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REVIEW

Oil Spill Modeling towards the Close of the 20th Century: Overview of the State of the Art

MARK REED†*, ØISTEIN JOHANSEN†, PER JOHAN BRANDVIK†, PER DALING†, ALUN LEWIS‡, ROBERT FIOCCO‡, DON MACKAY§ & RICHARD PRENTKI¶
†*SINTEF Applied Chemistry, Environmental Engineering, 7034 Trondheim, Norway*
‡*Alun Lewis–Oil Spill Consultancy, 121 Laleham Road, Staines, Middx, TW18 2 EG, UK*
§*R.J. Fiocco Associates, 77 Pine Grove Avenue, Summit, NJ 07901, USA*
¶*Environmental Modeling Centre, Trent University, Peterborough, Ontario KI9J0 7B8, Canada*
‖*Minerals Management Service, Alaska Region, Anchorage, USA*

The state-of-the-art in oil spill modeling is summarized, focusing primarily on the years from 1990 to the present. All models seek to describe the key physical and chemical processes that transport and weather the oil on and in the sea. Current insights into the mechanisms of these processes and the availability of algorithms for describing and predicting process rates are discussed. Advances are noted in the areas of advection, spreading, evaporation, dispersion, emulsification, and interactions with ice and shorelines. Knowledge of the relationship between oil properties, and oil weathering and fate, and the development of models for the evaluation of oil spill response strategies are summarized. Specific models are used as examples where appropriate. Future directions in these and other areas are indicated © **1999 Elsevier Science Ltd. All rights reserved**

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Introduction

The purpose of this paper is to present an overview of the different approaches applied in numerical models of the behavior and fate of oil spilled in the marine environment. This review focuses primarily on developments since 1990, relying on existing published state-of-the-art reviews (Spaulding, 1988; ASCE, 1996) to summarize earlier work.

A large number of oil spill models are in use in the world today. These range in capability from simple trajectory, or particle-tracking models, to three-dimensional trajectory and fate models that include simulation of response actions and estimation of biological effects. Many of these models are mentioned here; a set of one-page summaries is included elsewhere in this volume.

Two models purporting to contain the same algorithms may give quite different results from the same input data. Implementation is critical to algorithm performance. Furthermore, performance of one algorithm will be affected by performance of other algorithms in the model, a clear example being the relationships among spreading, evaporation, emulsification and natural dispersion.

The close interdependence of oil spill weathering processes is well known. Many of the advances in our understanding of weathering over the past decade or two are reflected in an increased awareness of these interactions (see Fig. 1). The nature of these interactions therefore comprises a significant portion of the following discussions.

*Corresponding author. Tel: +47-73-59-1232; fax: +47-73-59-7051; E-mail: mark.reed@chem.sintef.no

Transport and weathering processes

Advection

Oil moves horizontally in the marine environment under forcing from wind, waves, and currents. Being itself a fluid with a density only slightly less than that of water, oil is also transported vertically in the water column in the form of droplets of various sizes. Both vertical and horizontal current shears are therefore important factors in the net motion of oil at sea.

Early oil spill models were typically two-dimensional surface models, using constant or variable parameters to link wind and current velocities to the velocity of the surface oil slick. Recent work by Reed *et al.* (1994a) suggests that, in light winds without breaking waves, 3.5% of the wind speed in the direction of the wind gives a good simulation of oil slick drift in offshore areas. As wind speed increases, oil will be dispersed into the water column, and current shears become more important. Field, laboratory, and modeling studies (Johansen, 1984; Elliot *et al.*, 1986; Delvigne and Sweeney, 1988; Singsaas and Daling, 1992; Reed *et al.*, 1994a) have clearly demonstrated the importance of the vertical dimension in oil movement. These studies have demonstrated that natural entrainment of oil can play an important role not only in mass balance calculations, but also in determining the spatial and temporal distribution of oil on the sea surface.

Studies of the *Braer* oil spill off the Shetland Islands (Reed *et al.*, 1993; Ritchie and O'Sullivan, 1994) further underscore the importance of entrainment in both mass balance and transport of spilled oil. The *Braer* went aground within 100 m of the Shetland Islands Coastline, and released over 80,000 tonnes of crude oil into the surf zone. The released oil was mixed into the water column, and appears to have been largely transported southwards, almost directly against the wind (Proctor *et al.*, 1994; Ritchie and O'Sullivan, 1994; Spaulding *et al.*, 1994). Observations of experimental oil spills described in Reed *et al.* (1994a) further demonstrate the importance of subsurface transport to simulate oil slick trajectories realistically over a range of oil types and environmental conditions. Youssef and Spaulding (1993) derive a wind and wave current model that successfully reproduces the above observations, assuming a mean transport depth of 2.5–5 times the wave height.

Advective currents in oil spill simulations may be derived from current atlases or other static approximations. Direct or indirect linkages to hydrodynamic models are becoming much more common, as the latter have become more widely used and easily applied (e.g. Elliott *et al.*, 1992; Howlett *et al.*, 1993; Hodgins *et al.*, 1995; Morita *et al.*, 1997). Direct coupling between oil spill and hydrodynamic forecast models is common in operational oil spill response systems (Galt, 1994; Martinsen *et al.*, 1994). Input of surface currents from real-time radar measurements is also possible (e.g. Howlett *et al.*, 1993; Hodgins *et al.*, 1994), but set-up times for such systems tend to limit their usefulness. Surface drifting buoys represent yet another source of real-time surface current data (Howlett *et al.*, 1993).

