13 Trajectory Modeling of Marine Oil Spills

Debra Simecek-Beatty and William J. Lehr

Hazardous Materials Response Division, National Oceanic and Atmospheric Administration,
7600 Sand Point Way NE, Seattle, Washington.

13.1 Introduction

While fingerprinting of oil is a common aid in identifying the source of an oil spill, techniques that estimate the past history of a "mystery" spill can also assist the forensic investigation. These techniques can include such procedures as estimating the age of the slick, based upon the degree of environmental weathering, and tracking the oil back to its possible source by time-reversing standard oil trajectory forecast models. In order to understand the usefulness and limitations of these techniques, it is necessary to understand current oil spill trajectory and fate forecasting methods.

Even a novice observer will notice that, when spilled on water, most oils quickly spread into a thin film. The oil will drift with certain persistence, mostly likely downwind or, in the case of a strong current, with the surface flow. Eventually, waves rupture and tear the film into smaller and smaller patches. Because the sea is in constant motion, random swirls and eddies disperse the oil patches further apart. While water moves horizontally and vertically leading to divergences and convergences at the surface, patches of floating oil primarily move horizontally at the sea surface and drift closer to areas where the water converges. Oil patches are often fluid and sticky. If they float into an area of convergence, they may adhere to each other and coalesce into a larger patch. The spreading, dispersion, and coalescence of oil fluctuate constantly. Describing such chaotic phenomena is not easy, but if we think in terms of averages, the movement and behavior of the spill are predictable. Today, computerized models can estimate the "most likely" behavior of an oil spill, in spite of the chaotic nature of the wind and sea conditions. This has not always been the case.

Before the 1960s, finding a mathematical model that predicted the movement of oil spilled on water was difficult. However, several events led to the rapid progress in oil spill modeling and research. In the United States, oil spill damage from the 1967 well blowout of Union Oil Platform A in the Santa Barbara Channel resulted in more oil spill regulation and increased research funding. There were also a series of "super" spills from tankers in 1967 and 1968 with the *Torrey Canyon* casualty being the most notable (Biglane, 1969). With the influx of oil spill research funding, a multitude of theoretical models was developed for predicting oil spill fate and behavior. The review by Fallah and Stark (1976) of the work prior to the mid-1970s is admirable, but for the most part, Stolzenbach et al. (1977) is considered the classic work of its time due to its comprehensive discussions on wind fields, advection, and oil weathering.

A rash of spills in the 1970s led to an influx of new ideas and methods for oil spill modeling. The *Argo Merchant* grounding in 1976 was one of the most studied oil spills in history, with over 200 scientists participating in the response effort. Five independent research teams provided operational forecasting of the oil distribution (Grouse and Mattson, 1977; Pollack and Stolzenbach, 1978). During the 1979 IXTOC-1 well blowout, then considered the world's largest spill, operational forecasting was fully integrated into the response effort and was used to direct cleanup activities (Hooper, 1981). In each incident, approaches to the forecasting problem varied from deterministic, via simple vector addition of the wind forecast and tidal current predictions, to statistical, using probability matrixes of the historical wind and current data. Observations of the oil distribution and, if available, satellite imagery were used to initialize and update the model forecasts. These early forecasting efforts tried to predict oil spill trajectories operationally in a manner similar to the way that meteorological offices use atmospheric models to routinely update weather forecasts. Other, and just as significant, modeling efforts occurred (Haung, 1983; Spaulding, 1988), but the *Argo Merchant* and IXTOC responses best illustrate the state-of-the-art for the times.

If a spill were to occur today, the "best guess" would probably be a compilation of outputs from different models (Daniel et al., 2002) or even from the same model if using different boundary conditions and data choices. More than one model may be used because a particular model may perform better in certain situations. Performance varies because the mathematical equations describing oil movement are complex, making an analytical solution impossible. To circumvent this problem, all spill models simplify the underlying equations to a certain extent by making assumptions. Therefore, one model's simulation of a particular aspect of an oil spill's fate and behavior may be rigorous, but it is likely to be weaker in other aspects. Discussions of the strengths and weaknesses of the current state-of-the-art oil spill models can be found in Yapa and Shen (1994), Anon (1996), Cekirge and Palmer (2001), and French-McCay (2004).

To some, oil spill forecasting is still considered a seat-of-the pants operation that relies on experience to manipulate both model input and parameters. Part of this perception is due to the use of nonrigorous mathematics, as simple physical laws cannot describe many aspects of oil spill behavior. Another complication is the general lack of real-time environmental data for model initialization. Even the initial release details about the location and amount of oil spilled are often sketchy. Therefore, any uncertainty in the release is directly translated into uncertainties in the forecast concentrations. At best, most spill modelers rely on empirically derived models to some extent and expect large uncertainties in the model input data. Despite these limitations, it is clear there has been some degree of success in oil spill forecasting.

