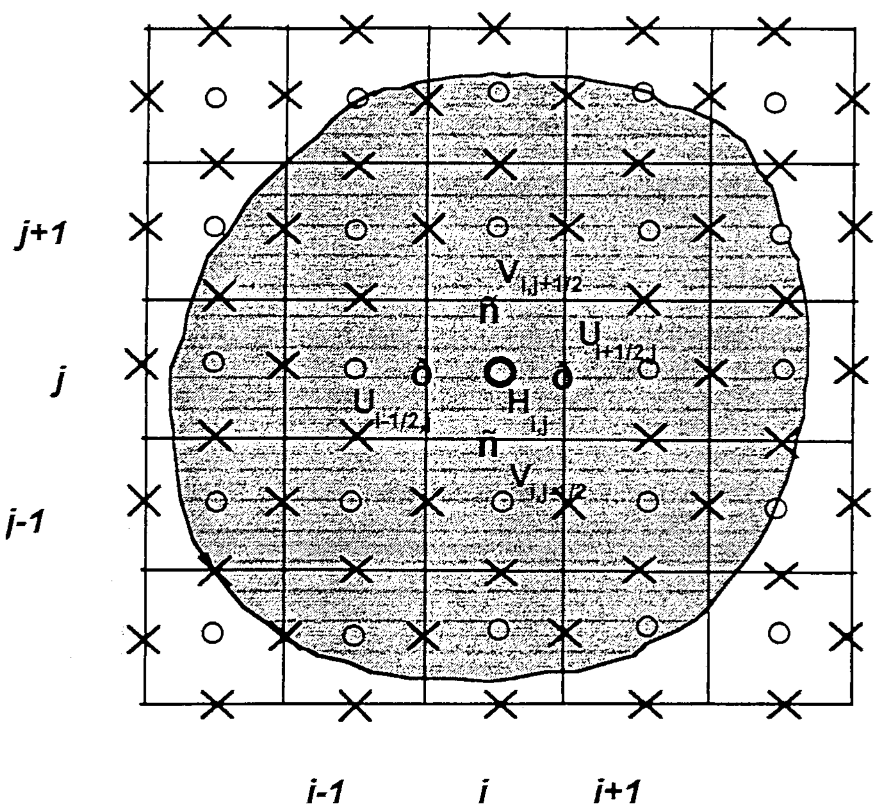

Figure 1. Eulerian grid pattern on successive time step.

The grid which is used in this technology is not quite Eulerian, because it is necessary to rebuild it at each time step. In traditional representation a Eulerian grid is defined by fixed spatial points, but here these "fixed" points are changeable. Nevertheless we will call it a "Eulerian grid" for simplicity. As soon as the Eulerian grid has been constructed, we can transport all properties of the media from particles to grid, and the values of H(x,y,t) and U(x,y,t) as grid's functions will be determined at fixed space points.

$$H_{ij}=\sum_{k=1}^{Nij} m_k/(g\rho_0\Delta x\Delta y) \qquad (21)$$

where g is the part of cell area "covered" by particles, m - mass of k-th particle, N_{ij} - number of particles in (i,j)-th cell, Δx, Δy - mesh width for x and y. Value of velocity U on the grid is the mean over the particles in some area around (i,j) -point. The procedure of reconstruction for U is a root-mean-square linear regression . After all values of grid functions (H ,U) have been determined , the subsequent numerical procedure may be split into the following three steps:

I. Calculation of intermediate values of U and H by the equations:

$$U_t=-g\nabla H-3\nu U/H^2 \qquad (1')$$

$$H_t=0 \qquad (2')$$

where all effects, connected with movement of media are neglected . At this stage all necessary characteristics of media are described in Eulerian representation.

II. Interpolation of U from grid to particles. New values of the mass of particles are calculated in accordance with the following relationship:

$$m_i(t+\Delta t)=m_i(t)+\Delta t(k_e+k_f)S_p, \qquad (22)$$

where S_p - area of individual particle. This parameter does not have a physical signification, but it is a suitable computational variable. At the end of this step media characteristics may be described in Lagrangian representation completely.

III. Transport all particle's properties with particles and new values of H and U to satisfy of the basic conservation laws for mass and momentum for every cell of the new Eulerian grid.

