Expected impact of oil spills in the Southern Ocean

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Abstract

This paper proposes a model of oil behaviour in ice-infested waters. It has been built on the basis of an ice formation model and a hydrodynamic model to respond to an oil pollution danger increasing proportionally to human presence and activities in Antarctica and describes the interactions between oil and ice. The main features of oil spreading and dynamics in an ice pack are taken into account in the model which is used for the simulation of possible spills in the Southern Ocean: in the short term in cold waters and in the presence of ice, and in the long term. The results show that the presence of ice completely modifies the classical spreading of an oil slick by shrinking its area, and by incorporating some oil in the ice structures. The quantity of oil initially entrapped in the ice may later induce a second spill. The divergent nature of the Antarctic ice strongly influences the oil evolution. The remaining oil is lead in the circumpolar current by the ice pack and is ejected eastwards. Information that can be drawn from the model is exemplified by case studies of oil spilling in the Southern Ocean and possible further applications are discussed. The results of this model could be helpful to managers and intervention teams during an accident.

1 Introduction

The consequences of oil pollution have been studied for several years in the Arctic Ocean. On the other hand, oil pollution in the Southern Ocean is rarely tackled because in the past, there was no oil extraction from the Antarctic continent and its continental shelf and since 1991, all industrial activities related to mineral resources are forbidden on the basis of the Madrid Protocol on Environmental Protection to the Antarctic Treaty. Nevertheless, the oil pollution
danger in the Antarctic exists and has been increasing proportionately to human presence and activities. Supply, scientific and tourist ships are cruising to and from Antarctic bases and may cause prejudice to the Antarctic environment.

On 28 January 1989, the Argentine supply and tourist vessel “Bahia Paraiso” grounded at Palmer station, the United States research base on Anvers Island on the western side of the Antarctic Peninsula. Eight hundred tons of diesel and jet fuel were spilled. The spill spread in the Bismark Strait area and caused significant bird mortality. Inaccessibility of the polluted sites worsened the situation. One month later, on 27 February, the Peruvian research vessel “Humbold” grounded in Fildes Bay on King George Island at the northern end of the Peninsula. Thirty-five tons of diesel oil were spilled, this time fortunately causing little damage. These accidents suddenly brought two facts to the attention of the public: the existence of a non-negligible risk of oil pollution in the Southern Ocean and the tremendous vulnerability of the Antarctic ecosystem. Efficient means should thus be available to obtain clear indications on the possible consequences of a spill and to react properly in case of emergency.

An oil spill in open water is an extremely complex assembly of interacting processes [1] so that the introduction of ice, as a supplementary constraint, does not make the development of such a model easier. Adequate models exist to simulate the behaviour of oil spilled at sea and some of them consider its interactions with the Arctic ice but, to our knowledge, no model is available for the specific Antarctic conditions. If it can be reasonably assumed that the behaviour of an oil slick is the same in Arctic and Antarctic oceans, the main difference will come from the dynamics of the Antarctic ice pack which is less constrained by the presence of coasts. It seems thus necessary to develop adequate tools able to predict the evolution of an oil slick in such a severe environment in order to assist in impact assessment studies. The present paper describes a model that simulates interactions between ice and oil, applied to a hypothetical spill in the Weddell Sea, which makes up a potential risk area because of the network of scientific stations on its coasts and the inherent traffic of supply vessels.

2 Oil drift in the presence of ice

The evolution of an oil spill in open sea is described by the general transport equation [2]:

\[ \frac{\partial c_{oil}}{\partial t} = -u_{oil} \cdot \nabla c_{oil} + \nabla \cdot \left( K_h \nabla c_{oil} \right) + \phi. \] (1)