13.2 Forecasting and Hindcasting Oil Spill Movement

Most spill models are flexible enough to allow for a wide variety of modeling techniques. In general, the models run in either a tactical mode, used for short-term forecasting from a known source or in a statistical mode, using historical environmental conditions to generate a long-term forecast. Occasionally, the modeler uses a forensic approach to investigate the past trajectory of an oil spill. Modelers call this approach a "hindcast" of the spill. After the fact, the trajectory of the oil is analyzed to determine a possible oil source and the most probable path of the spill. In hindcasting, the idea with either a forward or backward model run is to "re-forecast" the oil movement for a particular spill event and provide investigators an indication when and where the spill occurred. Selecting either a forward or backward option depends upon the question being asked.

The first option, running the model forward in time, is used if the location of the oil source is known or needs verification. Depending on the spill conditions, small errors in the location and time can cause significant changes in the trajectory. For example, a 30-minute error in the release time can be important in a tidal dominated area due to changes in the tidal phase. By comparing the spill trajectory to the reported release site with the timing and location of, for example, shoreline oiling, the modeler can further refine the likely timing of the release. Besides the location and time of the release, model inputs will include on-scene wind and current observations. Astronomical tides and historical current data are used if nothing else is available. Using this technique, the modeler can investigate where the spill occurred.

The second option involves running the model backwards in time from the location where the oil is found. This particular modeling approach attempts to answer the question, "Where could the oil have come from to contact this resource?" Perhaps an oiled shoreline or, even, oiled birds are discovered, but the source of the spill is unknown. Here, the model is run backwards using historical environmental data and statistical techniques to determine possible spill locations and times. Searches of the potential spill locations may expose a source, such as a submerged vessel or a vessel transiting the area and dumping bilge oil.

Even when using models in a hindcast mode, the modeler will be faced with incomplete environmental information. Uncertainty in the input data translates as uncertainty in the trajectory calculation, either in the forward or backward time sense. The traditional approach to hindcasting trajectories uses the most probable set of environmental data in a deterministic answer that provides a "best-guess" oil path and potential release point. However, doing so neglects valuable statistical information contained in environmental history for the spill area, a point recognized by meteorologists (Roulston and Smith, 2002) when making weather predictions.

There are two nonexclusive ways of incorporating statistical uncertainty into hindcasts. One way is to assume that the underlying major environmental parameters (e.g., general wind and current patterns) are exact and that internal parameters in the model vary according to known statistical distributions (Lehr et al., 1995, 1999). These "internal" parameters can be components of the spill model itself, such as drift factor, or wind and current fluctuations that occur at a smaller spatial or temporal scale than that used to define the major wind and current patterns. Jones (1999) has shown that the spill trajectory is particularly sensitive to temporal resolution of the winds. However, the time series of wind velocity at a data-recording site may be linked only in a statistical sense to the wind time series experienced by floating oil at a different location. Winds from a measurement location may not accurately represent winds over the entire area covered by the spill.

Another common method to incorporate uncertainty is to include the statistical variation directly within the large-scale wind and current data (Paluszkiewicz and Marshall, 1989). Usually, this is done in a forecasting mode but can also apply to hindcasts, particularly when one recognizes that the exact location and time of the spilled oil are uncertain. Paluszkiewicz and Marshall recommend using prior wind histories in any sample run rather than generating artificial wind histories from climatological data. When using either or both methods for including uncertainty in the output display, the modeler is faced with a significant challenge in presenting the resulting probability information in a manner that is easily understood by the model user. This is an area of active research.

13.3 Oil Spill Transport

Winds and currents play an important role in oil spill transport and, occasionally, oil moves in a direction that results in unexpected outcomes. For instance, during the 1967 grounding of the *Argo Merchant*, 27,000 tonnes of heavy fuel oil were spilled. There was a certain expectation of extensive shoreline oiling because the vessel was near shore. However, the spill essentially drifted out to sea due to offshore winds and currents. In contrast, the offshore sinking of the *Erika* in 1999 released approximately 14,000 tonnes of heavy oil and resulted in more than 100 km of oiled coastline.