Transport on scales of 10 to 100 m is important in determining the spreading of oil. Langmuir or windrow circulation is a key surface and near-surface process at these scales. Faller and Auer (1988), Li (1996), and Leibovich (1997) have developed methods for representing the effects of such convergence zones in oil spill models. Although their importance is recognized, these methods are not yet in general use.

Summary. Advection of oil is recognized as a three-dimensional process, with key mechanisms occurring over a wide range of scales. Increasing computational power will combine with this increased insight to produce rapid improvements in this area over the next decade.

Spreading

Slick thickness and area are key variables in oil weathering and transport models. Oil slick area (or film thickness) is used in the computation of evaporation, which determines changes in oil composition and properties with time. Oil film thickness is used by many models in the computation of the rate of natural dispersion, which determines the persistence (lifetime) of the oil on the sea surface. In addition, estimates of film thickness and slick area are required for evaluation of the potential efficiency of different oil spill combat methods, and for assessments of environmental impacts.

The now classical spreading equations developed by Fay (1969, 1971) and Hoult (1972) form the basis for most spreading algorithms in use today, even though it is widely recognized that oil spreading cannot be fully explained by these equations. Major observed factors not reflected in these equations are:

- formation of elongated slicks, with a thin film trailing behind the thick slick;
- reduced spreading rate of viscous oils;
- break-up of oil slicks into small patches;
- dependence of spreading rate on discharge conditions (surface versus subsurface, and instantaneous versus continuous releases).

Mackay *et al.* (1980a,b) proposed a 'thick-thin' variant of the gravity–viscous equation developed by

Fay and Hoult, with the thick portion feeding oil to the thin layer. However, the term representing the effect of the density difference between water and oil in the original Fay equation was included in a general spreading constant. The resulting spreading rate is therefore independent of the initial oil density and insensitive to subsequent changes in density caused by evaporation and emulsification. The recognition of a link between the thick and thin portions of an oil slick represented an advance, but the model lacked any physics-based relationship between the two phases of the slick.

Lehr *et al.* (1984b) proposed a revised model to account for the observed non-symmetrical spreading of oil slicks. The extension of the slick in the wind direction was presumed to increase with time in proportion to the wind speed, while the lateral spreading of the slick was represented by the original Fay equation for gravity spreading. On this basis, the slick was represented in terms of an elongated ellipse, rather than the circular disk predicted by the Fay equation. The spreading rate in the direction of the wind was represented by an empirical wind factor obtained from observations. This model did not account for variability in thickness within the slick.

NOAA (1994) has incorporated a corresponding spreading model in the ADIOS model, with the slick represented as an ellipse, elongated in the direction of the wind. The initial area of the slick is computed according to the area at the time of transition between Fay's gravity–inertial spreading and gravity–viscous spreading regime. Fay's surface tension regime is not used in the model, but instead the slick is presumed to stop spreading when it reaches a terminal thickness of e.g. 0.1 mm. This approach produces a slick with homogeneous thickness, contrary to the observations from full-scale experiments and accidental spills.

Johansen (1984) and Elliot *et al.* (1986) developed the concept of shear spreading, caused by natural dispersion and subsequent resurfacing of oil droplets. More recent experimental work in the laboratory (Delvigne and Sweeney, 1988) and in the field (Reed *et al.*, 1994a) strongly supports this approach, which is generally accepted as the correct explanation of the physics behind the spreading phenomenon, once gravity spreading has ceased.

Experimental studies have demonstrated that viscous oils spread more slowly than less viscous oils. This effect is not accounted for in the original Fay equations, but several attempts have been made to include this parameter in Fay-type spreading models. Based on experiments within a limited viscosity range, Buist and Twardus (1984) proposed to reduce the spreading rate predicted by the Fay equations by a factor depending on the viscosity ratio between oil and water. In a subsequent paper, Buist *et al.* (1989) performed a series of tests with waxy crude oils, and proposed a terminal thickness function incorporating the difference between the pour point of the oil and the ambient water temperature. Later, based on experiments in cold water (-1.5 to $1.3°C$), Venkatesh *et al.* (1990) proposed to replace the viscosity of water by the viscosity of the oil in the original Fay equations. El-Tahan and Venkatesh (1994) approach the problem on a theoretical basis, and tried to include an extra viscosity term in the force balance equation for oil spreading, representing the shear resistance in the oil. The authors compared the extended model with experimental data, and found substantial improvements compared to the original Fay equation. However, the limited range of experiments makes it questionable to extrapolate these results to other oils. This applies particularly to emulsion-forming oils, where the viscosity may be orders of magnitude larger than the viscosity range covered in the experiments.

Studies of oil spreading on cold water have also indicated that spreading tends to stop as the slick approaches a terminal thickness on the order of 1–8 mm, apparently depending on the viscosity of the oil (Venkatesh *et al.*, 1990). An empirical relation was proposed to account for the increase in terminal thickness with viscosity, but this correlation was not confirmed by later supplementary experiments (El-Tahan and Venkatesh, 1994). This implies that other factors could be responsible for the termination of spreading, such as solidification of the oil due to crystallization of the wax content at temperatures below the pour point of the oil.

Under natural conditions, oil spreading will not stop when the terminal thickness is reached. At this point, the oil slick will tend to break up into patches and small fragments due to wave action and current shears, and these patches or fragments will be spread due to oceanic turbulence. This is one of the reasons for the somewhat pessimistic attitude expressed by Lehr (1996) towards attempts to improve Fay-type spreading models: 'it is doubtful that any of these approaches will accurately predict the slick area over any extended time period because of the neglect of outside environmental factors'. The factors neglected in these approaches are mainly wave action and spreading induced by shear currents and oceanic turbulence, which are presumed to be the dominant long-term spreading processes (see Fig. 1).