Step III represents the approximation of transport part of equations (1) ,(2):

$$U_t+U\nabla U=0 \qquad (1'')$$

$$H_t+\nabla.(HU)=0 \qquad (2'')$$

and equations (15)- (17). At the end of this step media characteristics are transmitted from Lagrangian representation back to the Eulerian one.

One of the chief new procedures in PIC technology is the use a root-mean- square linear regression in velocity value reconstruction from particles to the points of the Eulerian grid. Special analysis of this procedure, which may be realized accurately for one dimensional equations, shows that numerical viscosity in this case depends on velocity derivatives and may be estimated by the expression

$$\nu_n \sim [(\Delta x U_{xx})/(U_x)^2] \times [F(C)/C] \times U\Delta x, \qquad (23)$$

where $C \equiv U\Delta t/\Delta x$ - Courant number, $F(C)$ - limited function and $F(C)/C \rightarrow 0$ if $C \rightarrow 0$, U_x ,U_{xx} - first and second spatial derivatives . This relationship differs from the traditional expression for numerical viscosity

$$\nu_n \sim \Delta x U(1-C)/2$$

Numerical experiments revealed a small value of numerical viscosity given by expression (23) and justified for a special type of two-dimensional currents and for the particular cases of spreading process.

Numerical experiments

It seems reasonable to take for the first step of numerical modeling a spreading of the fixed volume **V** of hypothetical oil on smooth snow surface. In the case of axisymmetric current, a self-similarity solution [Huppert E.H.,1982] and corresponded experimental data [Didden.N.,et al, 1982] exist, so we can test our numerical model using these results, for the case when mass fluxes due to filtration or evaporation are absent.

The numerical solutions at Figures 2-5 represent a radius of spilled oil versus a time in logarithmic scale and illustrate spreading of the given volume of oil ($1m^3$) with varying viscosity, initial radiuses and snow permeability . The solid line representing the corresponding analytical solution is

$$R(t)=0.894(g\Omega/3\nu)^{1/8}\, t^{1/8} \qquad (25)$$

The close agreement between numerical modeling curves and analytical solution at large times confirms the applicability of the proposed numerical technology. It is no wonder the difference between the first stage of flow curves corresponded to numerical and analytical solutions , since this stage of the spreading process is controlled by balance between gravity and inertia forces. For this regime the well-known self-similarity solution also exists, where $R(t) \sim t^{1/2}$ for axisymmetric case. Also we must keep in the mind that relationship (25) was obtained by assuming that the dimensionless Froude number $\mathbf{Fr} \ll 1$.

Self-similarity solutions are very useful if we want to understand the physics of separate regimes of motion, since they allow us to systematize results of many experiments when a dimensionless number of similarity have been constructed. Often self-similarity solutions are available only for one-dimensional or axisymmetrical cases, idealized initial spatial thickness distribution and spill source function. Different curves on Figure 2 show the influence of initial radius of spilled oil. It is clear that self-similarity solution describes radius as a time function well only at the last stage of motion. Also these simple experiments show that traditionally used relationship for "transition time" between gravity-inertia and gravity-viscous regime $\{t=(\mathbf{V}/g\nu)^{1/3}\}$ have a limited area of application. For the cases on Fig.2 this value is about 1-9 sec but we can see that the self-similarity solution is applicable after a period of about 20 sec.

The influence of oil viscosity on the spreading process is represented by Fig.3. All cases start from equal initial radius. Filtration also is absent in all cases. It is evident that disagreement between analytical and numerical solutions increases with lessening viscosity, when the initial spreading is more intensive.

The results of spreading simulations for different oil viscosity in the presence of filtration with constant permeability are shown on Fig.4. Time of spreading (up to full filtration) varies from 30 sec for viscosity 0.02 up to 50 min for viscosity 2.0.

Fig.5 represents the influence of snow permeability on the process of spreading. The permeability coefficient varies with the order of magnitude. For comparison, the self-similarity and numerical solutions are shown for the similar case without filtration.

Fig.6-8 represent a 3D picture of spreading and filtration processes for initial radius R_0=2.0m, ν= 0.2, and k_f=1.0.