There are two accepted methods for modeling oil movement on water: Eulerian and Lagrangian. The Eulerian representation of oil movement records the concentration of the oil patches or particles flowing past a fixed point. The Eulerian approach solves a simplified form of the classic advection-diffusion equation. Assuming two-dimensional flow, the Eulerian form of the equation follows:

$$\frac{\partial c}{\partial t} = -\nabla(cV) + \nabla(D\nabla c) + S$$

where:

c = the concentration of oil
t = time
V = advection velocity
D = horizontal diffusion coefficient
S = sources and sinks of oil
∇ = gradient operator

There are significant challenges to solving the equation. For example, most spills begin as small releases or point sources, such as a series of damaged tanks from a vessel aground. Over a period of days to weeks, the oil spreads over hundreds of square kilometers. The advection due to winds, currents, and turbulence has a different time and length scale a few weeks into the spill as compared to the initial release. There is an additional problem of numerical diffusion associated with hydrodynamic modeling, but this is a minor issue compared to the overall errors associated with oil spill model uncertainty (Barker, 2005). Solving the advection-diffusion problems often requires various statistical methods, which increases the computational complexity of the model.

The Lagrangian method represents a patch of oil as a set of particles and follows the path taken by each particle of oil as it moves relative to the earth. The velocity and direction are calculated as the particle changes position with time. In addition to tracking the overall movement of the spill, the particles also track the weathering of the oil (e.g., evaporation and dissolution).

Traditionally, oil spill modelers use a combination of Eulerian and Lagrangian methods. The velocity field for the currents and winds are derived using Eulerian techniques and are represented as individual velocity vectors at fixed points in the model domain. The method is useful for areas with historical data, such as tidal records or salinity and temperature, to predict the flow passed a fixed point. Oil patches are represented by individual particles that are sometimes called Lagrangian elements (LEs), spillets (French-McCay, 2003), or splots (Beegle-Krause, 2003). A major problem is translating numerous oil particles into a continuous concentration function. Usually, this is done by setting up a grid and counting the number of particles in each grid box. This may make concentration dependent on grid resolution. To adequately represent the concentration, a large number of particles and a fine grid are needed (James, 2002).

The modeler must take care to ensure the number of particles selected is sufficient to assure accurate and stable statistics. The number will vary with each spill situation. For a very large spill, 1% of the oil spilled would be significant and, consequently, a large number of particles should be used to model the spill movement. As an example, 1% of the 1989 *Exxon Valdez* spill represented about 410 m^2, a significant amount of oil. Therefore, 10,000 particles were used to represent the spill (Galt, 1991). In the event of a minor release, 1% may not be significant. Typically, 100 particles are used to represent smaller spills. Further analysis, with multiple model runs, can help determine the appropriate number of particles. To demonstrate this concept, an oil spill model was run twice with the same environmental conditions, but the number of particles chosen to represent the spill was different (Figure 13-1). Both outputs have similar movement, but the trajectory with 100 particles, Figure 13-1A, does not show a shoreline threat, whereas the model run with 1000 particles, Figure 13-1B, indicates shoreline contact.

In some instances, the modeler contours the particles and presents the output as the “best

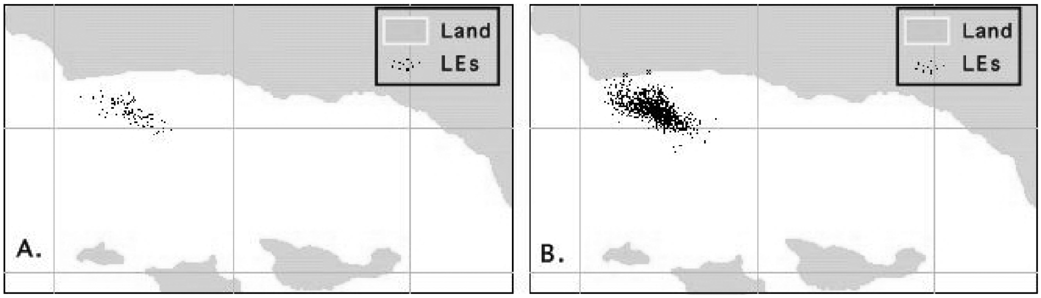

Figure 13-1 Comparison of a trajectory forecast with oil representing 100 (a) and 1000 (b) particles or Lagrangian elements (LEs).

guess" of the oil movement (Galt, 1997a). Since the particle separation is a measure of concentration, the analysis is very sensitive to the particle location. Determining concentrations for particles that are very close together or overlay each other becomes problematic. As Barker (2005) points out, it is not clear if two particles overlaying each other represent the same patch of oil. Modelers may contour the particles and present the best guess with a confidence level that, in general, is the bounding polygon of 99% of the particles. Selecting the appropriate number of particles is critical to the analysis, as one particle cannot give any uncertainty bound and, given a lengthy processing time, one million particles are not practical.