where \( c_{oil} \) is the mass concentration of oil usually expressed per unit area, \( u_{oil} \) is the net advecting speed, \( K_h \) is the horizontal dispersion coefficient representing the combined effects of turbulent dispersion and physical spreading due to surface tension, and \( \phi \) indicates the various processes of oil degradation. The presence of ice completely modifies the behaviour of an oil spill [3] so that each term of eqn (1) becomes dependent on the ice concentration.
Ice at sufficient concentration reduces the area available for oil, acts as a natural barrier, and alters consequently the normal evolution of the slick. In fact, oil does not simply move through the leads or the open areas in the ice pack because these zones are often obstructed by broken ice. Moreover, the closure of leads ejects an amount of oil onto the ice surface and under the ice layer [4]. In other respects, the ice pack loses its confinement role during spring and summer when the break-up releases partly or totally the oil trapped among the ice floes or in the ice layer. Observations during accidental oil spills and experiments [5], [6] reveal two regimes of oil drift in the presence of ice, separated by a threshold value of the ice concentration $c_{ice}$ (expressed as a percentage of ice surface per unit surface). The most commonly observed value of this threshold, below which oil and ice move separately, is about 30%.

In open water conditions, the wind stress and the ocean current are the main driving forces of the slick movement. Their equilibrium is expressed by:

$$u_{oil} = u_{water} + \alpha_{oil} D(\theta_{oil}) u_{air}$$

$$D(\theta_{oil}) = \begin{pmatrix} \cos \theta_{oil} & -\sin \theta_{oil} \\ \sin \theta_{oil} & \cos \theta_{oil} \end{pmatrix}$$

where $u_{oil}$ is the velocity of the centre of the slick; $u_{water}$, the surface water current; $\alpha_{oil}$, the wind drift factor and $D(\theta_{oil})$, the transformation matrix. $\theta_{oil}$ is a deflection angle equal to $40^\circ - 8\sqrt{u_{air}}$ when $0 \leq u_{air} < 25$ m/s and to zero for wind speeds greater than 25 m/s [7].

Both regimes should be continuously linked. A confinement function $f(c_{ice})$ is introduced to model the transition of oil drift from open sea to ice-infested water and vice versa. This confinement function is expressed by:

$$f(c_{ice}) = 0.5 + \pi^{-1} \tan(c_{ice} - 30).$$

in which $f(c_{ice})$ varies rapidly from 0 to 1 in the vicinity of a 30% ice concentration. The general oil velocity can thus be expressed by:

$$u_{oil} = u_{water} + \left\{ f(c_{ice}) \alpha_{oil} D(\theta_{oil}) + \left[ 1 - f(c_{ice}) \right] \alpha_{oil} D(\theta_{oil}) \right\} u_{air}.$$

The thickness and the concentration of ice are computed by a sea ice formation model [8] and the surface water currents by a three-dimensional circulation model [9].

3 Oil spreading and diffusion in the presence of ice

During the first stages after the spillage, the physical spreading of oil is the result of an equilibrium between the different forces (gravity, surface tension, inertial force, viscous forces) acting on the continuous slick [10]. The spreading equation used by Scory [7] is implemented in the model. It has been improved to take into
account the modified net surface tension introduced by El-Tahan and Venkatesh [11], which induces a strong reduction of the oil spill extent.

The oil-contaminated zone, $A_c$, by definition, contains the oil and the ice blocks floating in the surroundings of the oil pollution. It is expressed by the formulation proposed by El-Tahan et al. [12]:

$$A_c = \frac{A_0}{1 - c_{irr}}. \quad (5)$$

where $A_c$ is the extent of the contaminated zone and $A_0$ is the extent of the same slick obtained in open water conditions.

At low ice concentration, i.e. for $c_{irr} < 30\%$, the spreading is computed as done in open water. The ice concentration affects only the extent of the oil-contaminated zone. At high ice concentration, i.e. for $c_{irr} > 80\%$, Venkatesh et al. [13] have deduced from geometrical considerations that the horizontal diffusion of oil is stopped. In these conditions, the thickness of the oil slick can thus be greater than that of a slick spreading in open sea. That was confirmed by experiments in real situations [5], [6]. In some cases, more precisely if the oil thickness is greater than the threshold obtained by hydrostatic equilibrium, oil is allowed to flow over or even under the ice layer. Under ice, the oil fills the cavities and is simply maintained in this position by gravity forces, as long as the currents are not strong enough to flush it out. The under-ice storage capacity is far from negligible: in steady conditions, the equilibrium thickness of oil under flat ice is about 8mm [3]. However, the ice is not always flat and some local features such as refrozen leads can offer larger free volume. In this respect, the under-ice storage volume per unit area $T_{ui}$ can be written as a linear function of ice thickness [13], valid for ice layers greater than 0.5m:

$$T_{ui} = 0.021 h_{ice}, \quad (6)$$

where $h_{ice}$ is the ice thickness.