Lehr (1996) also points out that most spreading algorithms assume instantaneous release of oil in open water conditions, while real spill incidents may involve leaks which continue at a varying rate for hours or days. Methods used to predict spreading of instantaneous spills are questionable for cases with continuous spills. This is mainly due to the fact that as oil leaks from continuous spills, the oil will be moved away

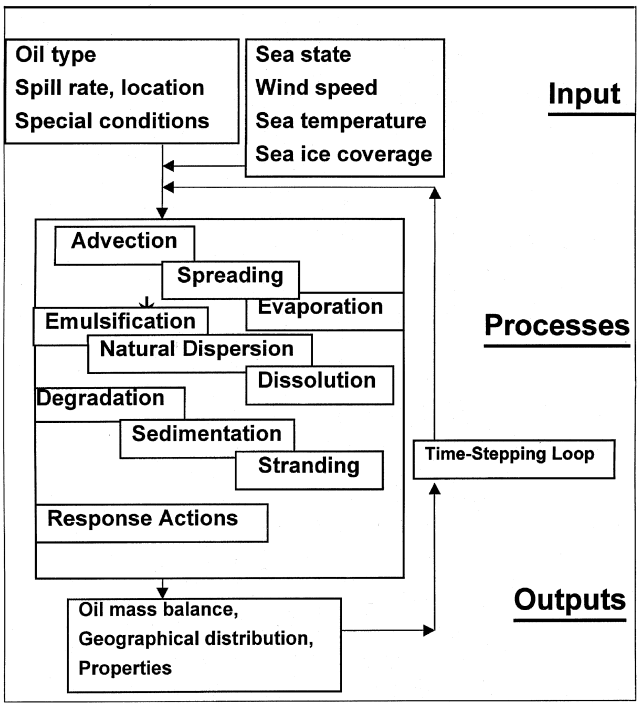

Fig. 1 General layout of oil weathering models. This schematic indicates that the weathering processes are closely interlinked; the output from one process algorithm will influence the behavior of others.

from the source with wind and currents. In such cases, at some distance from the source, lateral spreading forces will dominate, while spreading forces along the slick axis will be negligible. As pointed out earlier by Waldman *et al.* (1972), this implies that the oil will spread more in the manner of spreading in a channel (i.e. one-dimensional spreading, symmetric about the slick axis). In such cases, the slick cannot be considered as a homogenous entity (as in the Fay (1969, 1971), Mackay *et al.* (1980a,b), and Lehr *et al.* (1984a,b) models). Obviously, with a continuous release, the thickness and the properties of the oil in the slick will vary not only with time, but also with the distance from the source.

A sub-sea blowout from offshore exploration or production is one of the more serious situations leading to a continuous leak at a varying rate for hours or days. In such a case, the surface spreading of the oil will be governed by mechanisms other than gravity spreading. Sub-sea blowouts will generate buoyant plumes where the buoyancy flux is mainly related to the flow of gas released together with the oil. The oil will be transported to the surface together with the seawater entrained by the plume, and the surface spreading of the oil will be governed by the radial outflow of this entrained water. The oil film generated in such cases will be thinner than slicks formed by surface leaks, perhaps by a factor of 10 or more.

Theoretical and experimental studies of oil spreading from sub-sea blowouts were initiated in the early 1980s (Fanneløp and Sjøen, 1980; Milgram, 1983; Milgram and Burgess, 1984), and refinements of these models have continued up to the present (Swan and Moros, 1993; Rye and Brandvik, 1997; Zheng and Yapa, 1997). This recent work implies that predictions of the surface spreading may be made with acceptable accuracy for sub-sea blowouts from moderate water depths. However, for releases from greater depths (e.g. 500 to more than 1000 m), modifications of the present models will be necessary, particularly due to the expected formation of gas hydrates.

Summary. In summary, for instantaneous spills, Fay-type spreading models may provide adequate predictions of the film thickness in the thick part of the slick, where the major fraction of oil volume will be found. Such models are appropriate at least during the early stages of a release. Modifications of the Fay model for effects of oil viscosity and termination of spreading should be considered for future development. Linking spreading to dispersion probably best represents the recognized physics of the spreading process after initial gravity–viscous spreading is complete.

For continuous spills in open sea conditions, where lateral spreading will be dominant some distance downstream from the source, one-dimensional Fay spreading models seem to be more relevant than the radial spreading models used for instantaneous spills. Modifications for effects of oil viscosity and termina-

tion of spreading should also be considered in this case. For sub-sea blowouts, where the Fay equations are inadequate, surface spreading may be predicted by use of model concepts based on buoyant plume theory, allowing for significant differences in behavior (for example, hydrate formation) as a function of oil composition, temperature, and depth.

Evaporation

Estimates of evaporative losses are required in order to assess the persistence (lifetime) of the spill, and are also the basis for estimates of changes in oil properties with time. Simple methods have been widely used, mainly based on an analytical model proposed by Stiver and Mackay (1984). A model of this type is used by NOAA in the ADIOS model. More recently, Fingas (1997, 1999) has proposed a simple empirical method derived from small-scale pan evaporation experiments. Jones (1997) has recently compared predictions made with the different evaporation models, and discussed data requirements and characteristics of the models.