The oil spill trajectory should represent more than one model run (Galt, 1997b). The first set of model runs represents the standard trajectory forecast or "best guess" and uses the best-available data. The second set of model runs, the "uncertainty analysis," uses the expected errors in the input data. Each model run will have slightly different initial conditions that represent various "what-if" scenarios. This is particularly important because model input data are generally imprecise and limited during an emergency response. Real-time meteorological and oceanographic measurements are notoriously sparse. In these situations, the investigator will explore alternative spill scenarios, such as the effects on the slick movement if the surface current was 50% less than initial reports.

Other possible errors in the model input data are the location of the spill site and the distribution and amount of the floating oil. Initial estimates of the amount of oil spilled are often unreliable due to calculating release rates under adverse conditions (e.g., bad weather, grounding, or collision). Visually observing the resulting slick to estimate the amount of oil floating on the surface is inaccurate (Research Institute, 1983). Other potential errors result from reports of oil that are actually naturally occurring phenomena, such as kelp beds, silt plumes, algae, and jellyfish (NOAA, 1996). It is not unusual for emergency responders to collect oil spill observations using nonstandardized techniques and, as a result, observational reports vary between observers. Standard practice for reporting visual observations of oil on water is described in the American Standards for Testing Materials (ASTM, 1997).

Unfortunately, techniques for estimating uncertainty in observational errors have yet to be developed. To account for these types of uncertainty and others, multiple model runs with varying inputs are commonly used. In general, the model runs are averaged and the response community is presented with a "best guess" of where the oil is likely to go. The model runs that provide answers outside the average are interpreted as model "uncertainty."

13.3.1 Wind

When the wind blows across the sea surface, the oil slick drifts with the waves and currents.

Traditionally, oil spill modelers couple oil transport by wind-driven waves and the shear stress on the oil slick into one term called the "wind drift factor." Perhaps the best-known rule of thumb in oil spill modeling is the "3% rule" (Smith, 1976; Huang, 1983). This rule actually has some theoretical basis (Wu, 1983) and has been verified in observations of accidental oil spills and field and laboratory experiments (Fallah and Stark, 1976). The 3% rule represents average conditions, but in the experience of the authors and others, the actual factor ranges from 1% to 6% (Lehr and Simecek-Beatty, 2000). For example, heavier oils are often subject to overwash. While submerged, they will only drift at the speed of the water current and, hence, will have a net lower drift speed than that given by the 3% rule. On the other hand, oil caught in the "valleys" or convergences in the windrows will move faster than normal (Leibovich, 1997). This uncertainty is modeled by randomly selecting a slick drift between 1% and 6% of the wind speed for each particle at each time step.

Oil drifts at an angle of about 10° (Madsen, 1977) to the wind (to the right in the northern hemisphere and left in the southern hemisphere). Trajectory modelers may not include the deflection angle, as the marine forecast for the wind direction is generally not accurate to within 10°.

In general, the largest input error for the oil spill model is the wind forecast. The accuracy of the forecast depends on, among other things, special weather features, length of the forecast period, and ability of the forecaster to localize his/her prediction to the spill site. Optimum forecast periods are usually between 6 to 24 hours. Beyond 5 days, a wind forecast based on numerical predictions is generally no better than climatology. Lehr et al. (1999) discuss typical ranges of forecast errors in the wind direction and speed. They report two different approaches for entering wind uncertainty into oil spill models: (1) ask the marine forecaster about wind uncertainty; or (2) use an algorithm to simulate forecast uncertainty. For the forensic investigator, this is an important consideration if the on-scene weather observations are not available near the spill site and the only other available information is archived weather forecasts.

The first approach, and by far the easiest, requires a good verbal briefing by the meteorologist, who can provide information about wind shift timing, the strength of the pressure gradient, location of high/low fronts, and local land effects (i.e., sea breeze, topography). With this approach, a constant, time-dependent wind vector is assumed to represent the entire spill area. The wind file containing the meteorologist's best estimate and error estimate can then be fed directly into the model. The challenge with this approach is converting a verbal or written forecast into a file form to enter into an oil spill trajectory model. Most forecasters use standard words and phrases that can be easily translated to a digital format. For example, the wind forecast may indicate winds from the south at 10 m/s for 12 hours, becoming southwest at 5 m/s. If the forecaster indicates the forecast wind shift could be off by 3 hours, the wind direction off by 20°, and the speeds by 3 m/s, the original wind file is modified or an additional file is created with this data. Further details on this approach can be found in Lehr et al. (2003). The second approach adopts a more automated slant to estimating wind data error. This approach uses algorithms based on past weather forecast accuracy records (Lehr et al., 1995, 1999, 2003). While this method may be easier to implement, there is no confirmation yet that it produces superior results than that achieved by a skilled weather forecaster and an experienced modeler.