As time passes, the turbulent diffusion exceeds this first spreading and becomes the predominant factor in the further evolution of the spill. In the model, the influence of the horizontal diffusion is computed as in the particle approach. The random walk technique is used to calculate the new position of the different small slicks. With growing ice concentration, the oil diffusion must be reduced and the simplest way to express this relation is to multiply the horizontal diffusion coefficient $K_h$ by the fraction of free area and to set it to zero when ice is too concentrated. The horizontal diffusion coefficient is thus computed according to:

$$K_h = \begin{cases} K_h & \text{for } 0 \leq c_{irr} < 0.3, \\
(1 - c_{irr}) K_h & \text{for } 0.3 \leq c_{irr} < 0.8, \\
0 & \text{for } c_{irr} \geq 0.8. \end{cases} \quad (7)$$
4 Weathering

The oil physical and chemical characteristics and associated processes, such as density, viscosity, pour point, surface tension, evaporation, emulsification, dispersion, and dissolution are affected by low temperatures and the presence of ice and most of these processes are slowed down. More details are given in [14].

5 Test cases: short term evolution

Ideally, the evaluation of a model needs several complete sets of data that cover most of the possible scenarios and conditions that the model is designed to handle. However, available quantitative field data on oil spills in broken ice are extremely limited. Moreover, most of these data concern crude oil types, which are not very common in Antarctica but, for lack of something better, they are used to compare the model with reality. In these circumstances, the model described above has been tested for possible hypothetical cases. The results presented here concern the short term evolution in cold waters and in the ice pack.

First, the equilibrium thicknesses of spills in cold waters compiled by El-Tahan and Venkatesh [11] for some typically North American oils and those computed by the model are given in Table I, which shows the capabilities of the present model in reproducing the reduced spreading of oil in cold waters.

Table I: Comparison between computed equilibrium thicknesses and observations [11].

<table>
<thead>
<tr>
<th>Oil type</th>
<th>Dynamic viscosity (mPa.s)</th>
<th>Density (kg/m³)</th>
<th>Observed equilibrium thickness (mm)</th>
<th>Computed equilibrium thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prudhoe Bay</td>
<td>500</td>
<td>915</td>
<td>3.03</td>
<td>3.79</td>
</tr>
<tr>
<td>Prudhoe Bay</td>
<td>570</td>
<td>915</td>
<td>7.30</td>
<td>6.27</td>
</tr>
<tr>
<td>ADGO</td>
<td>234</td>
<td>952</td>
<td>2.00</td>
<td>2.27</td>
</tr>
<tr>
<td>Prudhoe Bay</td>
<td>450</td>
<td>915</td>
<td>1.30</td>
<td>1.82</td>
</tr>
</tbody>
</table>

The discrepancies between results and observations are acceptable if one bears in mind that the processes concerned are very sensitive to the physical properties of oil. These are certainly not easy to measure and e.g., Whiticar et al. [15] give the dynamic viscosity of “Prudhoe Bay” oil at 0° as ranging from 19 to 577 mPa.s.

Secondly, the ability of the model to take into account the presence of ice in and around an oil slick in the first stages after a spill has been tested by simulating two observed spills [16]. Both slicks concerned an oil volume of respectively 0.136 m³ and 1.09 m³ of Prudhoe Bay crude oil, which had a density of 914 kg/m³ and a dynamic viscosity of 500 mPa.s. The oil was released in the presence of ice with a concentration varying between 38% and 62%. Fig. 1 gives
an estimation of the contaminated area provided by the model and compares it to
the observations available for each spill. Even if there is only one observation for
each of these spills, this figure shows that the model satisfactorily reproduces the
initial oil spreading in these conditions. This figure also gives the early spreading
of oil in the absence of ice. The comparison between situations with and without
ice indicates that the main influence of the ice is an increase of the total
contaminated zone.

