Trajectory Analysis for Oil Spills

J. A. Galt
National Oceanic and Atmospheric Administration
Hazardous Materials Response and Assessment Division
Seattle, Washington USA

ABSTRACT

Trajectory analysis used for decision support during spill response activities is a complex process that must merge information from a variety of sources. Included in the analysis must be an understanding of the characteristics of the pollutant and how it might change or modify its characteristics once it is released into the environment. It is also necessary to describe the characteristics of the oceanographic and meteorological processes that contribute to the movement and spreading of the pollutant. Computational procedures that can be used to represent these processes must be developed and implemented in such a way that they can be run on the typically sparse data sets that are available during actual spills.

Given the tools of trajectory analysis it is necessary to develop a clear understanding of what has been left out of the procedures so that known deficiencies and uncertainty can be factored into the final analysis. It is then necessary to explore possible alternate scenarios that might result from errors in any of the forecast data that are used to carry out the analysis. Alternate model use strategies can provide short term forecasts and long term threat distribution probabilities as well as statistical estimates of other situations that could develop.

All of the information components that are developed as part of the trajectory analysis must be synthesized into a technical briefing that focuses on the needs of the spill responders and is relevant to the possible options that are available to them. This briefing should cover physical processes that could effect response operations, such as weather and sea conditions, as well as the expected movement and spreading of the pollutant. The briefings must also provide estimates of the reliability of the forecasts and careful exploration of alternate, less probable, scenarios which may threaten high value resources. Finally, the briefing should provide suggestions for ways to resolve uncertainties, including proposed measurement techniques, reconnaissance or monitoring operations.

This paper will to go through a description of some of the more important processes that need to be factored into trajectory analysis considerations and the preparation of a trajectory briefing.

Introduction

Research on oil spills is a difficult job. The reason for this is that research spills are extremely rare events. Even the few that manage to get through the permitting process are hard to manage because the ocean is not a very easy place to find transient micro-concentrations of complex chemicals. In general, then, the understanding of how spilled oil behaves in the marine environment has had to be inferred from some laboratory studies and observations at accidental spills. Both of these methods of investigation have added to our understanding of the behavior of spilled oil. Over the years many research organizations have contributed, particularly centers such as the Institutt for Kontinentalsokkel-Undersokelser (IKU) in Norway, Warren Springs Laboratory in England, the Centre National Pour L'exploitation des Oceans (CNEXO) in France, scientists from Environment Canada, researchers from my own organization in the National Oceanic and Atmospheric Administration (NOAA), and a number of industry sponsored research projects. (I will not try and outline particular papers or reports since most of them will be found in the Oil Spill Conference proceedings, or in the Arctic and Marine Oilspill Program (AMOP) proceedings; interested readers will want to review these sources in some detail anyway.) Having spent a number of years looking at accidental oil spills, I have had an opportunity to make a number of observations which were typically done under uncontrolled conditions and during the intense and conflicting pressures that occur during emergency response activities. Any of these observations taken by themselves are little more than anecdotal but, taken together, and woven in with the information from laboratory studies, they have led to some opinions which seem to me to be generally true. I will attempt to outline some of these observations and explain them to my present level of understanding.

When oil spills into the marine environment a number of different processes take place; some of these processes are somewhat unique to oil, some could be expected for any floating fluid substance, and some are more closely related to the behavior of floating particles. In all these facets of spilled oil behavior, an understanding of the complex geophysical fluid dynamics of the upper ocean is important for the determination of the movement and spreading of the pollutant. The complex interaction of all of these processes is difficult to predict, or even formally describe, and, as a result, the history of trying to predict the movement of spilled oil is filled with "rules of thumb", algorithmic solutions, and simple models that are borrowed from somewhere else. All presently available oil spill models show this patchwork and heuristic ancestry.

The use of any model or algorithmic procedure to describe the movement of pollutants is subject to all sorts of errors and the resulting prognostications will be more or less useful, depending on the context of their use. Clearly, the task of deciding whether a model is any good (i.e., useful) cannot be carried out independent of the system which provides the input data for the model or models, the hardware or software for it to run, and the communication procedures that are used to present the results in a meaningful way. Ultimately, the information that is available for estimating the movement and spreading of pollutants along with an understanding of the potential uncertainties inherent in the procedures must be factored into the response capabilities and plans put together to react to threats that are associated with accidental releases.