For the investigator, using a single wind vector based on a verbal briefing of the marine forecast may be sufficient in offshore areas over short length scales. As the oil moves closer to shore, a single constant wind vector could misrepresent effects due to topographical steering of the winds and other localized phenomena. Discussions with the forecaster about these effects can reduce the overall error in the analysis.

An approach that is becoming more accepted in the oil spill modeling community involves importing a time-dependent and spatially varying wind field from an atmospheric model. Careful consideration is needed before importing winds from an atmospheric model. Discussions with a local meteorologist can provide insight to the investigator about the availability of models for a specific area and the model limitations for the time frame of a particular spill event. Atmospheric model resolution ranges from a kilometer to several hundred kilometers (Table 13-1). For most instances, the regional meso-scale models are suited for oil spill trajectory modeling.

13.3.2 Currents

The ocean has three types of current systems that can transport oil: density-driven; wind-driven; and tidal. Offshore, the density-driven currents are often regarded as slow and not varying very much in speed or direction. Therefore, their variance is of less importance for most oil spills since small spills have time scales of a few hours to several days. Density-driven flow can be important in estuaries and in the nearshore coastal areas due to freshwater outflow. Generally, the investigator's focus will be on spills in estuarine environments and areas with coastal flow over the continental shelf with well-mixed conditions. In these locations, the wind-driven and tidally driven currents are of the most interest and have length and time scales that range from tens to hundreds of kilometers and a few hours to weeks (Table 13-2).

Table 13-1 Grid Resolution of Atmospheric Models Modified from Kalnay (2003)

Atmospheric models	Grid resolution
Climate	Several hundred kilometers
Global weather	50–100 km
Regional meso-scale	10–50 km
Storm scale	1–10 km

One of the more important advances in the development of oil spill modeling capabilities in the last 20 years has been in ocean circulation forecasting. In a few regions, oil spill modelers have the ability to import time and spatially varying current forecasts that are automatically updated every few hours (Beegle-Krause, 2003). Numerical models are initialized with real-time observation data (e.g., water level, satellite altimetry, and sea-surface temperature), and a circulation forecast is made using meteorological and, if needed, river flow forecasts. Other technical advances are nested grid systems that use a low-resolution, global ocean model to provide boundary conditions for high-resolution, regional models. In general, the modeler ensures quality-assurance standards are in place before importing the current predictions. Using standardized data exchange protocols (Beegle-Krause et al., 2003), these types of current predictions are now routinely imported into oil spill trajectory models.

In areas without a real-time regional circulation model, simulating the current becomes complicated. Ideally, a three-dimensional hydrodynamic model (e.g., Blumberg and Mellor, 1987; Blumberg and Herring, 1987) would be modified for the spill site. The models are sophisticated and require extensive oceanographic data for input. In a spill response situation, acquiring relevant real-time data, such as salinity and temperature at depth, is highly unlikely. To work around this problem, modelers may use a combination of real-time measurements, such as the wind

Table 13-2 Estimated Length and Time Scale of Oil Movement Due to Surface Current Transport

Surface current	Length scale	Time scale
Ocean circulation	1000's of kilometers	Months to years
Coastal flow	100's of kilometers	Weeks
Estuarine circulation	10's of kilometers	1 to 2 days
River	10's of kilometers	Hours to days

direction and velocity, astronomical tidal predictions, and historical data for the ocean measurements at depth [e.g., *NODC* (Levitus) *World Ocean Atlas*, 1994]. The difficulty is that the historical records are often short and collected under environmental conditions very different from that for the spill. For example, the data may be collected for a few weeks during a research cruise years before the spill incident. Even if the data were available to run the model, it is very difficult to adjust the current distribution or patterns from on-scene observations. If such adjustments are made, they must be done in such a way that ensures continuity is preserved. Failure to consider conservation of mass when modifying the currents can result in unintended convergences or divergences in the modeled circulation.

Two-dimensional hydrodynamic models provide a relatively simple and quick method for creating a circulation pattern based on bathymetry and fluid conservation laws. Key advantages for using a 2D model are the minimal data requirements while still conserving mass. The models are usually depth-averaged and assume the circulation is slowly varying and, therefore, steady-state. Updating the model from on-scene observations of the currents is generally straightforward. Because the current patterns conserve mass, the modeler can add multiple patterns to describe specific characteristics of the spill area. Examples of 2D hydrodynamic models used for spill response can be found in Galt (1975, 1980), Galt and Payton (1981), Proctor et al. (1994), and Sankaranarayanan and French McCay (2003).