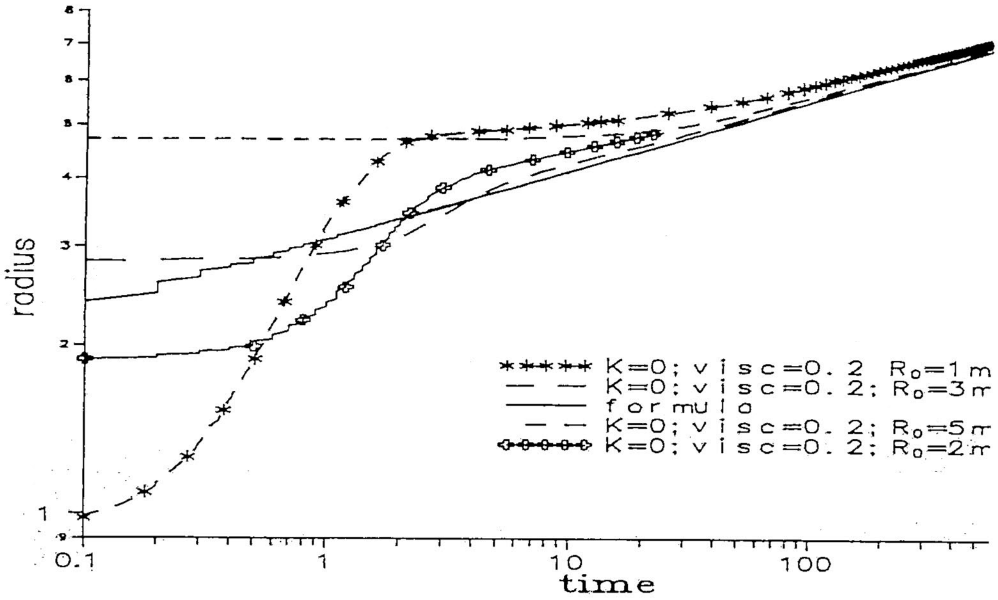

Fig.2 Influence of initial radius on the process of spreading

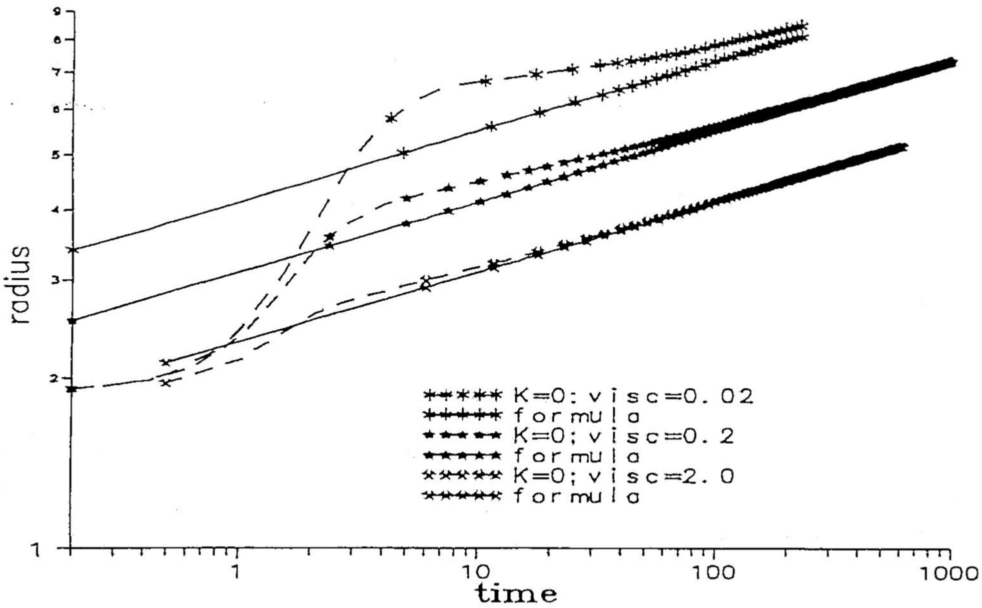

Fig.3 Results for varying oil viscosity

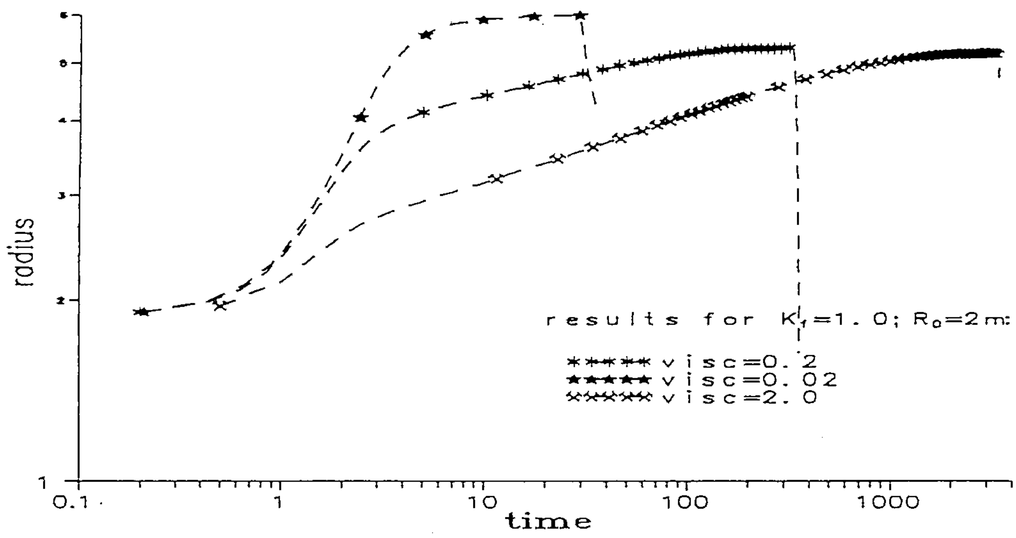

Fig.4 Numerical results for varying viscosity with filtration

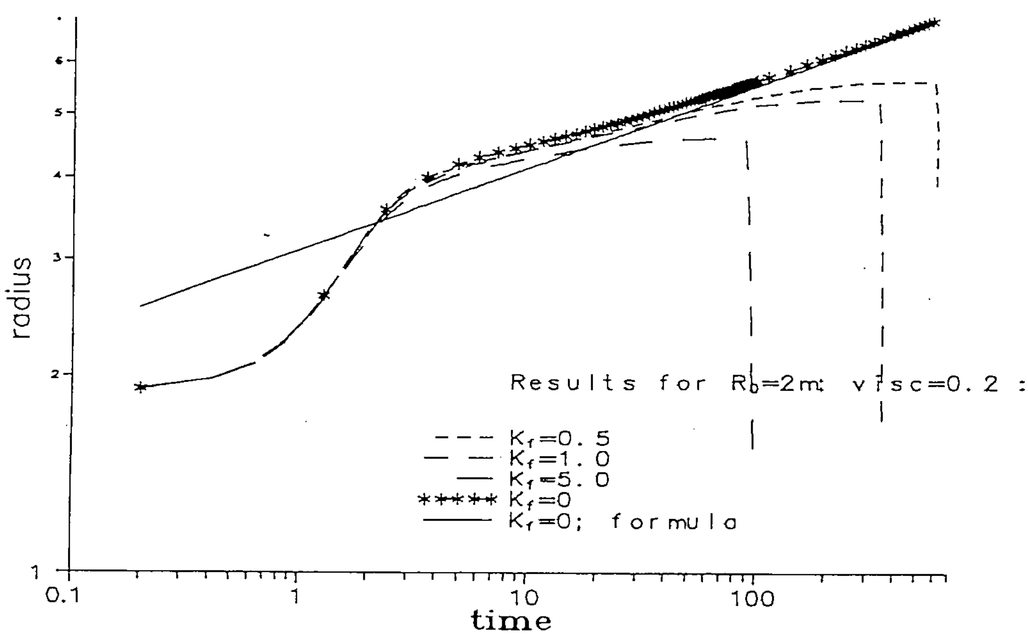

Fig.5 Numerical results for varying snow permeability

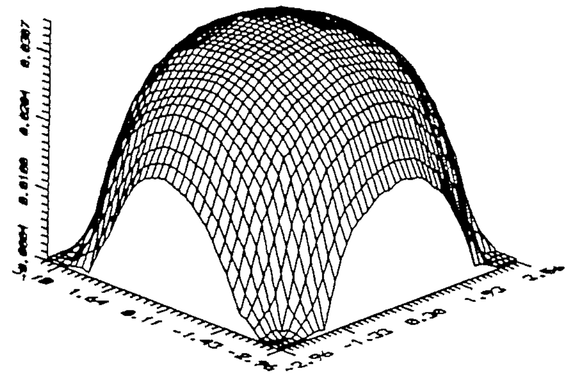

Fig.6 Initial shape of the spilled oil

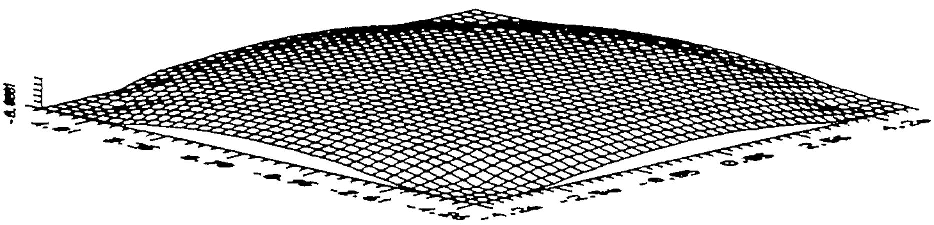

Fig.7 Thickness distribution for t=10 sec.

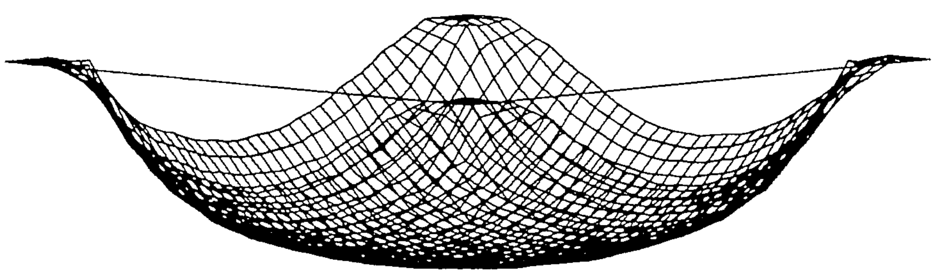

Fig.8 Shape of the filtrated oil corresponded to Fig. 7

Table 1. Numerical value of modeling parameters