Pollutant trajectory analysis is a synthesis procedure that should include; 1) a description of physical processes, 2) development of the computational and statistical analysis procedures, 3) algorithmic error analysis, and 4) the melding of information products into the broader response activity. This paper will go through a description of some of the more important processes that need to be factored into trajectory analysis considerations. By this, I mean that the processes mentioned have all appeared to significantly affect, or even control, the movement and spreading of spilled oil, the understanding and correct interpretation of observations obtained during spills, or the use of analysis results in the broader context of spill response.

The next section describes the characteristics of oil that are relevant in determining its behavior once it has been spilled. The third section discusses the physical processes that take place in the upper ocean that are of importance in determining the movement and spreading of a pollutant. The fourth section describes the use of historical and forecast information about the ocean and atmosphere and the statistical implications of using this data in trajectory analysis. The fifth section of this paper describes the various ways that oil spill models use algorithmic procedures to explore situation space, interact with observational data so as to self-calibrate and improve performance and, finally, to understand potential uncertainty in predicted results. The final section considers a number of alternate model use strategies and the various options for the use of information available from model results, within the larger context of oil spill response.

Characteristics of Spilled Oil

When oil is being transported in bulk it approximates a homogeneous material and has a number of macroscopic properties that help describe its initial behavior if spilled. These include its pour point, density, surface tension, and viscosity.

The pour point of an oil is a variable that is hard to precisely measure. Individual measurements of the same oil may vary, but the concept is clear enough. As the temperature is reduced, oils will eventually congeal and take on the character of a semi-solid. As a practical matter, when the ambient temperature is below the pour point, the cargo is typically shipped at elevated temperatures. Obviously if the spilled pollutant is a solid or semi-solid then it behaves quite differently than if it is a fluid. For example, during a spill in the Delaware River of a heavy industrial grade oil whose pour point was greater than the temperature of the water (the*Presidente Rivera, 1989*) the clean up, at times, consisted of picking up melon sized globs of oil that were about the consistency of Vaseline (Dale, 1989). It is common for asphalt and some bunkers to congeal when spilled and form floating patches or blobs of oil.

The density of oils vary from about 0.85 to 1.07 g/cc. This density is the major factor in determining whether the oil will float, or sink. The vast majority of oils are lighter than water and float (the density of freshwater is 1.0 g/cc, ocean water densities are about 1.02+ g/cc). Gravitational forces are initially responsible for the spreading of oil that is spilled. The surface tension and the viscosity of the oil will determine how easily it flows and whether it tends to form a thin film or breaks up into smaller floating droplets. The various potential balances between the processes described by these three properties was the subject of an early laboratory study on oil spreading (Fay, 1971) and has been revisited by later field studies (Lehr, et. al., 1984). These later algorithms provide some insight into the very early spreading that takes place when oil is spilled, but they fail relatively quickly because the dynamics of the ocean wave field will dominate these weak forces, and, because the actual properties of the oil start to change as a result of weathering. As a practical matter, these balance algorithms can describe the thicker segments of an oil spill for a few hours under light and moderate wind conditions but are not successful in describing sheen boundaries even during the initial period of spills.

During the early part of a spill (particularly under low wind conditions) when the oil is still relatively fluid and homogeneous, the equilibrium thickness of the oil is very thin; what is typically seen is a thin film (on the order of microns thick). Since the thicknesses of these thin films are on the order of wave lengths of light, normal sunlight interacts with the thin oil film and the colors that result can give some indication of oil thickness. There are a number of references that give approximate oil thickness based on the following sequence of visual clues (Fingas, et. al., 1979).

-- transparent sheen (no color, just a change in surface roughness)
-- silver sheen (lighter sky color reflected back to observer)
-- first trace of color
-- bright colors
-- dull colors
-- dark colors

It is tempting to try and use these visual clues when trying to estimate the amount of oil that is observed during an overflight. It turns out, however, that this is not generally possible. In a very short time the oil starts to weather and may form a crust that changes the way the thin films behave and the upper ocean dynamics become dominant in controlling the thickness distribution.