It is important for the investigator to carefully select the best available tool that is based on fluid conservation laws. Convergences and divergences in the flow, which are important for spreading and concentrating oil, need to be accurately represented to forecast or hindcast oil movement. Two especially problematic approaches used by the operational response community are "smoothing" of the circulation pattern and high-frequency radar (HF). The first approach involves the linear interpolation of one or two on-scene current observations to develop a spatially varying current. This may or may not involve smoothing "errant" vectors along the shoreline. The main issue with the approach is the blatant disregard to fluid conservation and, therefore, the modeling community routinely rejects it.

The second approach, the remote sensing tool HF radar, is used to measure and present the spatial distribution of the upper layers of the surface current direction and velocity by averaging small areas of the sea surface. In order to derive the current circulation, a complex process is used to remove the wind from the signal. The investigator should recognize that HF systems are not predictive tools. Oil spill modelers need to know the currents at least 24 to 36 hours into the future. To turn the system into a predictive tool, modelers need to know something about the forcing mechanisms responsible for transporting the water. At this time, modelers do not have the tools to analyze the HF data to understand the forcing mechanisms. Other problems include that placement of the HF antennas often results in blind spots in the nearshore areas. In the circulation pattern, this appears as areas without current. In addition, the output may show on-shore current vectors. In reality, there is likely a long-shore current transporting oil near the shoreline. This could lead to errors in predicting oil contact on the shoreline. Finally, the system cannot provide 3D current observation: the system measures the water movement at the surface.

Subsurface circulation models developed for response tend to be very simple due to the constraints involved with 3D hydrodynamic models. Pseudo-3D models, which are essentially modified 2D models, are the accepted practice. Since near-bottom drift data and higher resolution bathymetery (e.g., depressions or deep holes in the bottom) may not be readily available, oil moving along the bottom is often parameterized with a simple resuspension term. Unfortunately, issues with modeling and tracking submerged oil as described in Conomos (1975) are not much different than present-day capabilities (NOAA, 2004).

13.3.3 Turbulent Diffusion

Modeling turbulence in the ocean is a complex process that requires complicated computer simulations. Most oil spill models use simplified formulas to simulate mixing. In general, a particle-tracking scheme is used with turbulent diffusion represented by random movement of the particles. A common approach is to represent turbulence using a constant diffusion coefficient, but there are other options. James (2002) offers an alternative to uniform turbulence, but the formulas may not be practical. Elliot (1992) has developed empirical formulas that relate horizontal diffusion to the tides and wind. Thibodeaux (1979) suggests the horizontal dispersion coefficient can be estimated by comparing successive aerial observations of the surface slicks. In practice, the method is not used because the dispersion coefficient estimated on the first day of a spill event will be different seven days into the spill due to advection of the oil by larger-sized eddies. Some researchers suggest that diffusion is proportional to the depth of the region. Most spill models assume constant and uniform dispersion coefficients, which are based on historical measurements such as those presented in Okubo (1971). The appropriate coefficient is dependent on the scale of the spill and model prediction and the location of the release. The oil spill modeler may adjust the turbulent mixing term between model runs if the model output does not completely match the observations of the oil distribution.

13.4 Evolution of an Oil Spill

Due to oil spreading, evaporation, dispersion, emulsification, dissolution, oxidation, oil particle interaction, and biodegradation, oil changes its chemical and physical properties almost immediately when spilled into the water. Eventually, the amount of oil in the surface slick decreases over time.

13.4.1 Spreading

The major mechanism that rapidly changes the surface slick is spreading of the oil onto the water surface. The rate at which oil spreads is interactive with the other major weathering processes, both affecting and being affected by them. Oil begins to spread as soon at it is spilled, but it does not spread uniformly. Any shear in the surface current will cause stretching, and even a slight wind will cause a thickening of the slick in the downwind direction. Most spills quickly form a comet shape with a relatively smaller black- or brown-colored region trailed by a much larger sheen of colors varying from dull-colored to a rainbow or silver sheen. While the sheen covers a much larger area than the black or brown region, most of the oil is found in the latter since the sheen is orders of magnitude thinner (ASTM, 1997). This is unfortunate as formulas exist to estimate the thickness, and hence volume, of the sheen. However, no such formulas exist for the thick part. Experimental oil spills have confirmed a commonly used rule-of-thumb that approximately 90% of the oil volume is located in about 10% of the slick area (Research Institute, 1983). The personal experiences of the authors indicate that this is not unusual during the early stages of the spill for 90% of the oil to be found in the leading edge of the slick rather than in the trailing, thin, silver and rainbow sheens.