N	Volume [m^3]	Viscosity kg/m/sec	Porosity $E=1-\rho_s/\rho_i$	Permeability coefficient [m^2]$\times10^{-10}$	Initial radius of spreading oil, R_o [m]
a1	1.1	0.2	0.4	0.0	1.0
a2	1.1	0.2	0.4	0.0	2.0
a3	1.1	0.2	0.4	0.0	3.0
a4	1.1	0.2	0.4	0.0	5.0
b1	1.1	0.02	0.4	0.0	2.0
b2	1.1	0.2	0.4	0.0	2.0
b3	1.1	2.	0.4	0.0	2.0
c1	1.1	0.02	0.4	6.0	2.0
c2	1.1	0.2	0.4	6.0	2.0
c3	1.1	2.0	0.4	6.0	2.0
d1	1.1	0.2	0.4	3.0	2.0
d2	1.1	0.2	0.4	6.0	2.0
d3	1.1	0.2	0.4	30.0	2.0

Conclusion

The preliminary analysis of theoretical background, numerical technique possibilities and the result of pilot numerical experiments shows that the model discussed in this report is suitable enough for investigations of oil behaviour in ice conditions.

The model can describe existing analytical solutions. In addition this model can also describe sufficiently more complicated situations (different types of spill, spills in regions with complicated geometry). It is possible also to take into account various processes, such as, for example, the oil properties change at low temperature during the spreading process. It seems prospective to use the model for planning the field and laboratory experiments and for evaluation of their results. The model is compatible with oil spreading model for calm water. It seems reasonable to use the similar model for describing the oil spill under ice, in broken ice and on the ground.