We have already made several references to upper ocean dynamics and the fact that they will tend to dominate the spreading of oil films. This is invariably the case unless the winds are very light. The essence of this process is that as wind starts to blow over water, waves start to form and these result in the surface being deformed. This deformation alternately stretches and compresses segments of the sea surface. For even relatively light winds these small scale deformations are able to rupture thin oil films and they start to appear as streaks and streamers rather then as a continuous patch of pollutant. As oil films are torn apart and compressed into streaks the equilibrium thicknesses are no longer controlled so much by the initial properties of the oil as they are by the wind. As a general rule, for oils that float the initial properties are of some importance, during the first couple of hours of the spill, but very quickly it is the weather and ocean dynamics that determines the distribution of the oil.

After oil spends even a very short time floating on the ocean surface it starts to weather and change its physical characteristics. Initially, the more volatile components of the oil evaporate and, to a lesser extent, some fraction of the oil will dissolve into the water. This process will continue and, for very light crude oils and light refined products (i.e., gasoline or kerosene), it may eventually account for the loss of a major fraction of the pollutant. For heavier oils, a more likely process is for the weathering oil to reach a stage where it can form a mousse, or water-in-oil emulsion. When this happens the oil starts to form a water in oil emulsion and some dramatic changes take place in its physical characteristics. As mousse forms, the viscosity of the mixture increases rapidly and the color changes from blacks to colors that may range from black, to brown, to the color of red- lead paint. As the water content of the mousse goes up, other weathering processes such as evaporation and dissolution slow down. Eventually, mousse formation may lead to a mixture that is up to about 75% water, which of course just about quadruples the oil volume. Since this mix may be as sticky as peanut butter, the problems of clean-up and recovery are magnified considerably.

As the viscosity of the mousse and its stickiness increase, it often becomes so stiff that it no longer behaves like a simple viscous fluid and it actually takes on the characteristics of a visco-elastic material. This gives it enough structure so that additional weathering causes a surface skin to form and you are likely to see a non-homogeneous material with a crust of slightly more weathered mousse surrounding a less weathered core. As this coated mousse is subject to increased mixing from energetic wave action, the crusts can be torn or ruptured and relatively less weathered mousse is released. This leads to spills occasionally showing apparent rejuvenation in their physical and chemical behavior. This phenomena has been noted at a number of spills. A good example occurred during a spill of crude oil in the Gulf of Mexico (the*Mega Borg, 1990*) (Research Planning, Inc., 1992 and Pearlman et. al., 1992).

The continued exposure of weathered mousse to wave action and small scale surface divergences continues the process of stretching and tearing patches of mousse into smaller bits. This often leads to a more or less continuous breakdown of large slicks into smaller and smaller patches. It is not uncommon to see large spills degenerate into fields of dinner plate size patches, and then into hand size tarballs, which ultimately go to coin size tarballs. On the macro scale there seems to be a minimum size tarball which is about the size of a small coin. A possible physical reason for this is that this corresponds pretty well to the minimum size of small capillary waves. Alternate explanations might be that below this size routine observations would be very difficult or that very small tarballs would be the ones most likely to be quickly weathered by photo-oxidation or bacterial processes.

At this point it is interesting to note that the oil which was initially spilled as a homogeneous fluid has gone through a number of transitions that first make it less homogeneous, then tends to make it behave more like a visco-elastic material and ultimately more like a collection of solid particles. Perhaps not surprisingly, simple algorithms that try and concentrate on initial bulk properties are not valid descriptors of spilled oil behavior over the life of a spill. This also suggests that simple computational procedures that are used during spills should be tied to observational data and must be corrected with real time feedback. Although this is pretty standard for weather forecasting, it somehow does not seem to be as widely understood within the oil spill research community.

It is possible for some hydrocarbons to dissolve into water and the amount varies depending on the particular components that are being considered. The actual amount of oil that thermodynamically dissolves is very small and, if this was all there was to it, we could safely say "oil and water don't mix". However, this is not all there is to it. Most oils have at least some molecules that have natural surfactants attached to them. In addition, some weathering processes create surfactant groups that attach to the oil. Finally, an active response strategy may add surfactants (dispersants) to the oil. In any of these cases small droplets of oil can form with oil interiors (non-polar molecules) and a coating of slightly polar molecules (typically with an -OH group) that fit well into the water structure. These micelle-like droplets can disperse into the water orders of magnitude more oil than could actually dissolve and this can become a significant factor in the overall oil budget. A number of experiments have been carried out to determine the droplet size distribution associated with this process (Thomas and Lunel, 1993). The interest in this data is due to the fact that very small droplets will have such small buoyancy forces that turbulence in the ocean will dominate their movement and they will not return to the surface. On the other hand larger droplets will refloat and potentially coalesce to reform a surface slick. As a practical matter, droplets that are smaller then 50-70 microns will resurface so slowly that they can be considered as dispersed into the water column.