We distinguish here between pseudo-component and analytic methods. In the pseudo-component approach, the fraction evaporated is computed as a function of time and temperature alone. In such models, the oil is divided into a number of 'cuts' or 'fractions' specified in terms of intervals in boiling point temperature. The volume fraction in each of these cuts is obtained from true boiling point (TBP) data obtained by a standard ASTM-method. These volume fractions are converted into mole fractions on the basis of the average specific gravity and molecular weight of each cut. The vapor pressure of each cut is computed from the average boiling point and the oil temperature by means of empirical or semi-empirical formulas. On the condition that the partial pressures of these components are negligible in the ambient air, the evaporation rate for each cut is presumed to be proportional to the partial vapor pressure of each component. The actual rate of evaporation depends also on a mass transfer coefficient, which is related to the temperature and the surface wind speed. Fingas (1997, 1999) argues that the wind speed is not a relevant parameter.

Jones (1997) has modified this method by introducing an empirical relation between molar volumes and boiling point, based on data for *n*-alkanes. In this way, the pseudo-component model may be used in spite of the common lack of data on specific gravity of the boiling point cuts. The same author has also introduced an empirical equation for determination of the vapor pressure as a function of boiling point and oil temperature. This equation is said to produce more realistic pressure values, particularly at high boiling points, than the Clausius–Clapeyron equation and Trouton's rule used in Payne *et al.* (1987).

A similar pseudo-component concept is used in the SINTEF weathering model (Daling *et al.*, 1997). However, the mass transfer coefficient in this model is based on formulations commonly used for computations of surface of fluxes of momentum, heat and moisture in open sea (Smith, 1988). This implies that the mass transfer coefficient is proportional to the wind speed, with the air–sea drag coefficient used as the factor of proportionality. However, as shown by Amorocho and DeVries (1980) and Blake (1991), the drag coefficient depends on the wind speed due to changes in the surface roughness of the sea with the sea-state. The drag coefficient for near-neutral conditions appears to increase from a constant value of about 1×10^{-3} at wind speeds under 6 or 7 m/s, where white caps start to form, to about twice that value at 20 m/s (Amorocho and DeVries, 1980).

Due to the large data requirements and computational complexity of the pseudo-component concept, simpler methods have been proposed, such as the so-called analytical method developed by Stiver and Mackay (1984). This method is used presently in many oil drift models, as well as by NOAA (1994) in the ADIOS model. The method is based on several simplifications, including the questionable assumption of a linear relationship between the boiling point of the liquid phase and the fraction lost by evaporation. This linear relation is specified in terms of an initial liquid phase boiling point temperature and the gradient of this boiling point temperature versus the fraction evaporated.

It should be noted that the liquid phase boiling point data required in the analytical method are different from the data that are provided by the standard True Boiling Point curve. For this reason, a subroutine for calculation of the initial boiling point based on the TBP curve is included in the ADIOS model (NOAA, 1994). This subroutine calculates by trial and error the temperature at which the vapor pressure above the fresh oil is equal to the atmospheric pressure, and contains essentially the same algorithms as required for calculations of the vapor pressure of the remaining oil fractions in a pseudo-component concept.

When Jones (1997) made his comparisons between the extended analytical model and the pseudo-component method, he found that the extended analytical method in general predicted significantly larger evaporative losses than his own pseudo-component model. He presumed that the difference could be explained by the use of different algorithms for calculating vapor pressures in the two models. The high evaporative losses predicted by the analytical model may also in part be explained by the postulated linear approximation of the boiling point curve.

In the derivation of the analytical method, Stiver and Mackay (1984) also introduce the evaporative exposure parameter τ. They show that the relation between the evaporative loss and this parameter is thermodynamic in nature and does not depend on how the exposure is achieved. Hence, the relation is only a function of the initial oil composition and the oil temperature. For constant wind speed, the evaporative exposure parameter may be expressed as $\tau = Kt/h$, where K is the surface mass transfer coefficient, h is the initial film thickness and t is the exposure time. This implies that if the evaporative loss is computed as a function of time for one combination of wind speed and initial film thickness, the results may be used for any another combinations of wind speed and film thickness by a simple time scaling. The same applies to cases with variable wind, where the exposure is obtained from the integral $\tau = \int (K/h)\, \mathrm{d}t$.

Johansen and Skognes (1988) applied this concept in a statistical trajectory model in order to reduce the computational requirements of the evaporation calculations. In this model, the evaporative loss is computed as a function of time for a selection of crude oils at a chosen reference condition (defined in terms of a fixed initial oil film thickness and a constant wind speed). These results are tabulated in a file, which is later read during the start-up of the trajectory model. During the trajectory simulations, the evaporative loss is determined by simple interpolation, on the basis of the integrated evaporative exposure along each trajectory.

This approach could also be based on empirical evaporation data from laboratory-scale evaporation experiments, provided that the resulting evaporative losses are related to relevant evaporative exposures. Fingas (1997) has conducted such experiments for a variety of crude oils and oil products, and derived simple empirical relations for prediction of the evaporative loss as a function of time, based on commonly available distillation data for oils (i.e. per cent by weight distilled at 180°C). However, Fingas (1999) also concluded from these experiments that wind speed and exposed surface area do not significantly influence the evaporation rate. For this reason, he advocated that his correlations should be used with no corrections for film thickness on wind speed, but with a minor correction for temperature. These conclusions are not at present generally accepted in the field of oil spill modeling, and run counter to most prior work in this area.