Figure 1: Early evolution of the contaminated area: released volume of 0.136m³
without ice (solid line) and in the presence of ice (dotted line), released
volume of 1.09m³ without ice (dashed line) and in the presence of ice
(dash-dot line), observations [16] (grey rectangles).

6 Test cases: long term evolution

It was not possible to gather sufficient information and observations to reproduce
satisfactorily the Bahia Paraiso accident occurred in 1989. According to the
weather operator, Palmer Station, located two miles away from the wreck, was
performing some weather observations prior to April 1989, but there is no daily
record of those observations. Due to this lack of information, a scenario has been
designed to simulate the long term evolution of the oil behaviour under the
influence of ice. This test studies the oil drift within the ice pack and evaluates
the spreading and weathering of an oil slick. Due to the absence of relevant data
in these extreme conditions, the following results are only indicative. They have
been used in the contingency planning for oil spill response in Antarctica of the
British Antarctic Survey [17].
In this scenario, 500m³ of marine gas oil are released at the position (39°W, 72°S) in mid-February. At this period, the ice concentration around the slick is 54% and the sea surface temperature, -1.8°C. The position and the date have been chosen in order to make possible the comparison of the results with the observations from Launiainen and Vihma [18] who studied the drift of buoys deployed on ice floes. They also correspond to the minimum of the ice cover which allows a certain marine traffic with its associated risks of accident, this giving some realism to the scenario.

Fig. 2 compares the trajectories of the buoy and the mass centre of the oil spill. This rough comparison is justified because the ice concentration is most of the time higher than 30% (Fig. 3) and ice and oil tend thus to move together.

The oil trajectory is to some extent compatible with the drift of the buoy and clearly shows the influence of the clockwise Weddell Gyre. One has to recall that the model runs with averaged meteorological inputs and is not able to reproduce all the details of reality. Moreover, the systematic delay in time might also be explained by the fact that the sea ice model computes the drift of the whole pack ice and does not take into account the small scale behaviour of the floes such as collisions and rotations.
Figure 3: Evolution of the computed ice concentration along the track (Day 0 is 14 February).

Figure 4: Evolution of the slick shape one week after the release.
The simulation confirms that, when the oil slick approaches 60°S, it is swept away by the Antarctic Circumpolar Current. Around this latitude, the ice and oil trajectories begin to break away. It corresponds to a situation where the ice concentration is of the order of 30% and where oil and ice begin thus to have their own motion differently affected by the wind. Fig. 2 also shows that the pollution is visible during 38 days and then is incorporated into ice. After 260 days oil trapped in ice begins to leak due to ice melting and the pollution is again visible. The evolution of oil weathering in the presence of ice is discussed in [3] and [14].

Finally, the particle approach gives the possibility of providing a realistic representation of the slick shape. Here, the 500m³ oil volume is divided into 50 particles of 10m³ and Fig. 4 describes, as an example, the slick shape after 7 days, which is characterized by its stretch along the average direction of the oil drift.

Conclusions

On the basis of existing literature and observations, interactions between ice and oil are identified and introduced in a sea ice formation model to study the possible fate of oil pollution in the Weddell Sea. It appears clearly that the ice pack completely modifies the evolution of an oil slick and acts as a moving boundary, controlling the spreading and the drift of an oil slick.

Some short term tests have been carried out with the model and have reproduced the oil spreading on cold water and in the presence of ice. The long term scenario shows that a part of the initially released oil may cause later and further away a second pollution event. The computed oil drift is in satisfactory agreement with the buoy trajectory.

As logistical difficulties inherent to the Antarctic area hamper appropriate reactions in the very beginning of an accident, this model could help to localize a pollution hidden in the ice pack and forecast its reappearance during the melting season. Without prejudice to complementary efforts concerning its validation, a major interest of the present model is to provide a tool able to deliver such information to authorities and intervention teams.

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References