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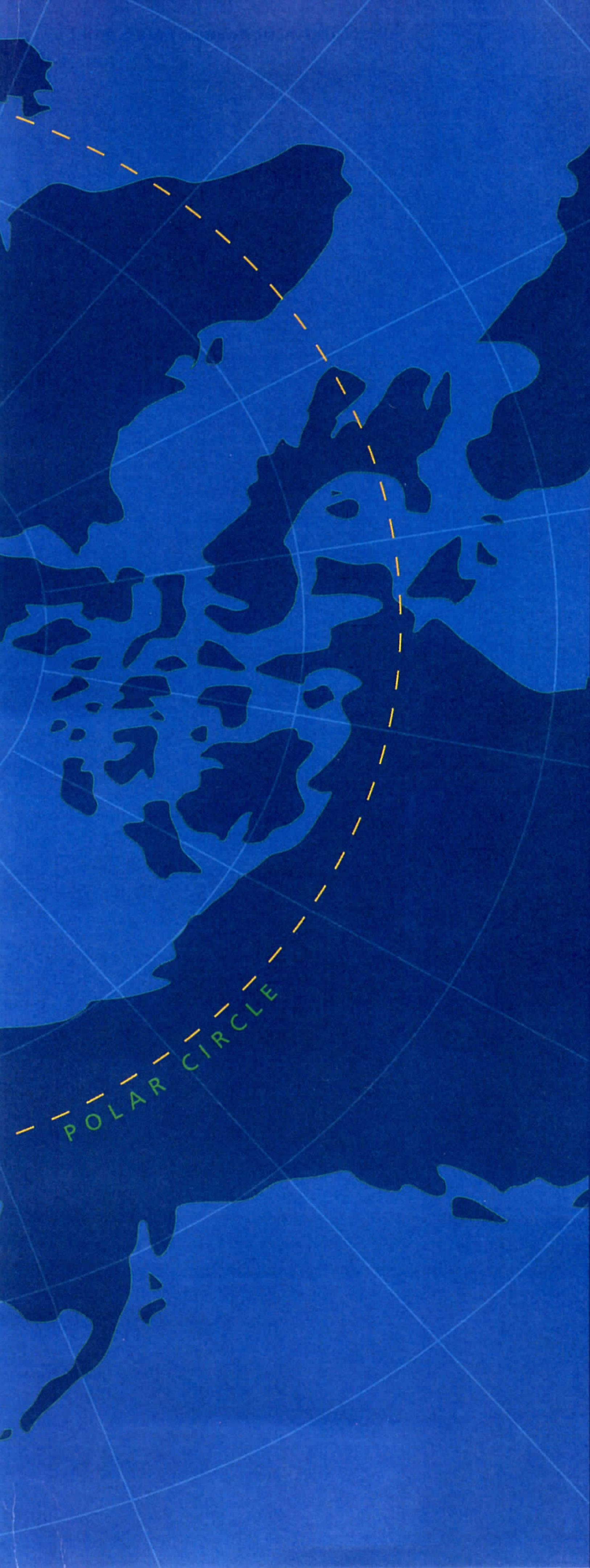

The three main cooperating institutions of INSROP

Ship & Ocean Foundation (SOF), Tokyo, Japan.

SOF was established in 1975 as a non-profit organization to advance modernization and rationalization of Japan's shipbuilding and related industries, and to give assistance to non-profit organizations associated with these industries. SOF is provided with operation funds by the Sasakawa Foundation, the world's largest foundation operated with revenue from motorboat racing. An integral part of SOF, the Tsukuba Institute, carries out experimental research into ocean environment protection and ocean development.

Central Marine Research & Design Institute (CNIIMF), St. Petersburg, Russia.

CNIIMF was founded in 1929. The institute's research focus is applied and technological with four main goals: the improvment of merchant fleet efficiency; shipping safety; technical development of the merchant fleet; and design support for future fleet development. CNIIMF was a Russian state institution up to 1993, when it was converted into a stock-holding company.

The Fridtjof Nansen Institute (FNI), Lysaker, Norway.

FNI was founded in 1958 and is based at Polhøgda, the home of Fridtjof Nansen, famous Norwegian polar explorer, scientist, humanist and statesman. The institute spesializes in applied social science research, with special focus on international resource and environmental management. In addition to INSROP, the research is organized in six integrated programmes. Typical of FNI research is a multi-disciplinary approach, entailing extensive cooperation with other research institutions both at home and abroad. The INSROP Secretariat is located at FNI.