Jones (1997) compared predictions with his pseudo-component model at different wind speeds and oil film thicknesses with the predictions based on the empirical equations proposed by Fingas, and concluded that the empirical correlations in general produced significantly smaller evaporative losses than the pseudo-component method. However, as Jones (1997) points out, Fingas used low wind speeds and relatively thick oil to establish the parameters in his model. When examining the results under such conditions, Jones found that the models were in good agreement. If the evaporative exposure relevant for the laboratory conditions could be established, adjustments of the empirical predictions for other conditions (wind speed, film thickness) could be made. However, further tests at other wind speeds and comparisons with calculations based on the pseudo-component concept should be made before such adjustments can be recommended for general use.

Summary. In summary, different methods for computation of evaporation have been discussed in this section, including the pseudo-component method, the analytical method and the more recent empirical method. The discussion may be concluded as follows.

The popular analytical method developed by Stiver and Mackay is based on distillation data not readily available. Introduction of methods to derive the required data from standard distillation data will obviously reduce the primary advantage of the analytical method, i.e. its simplicity. The analytical method is also based on questionable assumptions, which tend to produce overestimation of the evaporative losses.

The surface mass transfer coefficient formula originally proposed by Mackay, which is used in many models to date, should be examined critically, together with alternative formulations based on sea surface exchanges of momentum, heat and moisture.

The pseudo-component method seems to be the most reliable and flexible of the discussed methods. However, the computational intensity and the high data requirements of the method may still justify a search for simpler methods (empirical correlations) or 'shortcuts' (i.e. application of the evaporative exposure concept).

Natural dispersion

Computation of natural dispersion is required for assessment of the lifetime of an oil spill. The rate of natural dispersion depends on environmental parameters (i.e. the sea-state), but is also influenced by oil-related parameters, such as oil film thickness and oil properties (density, surface tension and viscosity). Emulsification will contribute significantly to the persistence of oil spills, mainly due to the sharp increase in viscosity and the increase in slick thickness with water content (retarded spreading, increasing volume, reducing natural dispersion).

Loss of oil from the surface slick due to natural dispersion can be computed by equations originally proposed by Mackay *et al.* (1980a,b). This concept is

based on an estimate of the fraction F of the sea surface subjected to dispersion per unit time, supplemented by an estimate of the fraction F_B of the entrained oil containing droplets with a size small enough to be permanently dispersed in the water column. The total rate of entrainment (m^3/m^2 s) is obtained by multiplying F by the oil film thickness. The rate of permanent dispersion is then found by multiplication of this product with F_B.

Mackay *et al.* (1980a,b) postulate that the fraction F depends on the sea-state, with an increase proportional to the square of the wind speed. The fraction permanently dispersed is, on the other hand, supposed to be independent of the sea state, and influenced mainly by the oil film thickness and the properties of the oil (i.e. the viscosity and the oil/water surface tension). Thin oil films with low viscosity and low surface tension are thus postulated to disperse more rapidly than thick oil films with high viscosity and high surface tension.

In some models (e.g. Payne *et al.*, 1987; Reed *et al.*, 1989c), only the thick portion of the slick is considered, whilst Mackay *et al.* (1980a,b) applied the dispersion equations for both the thick and the thin portions of the slick. By neglecting transfer of oil from the thick to the thin portion of the slick (where the fraction of permanently dispersed oil will be enhanced) these models may underestimate the overall dispersion rate.

Dispersion models based on the experimental work of Delvigne and Sweeney (1988) have now become more standard. Delvigne and Sweeney conducted investigations of natural dispersion of surface oil due to breaking waves in a small laboratory flume, and in a larger test basin. On this basis, an empirical relation was derived for the entrainment rate (dispersed mass per unit time) as a function of oil type and breaking wave energy. The authors also determined relations for predicting the droplet size distribution of the entrained oil as a function of the same parameters. The experiments revealed a common feature of the droplet size distribution of the entrained oil for all the experiments. The number of droplets in a certain diameter class could be related to the droplet size with a common power law relationship, independent of the type of oil and the wave conditions. From this general observation, an expression was derived for the droplet size distribution of the oil mass entrained by each breaking wave: $Q_{d \leqslant D} = CD^p$.

In this equation, $Q_{d \leqslant D}$ is the entrained oil mass per unit area included in droplets up to a certain diameter D. The exponent $p = 1.7$ was derived from the observed power law distribution of the droplet size determined from the experiments. The factor of proportionality C was found to depend on the oil type and the height of the breaking wave H, i.e. $C = aH^q$, where the dispersion coefficient a could be related to the oil type in terms of the oil viscosity. The exponent q was found to be 1.14 from the wave flume experiments, while a slightly larger value ($q = 1.4$) was found in later small-scale experiments (Delvigne and Hulsen, 1994).

Based on the limited viscosity range in the wave flume experiments, the authors postulated that the dispersion coefficient a was inversely proportional to the viscosity of the oil. However, in the subsequent small-scale experiments in an extended viscosity range, this postulated relationship was not confirmed. Instead, the authors concluded that the coefficients were very similar for all low-viscous oil types and weathering states with viscosity less than 100 cSt (centi Stokes, unit for kinematic viscosity, 1 cSt $= 10^{-6}$ m^2/s). For viscosities above this range, the coefficients decreased considerable with increasing viscosity. Thus for an increase in viscosity from 100 to 1000 cSt, the dispersion coefficient was found to be reduced by about two orders of magnitude (Delvigne and Hulsen, 1994). This agrees with observations that the dispersion rates of emulsified oils will be significantly reduced compared to non-emulsified oils (e.g. Reed *et al.*, 1994a).

The dispersion rate applies to the mass entrained by each breaking wave. In order to obtain an expression for the entrainment rate, the equation must be multiplied by a rate factor F_w. This factor is obtained from the white cap coverage, which is divided by the mean wave period to obtain the fraction F_w of the sea surface hit by breaking waves per unit time.