How dispersed oil droplets are formed is determined by the available ocean turbulence that provides the mixing and the viscous or visco-elastic properties of the oil. There is not a great deal of data on this process, but there are some fragments that can lead to the following speculations. For a wide variety of oils the initial size distribution of droplets appears to be independent of the type of oil. In these cases the length scales of the ocean turbulence seem to control the process and peaks in the size distribution are typically in the 30 micron range. These particles would properly disperse. A closer look at the typical turbulent kinetic energy spectra for the ocean show an inertial sub-range that ends in a dissipation region where length scales are in the 10's of microns. For fresh oils the smallest scale shear stresses present in the ocean are sufficient to overcome the viscous resistance of the oil and thus tear it into a small droplet distribution that is determined by the water (viscous dissipation spectra) rather than the oil.

An obvious next question is what do we expect to happen as the oil weathers and the viscosity increases. At some point the available energy in the smaller length scales of ocean turbulence will not have enough shear stress forces to overcome the viscosity of the oil. When this happens larger droplets are still formed (since the larger length scales in the inertial sub range of the turbulent spectra have increasing kinetic energy available), but the smaller ones just can't be produced. As this process continues it becomes dependent on the oil rather then the ocean turbulence and eventually the mean in the droplet size distribution shifts to sizes greater then 70 microns. At this point, the dispersion into the water column is greatly reduced and droplets that are formed and forced under water tend to resurface and cannot be considered as permanent losses to the floating pollutant mass balance. Observational data indicates that oils are difficult to disperse if they have weathered to the point where their viscosity is in the two and a half thousand centistoke range. This, then, might be a reasonable guess for the viscous range where the balance between available turbulent kinetic energy in the ocean and shear resistance in the oil shift the mean in the particle size distribution over the 70 micron limit. As oil continues to weather and form a mousse, the viscosity and combined shear resistance continues to rise and we expect this process of increased particle size to continue. Ultimately, after the oil has a viscosity in the thousands of centistokes range, the oil particles appear to have a maximum probability of being in the small tarball range, i.e. about a centimeter or two. It is interesting that this coincides pretty well with the energy scale available from the smallest gravity waves that are typically present in the ocean and, at this point, the process may depend more on the stretching and bending of the surface boundary of the ocean, than its 3-dimensional internal turbulence.

The fact that oil is floating means that it is constrained to remain near the air/water interface and this has some profound implications with regard to its behavior. First, both the atmosphere and the ocean are important in determining its motion. Secondly, 2-dimensional surface movement is fundamentally different from the 3-dimensional movement that takes place within a fluid. It is hard to overstate the significance of this 2-dimensional versus 3-dimensional movement. If oil were to dissolve in the water column and spread as a 3-dimensional dissolved constituent, then spill response as we presently know it would not exist. This is because no known recovery procedures would be practical. (The problem would be like trying to recover smoke after it left a smoke stack.) In addition, the oil could never re-coalesce or re-aggregate to form high concentrations on distant beaches, or surface ocean convergence zones. And, finally, the dispersion and spreading processes would localize the size of the impact area reducing it by typically an order of magnitude. To put this in perspective one can consider the differences in the results of the spills from the *Exxon Valdez* (NOAA, 1989) and the *Braer* (Thomas and Lunel, 1993).

In general, any oil is subject to the same physical processes and tend to go through the various phases that are outlined above but there are significant variations for particular refined products and some crude oils. Some of these are perhaps worth a brief comment.

Light refined oils such as gasoline, jet fuel and diesel typically have very high evaporation rates and do not tend to create persistent slicks. They very quickly go to thin films and show lots of rainbow and silver sheens. If they reach a coastline within a few hours, a slight staining, or soot-like bathtub ring (in the case of diesel) is common. These oils don't usually form a mousse and don't result in a heavy or sticky residual to clean up. It should be noted that these lighter refined products do have a relatively high amount of light aromatics and tend to be more soluble and more toxic than heavier oils. So, even though these oils may not present an involved cleanup problem, they can result in an initial toxic shock to biota and persist as a biological threat problem in low energy marine environments.