Oil spreading is a complicating factor when attempting to learn where the oil could have initially been spilled. The comet-shaped appearance and elongation of the slick are due to winds, sea state, currents, and random eddies. As a diffusive process, spreading is not amenable to accurate hindcast predictions. Small variations in the environmental parameters can cause large variations in the time-reversed outcome.

Spill researchers have attempted to model spreading by two separate approaches. One deterministic approach balances spreading and retarding forces in a fluidic application of Newton's law. The most widely used such deterministic model was developed by James Fay of M.I.T. (Fay, 1969, 1971). Fay divided the spreading process into three separate phases, depending upon the major driving and retarding forces. When the slick is relatively thick, gravity causes the oil to spread laterally; later, interfacial tension at the periphery will be the dominant spreading force. The main retarding force is primarily inertia followed later by the viscous drag of the water. Fay therefore labeled the three phases: gravity-inertial, gravity-viscous, and surface tension-viscous.

As an alternative approach, researchers have attempted to model slick spreading as strictly a water turbulence phenomenon with the oil acting as a neutral tracer (Murray, 1972). Elliot (2004) showed that, for oil, such a process is non-Fickian, requiring a time-dependent diffusion parameter. While oil spreading is a diffusive process, it occurs in two dimensions and therefore, unlike three-dimensional spreading such as smoke from a fire, it is possible under certain circumstances to undergo an increase in oil concentration as the oil moves farther away from the spill site.

There are several different mechanisms that may cause these "collection" zones to occur. Wind and surface waves frequently induce windrow formation. This interaction results in vortices in the surface mixed layer of the ocean that are aligned in the general direction of the wind. Between the vortices, the surface water either diverges or converges. These vortices are called "Langmuir cells" and the flow associated with the cells, "Langmuir circulation" (LC). A conceptual diagram of LC is shown in Figure 13-2.

Operational oil spill models that incorporate Langmuir circulation have shown only limited success (Simecek-Beatty et al., 2001). Therefore, most spill models have generally neglected LC, even though such models may, mathematically, be quite complex (Payne et al., 1984; Lehr et al., 2000). Thorpe (1995), Leibovich (1997), and Li (2000) are among the few researchers who attempted to model LC effects on oil spills.

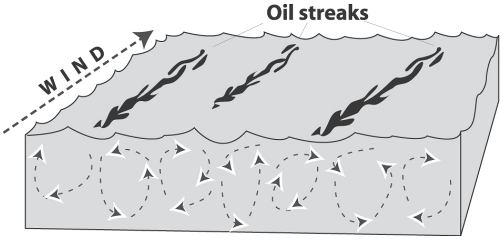

Figure 13-2 A cross-sectional view of an idealized oil spill in the sea. The arrows below the oil streaks represent the motion of these vortices. The oil is shown collecting in areas with converging surface currents.

If LC does have a measurable influence on oil slick behavior, it is likely that three major weathering processes would be altered. These are surface spreading of the oil, dispersion of oil droplets in the water column, and transport of the surface slick. It is worthwhile for the investigator to consider this process when hindcasting the oil movement and behavior.

Those attempting to track mystery spills back to their origin face two obstacles from spill spreading. In the first case, spreading is a dispersive phenomenon that obscures the spill source. Secondly, concentrations of floating oil may have been caused by natural mechanisms such as LC that are independent of the spill event.

13.4.2 Oil Weathering

For forensics, the chemical properties of spilled oil cause a greater challenge than a spill of a pure substance. However, the behavior of the mixture of hundreds of different organic compounds that make up the typical oil or refined oil product provides a useful tool for the investigator to both identify and estimate the age of the spill. The methods used to identify, or fingerprint, oil are described elsewhere in this book. This section will describe the significant changes in the chemical nature of oil exposed to the environment that are referred to as "*oil spill weathering*."

Major short-term weathering processes include evaporation, dispersion, and emulsification. These are the important drivers in both the mass balance of the spill and the overall physical behavior of the surface slick. Nevertheless, there are minor processes that, over a longer term, can cause significant alterations to the spilled oil. These minor processes comprise such changes as dissolution, sedimentation, biodegradation, and photooxidation. Discussions of these processes are found in Lehr (2001) and Fingas (1995).

