An update of an oil spill model and its application in the Bay of Biscay: the weathering processes

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Abstract

Towards collaboration between the Maritime Engineering Lab. (LIM) and the French National Meteorological Service (Météo-France), a forecasting system of the evolution of oil slicks released at sea is being improved. Both LIM and Météo-France have focused their researching lines to the weathering processes of spilled oil in the sea, adding them to their own existing models of transport. The main processes of weathering are included, as evaporation, emulsification and above all, their consequences on the physical-chemical properties of the oil (such as density and viscosity). In addition, a new distribution of oil droplets size is used in order to obtain an accurate simulation of vertical dispersion process.

These updates are tested with simulations runs in the Bay of Biscay. The knowledge of the area of the LIM (due to monitoring of the hydrodynamics fields and related works carried out in this zone) and the tracking of true events of marine pollution from CEDRE (Centre de Documentation de Recherche et d’Expérimentations sur les pollutions accidentelles des eaux) and Météo-France, will allow the validation of the forecasting system and the fight of oil marine pollution.
1 Introduction

In case of environmental crisis due to a pollution event by an oil spill, responders require forecasting tools. For this reason, it’s necessary to develop and improve permanently these numerical tools that take part in response planning tasks.

In this context, we present different updates incorporated into forecasting models. From an initial transport model of conservative pollutants (or floating objects), the physical and chemical processes inherent of the weathering of hydrocarbons have been included.

The three entities that take part in this works, LIM, Météo-France and CEDRE develop their main research activities into preservation of the marine and coastal environment (e.g. EspirIo [1], Daniel [2] and Gonzalez [3]). In particular, the French national weather service is charged to supply all the information related to a pollution event, such as meteorological and drift pollutant forecasts.

Starting by a coupled model of transport and weathering developed by LIM (Comerma [4]), the already existing forecasting system at Météo-France, have been updated. Owing the research effort of CEDRE about behaviour of oil at sea (Guyomarch [5]), an oil database will be available in order to calibrate and validate the updates included into the forecasting system. Finally, we present some preliminary results in the common studied area: the Bay of Biscay.

2 Transport model

The model MOTHY was developed by Météo-France to simulate the transport of floating pollutants in the marine environment in three dimensions. It’s defined as an integrated system that includes hydrodynamic coastal ocean modelling and real time atmospheric forcing with a global atmospheric model.

The transport processes already considered in the model are the horizontal advection due to ambient currents (wind and tide forcing), the turbulent diffusion by ocean turbulence and the buoyancy of oil droplets submerged within the water column. Other processes, like natural vertical dispersion due to breaking waves and mechanical spreading (homogeneous processes due to balance between extensive and maintaining forces) are updated and modified.

As a lagrangian model, MOTHY models the oil slick as a distribution of independent droplets that move in response to currents, turbulence and buoyancy. The hydrodynamics are obtained by a coupling between a 2DH barotropic model and a 1DV eddy viscosity model [2].

The 2DH model is forcing by tide and by winds and sea level pressure forecasts from a global atmospheric model. This depth-integrated barotropic model solves the non-linear shallow-water equations on a 1 or 5’ grid mesh.

The 1DH eddy viscosity model is constrained by depth-integrated current from the 2DH model, by surface wind and bottom frictional stress. This approach allows a rotation of current direction with depth.
On the other hand, turbulent diffusion is modelled by a three-dimensional random walk technique fitting by a diffusion coefficient and by the time step.

3 Weathering model

The weathering of hydrocarbons is an ensemble of physical and chemical processes that modifies the properties of initial released pollutant. We have considered those that have remarkable effects, in terms of modelling (non-conservative pollutant) and response. We take into account also the modifications of rheological properties due to these processes.

3.1 mechanical spreading

In the lagrangian model, the mechanical or natural buoyant spreading is implicitly simulated by the horizontal turbulent diffusion on the water surface. The model includes some methods to calculate the extension of the oil slick, considering the area related to the oil droplets distribution on the water surface.

The evolution of this area could be compared with other analytic expressions, for instance, the well-known Fay’s equations \[6\] where the area increases as a function of time and volume (equation (1)).

\[
A_{\Pi}(t) \sim \left( \frac{V^{2/3} \cdot t^{1/2}}{\nu^{1/6}} \right) \Leftrightarrow t \geq 1\text{ day}
\]  

(1)

where \(A\) is the area of slick (m²), \(V\) (m³) initial volume of oil spill, \(t\) elapsed time and \(\nu\) cinematic viscosity of seawater (m²/s).

Others authors, however, disagree with this simplest expressions, suggesting the inclusion of other parameter like oil viscosity (Reed et al. \[7\]).