The authors suggest that the oil droplet dispersion may be assumed to follow this empirical relationship for the range from the smallest size classes to the size where the entrained mass equals the local surface concentration of oil (oil mass per unit area). This implies that the predicted maximum droplet size will depend on the oil film thickness, as well as the sea-state and the type and weathered state of oil.

Summary. The method of Delvigne and Sweeney, which estimates the entrained oil mass per unit area and unit time, is the most common in use today. This basic methodology is used in the ADIOS model (NOAA, 1994), the SINTEF oil weathering (Aamo *et al.*, 1993; Daling *et al.*, 1997), OSCAR (Reed *et al.*, 1995a,b; Aamo *et al.*, 1997a,b), and OILMAP (Spaulding *et al.*, 1992).

The implementation of the approach may significantly affect model behavior. In some models, droplets below a certain threshold diameter are presumed to be permanently dispersed. This threshold diameter is typically assigned a value of 70–150 μm, based on recent field measurements of the size distribution of dispersed oil droplets (Lunel, 1993). However, the use

of a specific threshold diameter is questionable for several reasons. Entrained oil droplets tend to be dispersed permanently in the water masses when the magnitude of the vertical turbulent motions is high compared to the rise velocity of the droplets. When the turbulent motion dominates, dispersed oil droplets tend to be mixed down into the water column, and as a result, the rise time to the surface will increase. This implies that the limit for permanent dispersion should perhaps be related to droplet rise velocities and sea state, rather than the droplet size.

Moreover, dispersed oil droplets tend to lag behind the surface slick due to the wind-induced current shear in the upper part of the water column. The gradual resurfacing of droplets within a certain size range will then contribute to the observed elongation of the slick, where a tail of thin oil film will be formed behind a thicker portion of the slick. These processes have been included in oil drift models based on the particle concept (Johansen, 1987; Elliot, 1991; Reed *et al.*, 1994a). This process results in a flow of oil mass from the thick to the thin slick area, from which dispersion becomes more rapid. Although the thin area represents only a small fraction of the total surface mass at any one time, it may represent a significant loss mechanism integrated over time. The consequences of the choice of a certain threshold diameter (or rise velocity) for permanent dispersion should therefore be evaluated by sensitivity analysis.

Emulsification

In many models, emulsification is computed with an implicit algorithm originally proposed by Mackay *et al.* (1980a,b). The same authors in fact advocated the use of a simpler explicit algorithm, which could be expressed in differential form. This algorithm is used by NOAA in the ADIOS model, and also in a slightly modified form in the SINTEF weathering model. The simplified algorithm contains two parameters, defining the water uptake rate and the maximum water content. Both parameters may be derived from laboratory experiments, but the parameter for the water uptake rate must in some way be scaled to field conditions and different sea-states.

Experimental studies of emulsification for different crude oils have revealed that both the water uptake rate and the maximum water content vary significantly from one crude to the other, and that these parameters also are influenced by the state of weathering of the oils (Daling and Brandvik, 1988). In general, the maximum water content tends to decrease with the viscosity of the parent oil. The differences in the water uptake rate might be related to the chemical make-up of the oil (i.e. the content of resins, waxes and asphaltenes), but the results from a limited range of crude oils were not conclusive. Due to the significant differences in emulsification between different oils, Daling *et al.* (1990) recommended that the emulsification parameters should be determined on the basis of experimental data for specific oils.

Fingas *et al.* (1997, 1999) have recently presented a literature review of emulsification and related model concepts. These authors conclude that past emulsification modeling was based on first-order rate equations that were developed before extensive work on emulsion physics took place. They suggest that empirical data should be used as a basis for further developments of emulsification models, and that such models also should take into account the stability of emulsions formed by different oils (stable, meso-stable, unstable). The stability is a measure of the decrease in the water content of an emulsion when kept in stagnant conditions. Meso-stable emulsions will lose some water when kept at rest for e.g. 24 hours, while unstable emulsions will lose practically all the water when kept at rest for the same period.

While the apparent viscosity of a stable emulsion may be two to three orders of magnitude larger than the viscosity of the parent oil, the apparent viscosities of unstable emulsions are typically no more than an order of magnitude greater than that of the parent oil. These observations should be taken into account in the predictions of the viscosity of emulsions, which normally are based on the water content, independent of the character of the emulsions. The SINTEF oil weathering model (Aamo *et al.*, 1993; Daling *et al.*, 1997) uses emulsion stability in the computation of the appropriate viscosity used in the dispersion calculation.

Summary. Reliable prediction of emulsification and the associated viscosity changes presently relies on empirical observations, since established prediction methods have proven unreliable. Predictions based on oil composition are anticipated to be possible in the near future.

Oil–ice interactions

The behavior of oil in ice is complex, and difficulties in modeling the physics of ice movement and formation on scales of meters are magnified when the uncertainties of oil behavior are added. A very significant literature exists describing oil–ice interaction studies over the past 25 years. Dickens and Fleet (1992) and Fingas (1992) give extensive overviews of the subject up to the beginning of this decade.

More recent work has focused largely on spreading of oil in an under ice (Yapa and Belaskas, 1993; El-Tahan and Venkatesh, 1994; Yapa and Weerasuriya,

1997), but calibrations rely largely on small-scale, short-term laboratory studies. After the first hour or so, spreading in the field will be governed by ice lead dynamics, which tend not to be included in these solutions.