For most spills, evaporation is the major mechanism for mass removal from the surface slick (National Research Council, 2003). This includes both natural processes and cleanup attempts. It is quite possible to lose half of a light crude spill just due to evaporation. Small, light, refined product spills will typically disappear in less than a day due to evaporation unless high sea states drive the oil into the water column. Also, evaporation changes the chemical mixture of the slick as the lighter components evaporate more quickly than the heavier hydrocarbons. The structure of the molecule is of some importance. However, the major factor is molecular weight. The vapor pressures of hydrocarbons with a carbon number of 10 or above are orders of magnitude smaller than the vapor pressures of hydrocarbons with a carbon number of less than 10 and, hence, older spilled oil will contain disproportionate amounts of the larger hydrocarbon molecules. By comparing spilled oil sample characteristics to fresh oil, forensic investigators can estimate the age of the sample. For example, for an oil of known evaporation characteristics, the evaporations formulas in Wang's Section 7.4 can be inverted to give a guess as to the age of any surface slick samples.

Other major weathering processes, such as dispersion into the water column or the formation of a stable water-in-oil emulsion, do not affect the oil chemistry but are important for determining the amount of surface oil and the oil's rheological properties. Most weathering software programs use some version of the dispersion model developed by Delvigne and Sweeney (1988). They assume dispersion is affected by sea state, slick viscosity, and surface tension of the oil. While oil may not dissolve in water to any great extent, Delvigne and Sweeney recognized that it could certainly disperse as a cloud of droplets when subject to turbulent wave energy. These droplets will be in various sizes and will be subject to the conflicting forces of buoyancy and turbulence. For the smallest oil droplets (~50 to 70 μm), turbulence will win the battle and the droplet will not refloat to rejoin the slick. Dispersion becomes a dominant mechanism for low-viscosity oils under high sea state conditions (Lehr, 2001).

If the receiving water contains large quantities of particulate matter, dispersed oil may attach to these particulates in a process called oil-particle interaction, or sedimentation. The combined oil-sediment particles will typically have a different buoyancy than either alone. Usually, the buoyancy will be negative, and turbulence will be required to keep the oil-sediment particle from settling to the bottom. Very little research is available regarding the tracking and weathering of oil in the water column or on the bottom.

In one way, emulsification can be thought of as the reverse of dispersion. Rather than oil droplets dispersing into the water column, water is entrained in the oil. This causes significant changes in the volume, density, and, especially, viscosity of the slick. It is not uncommon for the viscosity of an emulsified oil to be two or three orders of magnitude larger than the viscosity of the fresh oil (Lehr, 2001). Emulsification will also change the way slicks drift with the wind when the oil is no longer a thin film. At this point, the slick has been torn apart into smaller pieces, some of which maybe overwashed by waves. This complicates hindcasting the movement and weathering of the oil. Not all oils will emulsify, and some oils will emulsify only after they have undergone some weathering. It appears that resins (Fingas et al., 2003) and, most importantly, asphaltene content play the dominant role in determining whether emulsification will occur. A common, but not necessarily reliable, rule-of-thumb is that crude oil will emulsify when these component contents reach 5% of the mass of the oil.

The two long-term mechanisms for the breakdown of hydrocarbons in the environment are photooxidation and biodegradation. The combination of hydrocarbons with oxygen is called "oxidation" with, in this case, photons providing the energy source. The newly formed oxidized compounds may affect the oil slick by increasing dissolution, dispersion, the formation of tar balls, or emulsification. Hydrocarbons, including those found in oil slicks, are a food source for many microorganisms. Examining the stages of the biodegradation can indicate the period of toxic exposure for the ecosystem due to the spilled oil.

13.5 Conclusions and Challenges

We have tried to provide the forensic investigator with a brief overview of present oil spill modeling capabilities. To understand the current state of knowledge, a historical overview of oil spill modeling development was presented. This was important as much of the original work is still used in today's models.

Understanding the difference between "forecasting" and "hindcasting" is key to identifying the best approach for investigating the movement and behavior of spilled oil. We attempted to clarify some of the problems with stochastic modeling and pointed out the challenges with presenting probability information to the end user.

We attempted to demystify the spill modeling process by disclosing some of the more practical modeling techniques. Oil spill modelers are notorious for using simple parameterizations to simulate oil movement based on the significant errors that exist in forecast fields. The challenge is to incorporate more rigorous approaches to emergency response.

Since oil changes its physical and chemical characteristics over time, we briefly described the evolution of an oil spill and oil weathering. To aid the investigator, we offered "rules-of-thumb" that are common in the oil spill response community but may not necessarily appear in peer-reviewed literature. The challenge is presenting useful knowledge gained by experienced responders to newcomers.

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