3.2 Evaporation

We have introduced a first order kinetics law to simulate the fraction of oil evaporated:

\[
\frac{dF}{dt} = \frac{K_e \cdot A}{V_0} \exp\left[6.3 - 10.3\left(\frac{C_1 + C_2 \cdot F}{T}\right)\right]
\]  

(2)

where:

- \(F\): evaporated fraction
- \(K_e\): coefficient of mass transfer
- \(A\): surface oil slick (m²)
- \(V_0\): oil spilled volume (m³)
- \(C_1, C_2\): distillation constants
- \(T\): temperature (K°)
and considering that \( K_\alpha = 2.5 \cdot 10^{-3} \cdot U^{0.78} \), where \( U \) is the wind speed (m/s).
The distillation constants are obtained from distillation curves of each hydrocarbon. Thus, there is a linear relation between evaporated fraction and boiling temperature (\( T_b = C_1 + C_2 \cdot F \)).

### 3.3 Emulsification

In the weathering model, we incorporate a simple first-order rate law for mousse formation, proposed by Mackay et al. [8] and commonly accepted:

\[
\frac{dY}{dt} = -KU^2 \left( 1 - \frac{Y}{Y_f} \right)
\]

However, at present, there are some interesting updates of this simplest equation, taking into account, for example the initial oil composition. In a recent work, Fingas [9], suggest a classification of emulsion by its components (asphaltenes, aromatics) and final rheological properties (viscosity and final water content). Thus, the formation of water-in-oil emulsions seems better understood and the implementation of its modelling results more accurate.

In this way, four clearly states of water-in-oil emulsions have been defined. These are established by their stability over time, appearance (viscous, fluid, colour) and by rheological measurements. The states are:

- Stable water-in-oil emulsions (brown solid materials, 80% water content)
- Mesostable water-in-oil emulsions (brown/black viscous liquids)
- Entrained water (black liquids, separated oil and water one week formation)
- Unstable water-in-oil (less than 10% water content after one week formation)

### 3.4 Evolution of oil viscosity and density

Due to weathering processes, some rheological variables of pollutant change dramatically. In the model, the evolution of viscosity and density of oil are considered.

As different authors noticed, density increase as a function of temperature, evaporated fraction and water content as follows [10]:

\[
\rho = Y \cdot \rho_w + (1 - Y) \cdot \rho_0 \left( 1 - C_T \cdot (T - T_0) \right) \left( 1 + C_F \cdot F \right)
\]

where:

- \( \rho \) : density of pollutant (kg/m³)
- \( \rho_w \) : density of seawater (kg/m³)
- \( \rho_0 \) : density of initial oil at \( T_0 \) (kg/m³)
- \( T_0 \) : oil temperature reference (K°)
- \( T \) : temperature (K°)
- \( C_T, C_F \) : adjusting parameters
Y: water content

These parameters must be adjusted with experiments in laboratory and depend basically on oil compounds properties. For the moment, the values of 0.0008 and 0.18 are adopted for the parameter $C_T$ and $C_b$, respectively [10].

The increase in density has to be introduced in the transport model, affecting the behaviour of buoyancy of oil droplets in the water column.

The increase in viscosity as a function of water content of the emulsion ($Y$), the environmental temperature ($T$) and evaporation ($F$) is reported as:

$$

\nu_f = \nu_0 \cdot \exp \left( \frac{C_3 \cdot Y}{1 - C_4 \cdot Y} \right) \cdot \exp \left( C_5 \left( \frac{1}{T} - \frac{1}{T_0} \right) \right) \cdot \exp \left( C_6 \cdot F \right)

$$

where:

- $\nu_0$: viscosity of initial oil at $T_0$ (kg/m³)
- $C_3, C_4, C_5, C_6$: adjusting parameters

Using the same criterions as defined in the ADIOS model [10], we take the averaged value of 5.0 for the $C_5$ and $C_6$ parameters. The value of $C_6$, however, could be greater in lighter products (like gasoline). Another time, the collected data in laboratory could improve the accuracy of these parameters.

3.5 Vertical dispersion

3.5.1 Principles of natural dispersion

Due to mixing processes as breaking waves, the initial oil slick floating over the sea surface is transformed in little oil droplets, causing the entrainment of pollutant in the water column. It’s the so-called oil-in-water formation process.

This vertical process depends on the mixing energy (wave height) and the oil’s properties (i.e. density and viscosity). Owning some studies in laboratory by Delvigne and co-workers [11], it is just needed three parameters in order to characterise this process of natural dispersion:

- Number $N(d)$ of dispersed droplets with size $d$
- An empirical constant, $C_0$ oil entrainment rate (depending on oil)
- The initial intrusion depth, $Z_m$

The most remarkable result of these experiments was the fact that exists a simplest relationship between the number of particles $N(d)$ and its diameter ($d$), obtaining a similar relative droplet size distribution independently of experiments conditions (eqn 6).

$$

N(d) \sim \left( \frac{1}{d^{2.3}} \right)

$$


As in oil spill lagrangian simulations, the volume of an initial oil spill is reproduced as a group of particles, which distribution of size follows some specific law. For the model runs, we followed the Delvigne common law (eqn (6)). Each particle (or group of particles with same diameter) simulates a proportion of the initial volume, function of its size. Some authors emphasise the relevance of using this distribution of droplets constant by size or constant by volume (see e.g. Varlamov [12]) and furthermore the range choice of this droplets distribution (minimum and maximum size).