The most realistic field data on the weathering of oil in the presence of sea ice are those reported by Singsaas *et al.* (1994). These data show that the processes of evaporation, dispersion, and emulsification are all significantly retarded in ice leads, contrary to the conclusions drawn by Payne *et al.* (1987) from meso-scale laboratory experiments. Wave-damping, the limitations on spreading dictated by the presence of sea ice, and temperature appear to be the primary factors governing the observed weathering rates. A key problem in achieving any improvement in modeling these processes lies in our very limited ability to model the behavior of the ice itself at the necessary spatial scales, which are on the order of meters. The real-time forecasting attempt reported by Reed and Aamo (1994), and the model development and hindcasting work by Johansen and Skognes (1995) exemplify the problems encountered when oil–ice interaction models are put into active use in the field. The present limited ability to model ice behavior at the 1–10 m scale also seriously limits the extent to which use can be made of the advances in modeling of oil spreading cited above. Ice coverage is a dynamic variable, and can change from 50% to 99% overnight, with extreme consequences for oil weathering due to changes in thickness.

Summary. The pessimistic view is that the modeling of oil weathering in the presence of sea ice remains at an ad hoc level, limited largely by the state-of-the-art in modeling sea ice physics at the appropriate scale. A more optimistic summary would take account of the advances that have been made in our understanding of oil weathering processes in the presence of sea ice. This new understanding has come primarily through fieldwork, the results of which have corrected misconceptions introduced through prior laboratory weathering studies. The optimistic conclusion, then, is that the next generation of oil-in-ice weathering models will simulate actual conditions better than earlier models, although remaining highly parameterized and lacking dynamic reliability.

Oil–shoreline interactions

Several published models now exist which include some level of dynamic representation of oil in the coastal zone. The most comprehensive of these is the coastal zone oil spill model COZOIL (Reed *et al.*, 1989c; Howlett, 1998). In addition to a relatively thorough representation of oil–sediment interactions, COZOIL incorporates a wave propagation model for the surf zone, a wave-induced long-shore velocity, and a representation of the shoreline that varies segment-by-segment. COZOIL was tested against wave data from the Alaskan Peninsula, and against data from the Amoco Cadiz oil spill (Reed and Gundlach, 1989).

Other models tend to assign a holding capacity and removal rate to each shoreline type (Torgrimson, 1980; Seip *et al.*, 1986; Shen *et al.*, 1987; Reed, 1989; Humphrey *et al.*, 1993). Holding capacity, or how much oil a given sediment type will retain per unit length or per unit area, is not well documented in the literature; Gundlach (1987) presents a summary of observations focused on this concept. Reed *et al.* (1989c) compute holding capacity from oil viscosity, sediment permeability and porosity, and tide level. Darcy's Law is used to compute penetration depth, allowing for the rising and falling of the tides while residual oil remains on the surface of the sediments. Humphrey *et al.* (1993) employ a simplified version of the approach, in which constant parameters replace the dynamic equations in COZOIL.

Summary. Most models reviewed calculate the mass remaining ashore as a first-order process. Values of the removal rate constant vary among models. The COZOIL model does not actually assign rates, but computes them based on sediment and oil properties, and the wave environment. The model proposed by Humphrey *et al.* (1993), the most recent model focused specifically on oil in coastal sediments, also uses a constant first-order removal rate. This simplified approach does not reflect the importance and the state of understanding of environmental conditions, as reflected in the wealth of more recent observations (e.g. Hayes *et al.*, 1991; Johns *et al.*, 1991; Pavia, 1992; Baker *et al.*, 1993; Michel and Hayes, 1993; Owens *et al.*, 1993; Sveum and Bech, 1993). Such simplifications may remain useful in cases where one is unable to observe or model the physical environmental variables.

Future efforts would appear best focused on models which include explicit descriptions of the processes active at the coastline, since continued use of highly parameterized models will not further our understanding of the underlying governing processes.

Oil properties

A weathering model keeps track of the changes in the composition of the oil due to loss of volatile fractions. Changes in the oil density are typically computed on the basis of evaporative loss and water uptake (emulsification). Computation of the viscosity of the oil in terms of the viscosity of the remaining fractions has been attempted, but produces unrealistic

values (Payne *et al.*, 1987; Fingas *et al.*, 1995). Instead, the viscosity of the weathered oil is often computed from the viscosity of the fresh oil at a standard reference temperature (25°C) and the fraction lost by evaporation. This viscosity can be scaled with temperature according to a chemical handbook formula. The increase in viscosity due to emulsification can then be computed from the viscosity of the weathered oil and the water content by a formula proposed by Mackay *et al.* (1980a,b). Experience has demonstrated that this computational approach can also introduce serious errors into the viscosity estimate, such that empirical data for each oil remain the surest basis available (Daling *et al.*, 1997). Fingas (1999) suggests a predictive methodology for emulsification based on oil composition, but the approach has not yet been tested.

Other properties, such as the pour point and the flash point of the oil, are also of interest in conjunction with assessments of different oil spill combat methods. These properties will also change with oil weathering, but predictions of these changes are probably best made in terms of empirical data for each individual oil.

Spill response

A primary purpose of oil weathering and transport models is to reduce the environmental impact of spills through improved selection of response strategies. A few oil spill models include some capability to simulate spill response actions. Published descriptions of such models are few. Reed *et al.* (1995b, 1999) and Aamo *et al.* (1997a,b) describe the oil spill contingency and response model OSCAR, developed specifically as a tool for quantitative comparison of alternative oil spill response strategies. The model couples weathering, surface trajectory, water column, and oil spill response components. The behavior of individual working groups, such as vessel-skimmer and helicopter-dispersant systems, are simulated, each with an assigned strategy and work area. Environmental factors such as winds and waves, and available daylight relate functionally to effectiveness of mechanical cleanup. The application of chemical dispersants is simulated based on observations from field trials (Daling *et al.*, 1995; Lewis *et al.*, 1995)

Conclusions

Future directions

Increasing computational power will continue to strengthen oil spill models, allowing more physical and chemical detail, and more direct coupling to hydrodynamic and meteorological models. However, there is no direct correlation between computational capacity alone and the quality of model results. Additional research is necessary to further our understanding in some fundamental areas.

Oil composition and properties

Emulsification is a key process in determining spill lifetime as well as the window of opportunity for spill response (Nordvik, 1995). Reliable computations of emulsion formation, stability, and associated viscosity at present require laboratory or field observations. Such observational data sets are expensive to acquire. The development of correlations between parameters commonly available through crude assay data and anticipated emulsion characteristics would be a valuable contribution. Fingas (1999) suggests a solution to this problem, based on the per cent asphaltene content in the weathering oil. This idea will clearly be pursued further.

Spreading and advection

Spreading is important in determining the fate of spilled oil through evaporation, emulsification, and natural dispersion. Emulsification and evaporation lead to decreased oil–water density difference, and increased pour point; these can be used to estimate the cessation of spreading as described by the classical gravity–viscous equations of Fay and Hoult. For most crude oils, this limit is attained very early in the development of an oil spill, at which point environmental forces govern. Processes at the scale of 10–1000 m, which are often at the sub-grid scale for hydrodynamic input data, need to be included in oil spill models. Langmuir circulation is a central process active at these scales, and several alternative approaches exist to allow this advance to take place (Faller and Auer, 1988; Li, 1996; Leibovich, 1997).

The representation of realistic spatial variability in thickness is another area that is poorly developed in present models. The application of thiessen polygons to estimate local thickness from Lagrangian elements (Galt, 1997, and personal communication) may prove useful in resolving spatial variations in average thickness, if the appropriate physical processes are included in the weathering and transport.

Release conditions are also relevant in determining initial spreading. Underwater releases, for example, result in very different initial surface distributions of oil than surface releases (Rye and Brandvik, 1997).

Natural dispersion and emulsification

Natural dispersion and emulsification are competing processes in the sense that each reduces the rate at

which the other occurs. Emulsification and slick thickness are important in determining slick lifetime, windows of opportunity for alternate response strategies, and environmental impact. Delvigne and Sweeney (1988) achieved a significant advance in algorithms for natural dispersion, but the resulting equation for dispersion rate is strictly a curve fit, with no grounding in fundamental physics or dimensional analysis. The same is true of all extant emulsification algorithms. Fingas (1999) appears to be close to a predictive capability for emulsification based on oil composition, but there is significant opportunity for new thinking and advancement in both these areas.

Oil–ice interactions

As discussed above, the prognosis for improved representation of oil behavior in ice-infested waters remains bleak until our capability to model the behavior of ice alone improves. The basic problem is that the processes governing oil behavior occur at scales of a few centimeters to a few tens of meters within an ice field. Ice model resolutions are typically at scales of kilometers, to account for effects at active boundaries, such that very crude, ad hoc parameterizations become necessary. Knowledge gained from laboratory experiments is of limited usefulness, due to limitations imposed by edge effects.

Oil–shoreline interactions

The behavior and fate of oil coming ashore has received extensive attention since the 1989 oil spill in Prince William Sound, Alaska. Model development has not made good use of this wealth of data, nor has development focused on representation of the underlying processes that are active in the coastal zone. Here is another area in which increased computational resources can contribute to allow more detailed physics to be represented in models.

Spill response

Oil spill response actions remain highly parameterized in most models. The leakage of oil from booms is an example of an area in which recent advances (e.g. Brown *et al*., 1996; Goodman *et al*., 1996; Grilli *et al*., 1996) appear mature enough for incorporation into spill model systems.

The effect of dispersant application on oil properties, particularly oil viscosity and emulsion stability, is key to accurate simulation of response success. Only limited data are available in this area, and the underlying mechanisms are incompletely understood. Applied research in this area could be fruitful.

Net environmental benefit analyses (NEBA)

Objective evaluation of the net environmental benefit of alternate oil spill response strategies during contingency planning and response requires the application of an oil spill model coupled to a biological exposure and effects model. Such systems of models are not new (e.g. Reed and Spaulding, 1981; Spaulding *et al*., 1985; Reed *et al*., 1989a,b), and in some cases are in use under national legislation (Reed *et al*., 1989b; French *et al*., 1996). Improved biological impact models, and direct linkages to oil spill and other pollutant fates models, will become more common in the near future, with development of a model specifically for NEBA already in progress (Singsaas, 1998).

Real-time data acquisition

Improvements in the acquisition, interpretation, and transmission of remotely sensed data will contribute to oil spill modeling in several ways. First, real-time updating of drift and spreading computations will become possible, relying on direct transmission from over-flight aircraft. Second, as our ability to measure slick thickness from aircraft improves, mass balance estimates will be much improved, and dispersion rates, both natural and chemical, will be measured more accurately than is possible today. The remote estimation of water content may also become possible, in which case synoptic weathering pictures can be built up to supply calibration and test data sets for models.

Third, the Internet is likely to result in significant changes in how oil spill models are designed in the future. Nearly real-time acquisition of input data, including winds, currents, and over-flight images can be achieved in this way, virtually world-wide. Model results can also be disseminated rapidly via the Internet. Whether or not advantages will be realized by executing model code at central locations, and downloading to branch nodes, remains to be seen.

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