3.5.2. Buoyancy

The oil droplets dispersed into the water column are driven by ocean’s turbulence but also by buoyancy. The buoyancy force depends on the density and size of the oil droplets, so that larger (more buoyant) droplets tend to remain in the surface layer whereas the smaller droplets tend to mix downwards because the turbulence. The vertical velocity ($U_B$) is [13]:

$$U_B = \frac{g \cdot d^2 \left(1 - \frac{\rho_{oil}}{\rho_w}\right)}{18 \nu_w}$$

where $g$ denotes the gravitational acceleration, $d$ the droplet size, $\rho_{oil}$ initial oil density, $\rho_w$ and $\nu_w$ density and viscosity of seawater.

In this way, in the numerical model, for each time step and for each particle, these two strengths (buoyancy and vertical dispersion) are balanced in order to define the vertical movement.

We have defined a critical diameter ($d_{crit}$) as the “maximum diameter of droplet’s oil that stays permanently within the water column”. Then, droplets greater than this $d_{crit}$ will be always on the water surface and drifted faster by wind and waves, elongating the initial shape of oil slick from wind direction (Figure 1).
4 Preliminary results

Some simulations have been made in the common study area: the Bay of Biscay.

4.1 Coupled models

In the diagram of Figure 2 is represented the influence of the pollutant properties in the drift and spreading modelling. Both evaporation and emulsification increase density and viscosity of the pollutant (mixture of oil and seawater). At the same time, information of spread area and dispersed percentage is needed to the weathering model. In this way, we talk of coupled models.

![Coupled models diagram](image)

4.2 Oil droplets formation

Until now, a linear size distribution of oil droplets, typically ranged to 50 until 500 µm, was used in the MOTHY model. In these runs, following the model suggested by Delvigne [11], we have deduced the maximum droplet size “at which the cumulative entrained mass of oil droplets equals the mass (or thickness:) of the surface slick”. So, the range of oil droplet size could be defined by the initial concentration of oil floating in the water surface (before a mixing event like a breaking wave).

In order to calculate the dispersed percentage of oil within the water column, we must obtain the critical diameter already defined. Typically, this diameter depends on oil density and ocean turbulence. There is not a clearly value of this diameter, ranged between 100 and 300 µm [7].

Now, a new distribution is tested. Five diameters were chosen, maintaining the 50-500 µm range. The number of each group of diameters has been deduced from relation (6), fixing the number of biggest droplet (Table 1). Some preliminary results showed that the $d_{crit}$ was closed to 300 µm. This value is
obtained by balancing the buoyancy of each droplet to the vertical random turbulent diffusion.

<table>
<thead>
<tr>
<th>Diameter $(d, \mu m)$</th>
<th>500.0</th>
<th>281.2</th>
<th>158.1</th>
<th>88.9</th>
<th>50.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of droplets $N(d)$</td>
<td>1</td>
<td>4</td>
<td>14</td>
<td>53</td>
<td>200</td>
</tr>
</tbody>
</table>

Table 1. Number of droplets for each diameter group

### 4.3 Test run

In Figure 3 we can observe the evolution of an oil spill (810 kg/m$^3$), during 5 days of simulation, caused by a northern wind of 10 m/s. We can distinguish clearly two parts: the slick (the head) and the tail of the oil spill. The slick moves faster to the Spanish coast, driven by wind-stress and represents approximately 70% of total volume. This slick is modelled by a dense cloud of large droplets (transport and buoyancy dominant), followed by a sparse tail (diffusion dominant).

![Figure 3. Evolution of oil slick simulation in the Bay of Biscay](image)

Using the Delvigne size distribution (Table 1), we can recognise two groups of droplets, those greater that remain on the water surface (the slick) and the little ones that mix downward the water column. The Figure 4 represents the evolution of the percentage of droplets within the water column, as a function of its size during the five simulated days.
5 Conclusions

An update of a forecasting system of oil pollution has been described. The main physical-chemical processes of the weathering of oil have been included in the model. These processes introduce remarkable changes into the rheological parameters of the pollutant, interacting with the drift modelling. Some parameters have to be calibrated with available data, e.g. laboratory experiments. In this way, a reduced oil database will be included in order to help the responders [14].

On the other hand, the modification of the oil droplets distribution introduces remarkable changes in the behaviour of the modelled slick. The fate of dispersed oil droplets is summarized by the critical diameter ($d_{crit}$). The vertical turbulence simulated in the model is calibrated in order to obtain a reasonable value of $d_{crit}$ obtained numerically for each kind of hydrocarbon. Unfortunately, there is a wide range of this value [7], [11], [12].

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