Heavy refined products such as intermediate fuel oils (IFO) and bunkers are, in some ways, the opposite of the lighter oils. The refining process has removed the lighter components and left them somewhat pre-weathered. As a result they don't change as much as they age and may result in quite persistent floating pollutant problems. These oils can occasionally form a mousse, but usually only slowly, and after a period of days. These oils may not spread into very thin films and often simply break up in smaller patches and then tarballs. It is also common for these oils to lose enough of their light ends so that they do not rapidly form sheens and the resulting scattered tarball fields are very difficult to observe using visual, or remote sensing techniques (Pearlman et. al., 1992). This, combined with the persistence of the tarballs, makes these spills quite likely to result in long range, and occasionally unexpected, beach impacts.

There are a few crude oils and some heavy bunker fuels that are heavier than water and thus don't float. These sinking oils are rare and any reliably documented observations of them are even more rare, but from the few encounters that we have seen, some behavioral characteristics are apparent. In anything but calm currents (i.e., a very small fraction of a knot), the oil will not settle out on the bottom without additional weathering or sedimentation. If the temperature of the water is above the pour point of the oil the differential surface tension seems to be such that the fluid oil typically disaggregates into small "BB-size" droplets that disperse and move throughout the water column pretty much like a neutrally buoyant tracer. In some cases, there is some indication that the distributed oil may favor the lower part of the water column. A good example of a very heavy residual oil that moved along the lower part of the water occurred in the Columbia River (the*Mobiloil ,1984*) (NOAA, 1984). In any of the cases that we have investigated, there is no tendency for the oil to aggregate or pool up and the dispersion processes appeared to follow 3-dimensional spreading laws, thus limiting the distances where the spill is directly observable to a few tens of kilometers. Again, this is in the absence of sedimentation. The incorporation of sediment with heavy oils has resulted in some aggregation offshore of impacted areas in the form of tarmats.

Physical Processes

One of the first questions after a spill is “where will the oil go?”. Any floating pollutant will move along with the water that it is floating on. Unavoidably, then, any attempt at spill trajectory analysis will require that we start looking at the currents, or circulation. This turns out to be a non-trivial problem and more often than not is poorly done . To start with, the patterns of the current are important; as well as the time scales of the movement. A single number (or vector) is never enough and, as the spill approaches the shoreline and encounters the complex shapes of cusps, spits, beaches and inlets, a surprising amount of detail may be needed. This turns out to be such a complex problem that virtually all spill models take the approach that some external computational module will solve the problem. The output from this stand alone hydrodynamic program (or perhaps a number of stand alone programs) will be used in the spill model as input data. There are many alternate ways that these stand alone hydrodynamic units can be designed, but there are some minimum general features that seem to be required for anything but the simplest cases. The approach should be able to deal with realistic geophysical shapes and be capable of variable scale resolution (since most significant spills start off small and end up large). To meet both of these requirements finite element analysis methods are useful, but finite difference procedures should also work if they are correctly configured.

In addition to the above mentioned requirements, there is an additional circulation feature that absolutely must be accounted for when describing any current field that is to support a trajectory model of floating pollutants. The divergence field of the flow has a profound influence on oil spill trajectories and, in many cases, dominates how the spill will end up and what options might be available for response activities. To be specific, floating material will collect at convergence points and along convergence lines. This has the effect of gathering together scattered patches of oil and, in some cases, widely separated tarball fields, to form new and greatly concentrated bands of oil. This process is absolutely dependent on the 2-dimensional movement of the oil (which is constrained to float on the surface), and the 3-dimensional movement of the water (incompressible flow where any vertical motion away from the surface must be compensated for by a horizontal flow moving together to replace it). There is no analogous behavior for full 3-dimensional pollutant dispersion and this is what makes the difference between smoke from a stack which is seen to disperse (always leading to smaller concentrations with increased travel time), and oil slicks which may spread out initially and seem to virtually disappear, only to converge again recreating a threatening spill perhaps hundreds of kilometers from where they seem to have gone away. To avoid this problem is one reason why chemical dispersants might be useful on an oil slick. It is also likely that if it were not for this process resulting in re-concentration in convergence zones, skimming operations at sea would be absolutely futile. It is also of interest to note that convergence zones are often associated with increased marine biological activity and become a local habitat for sea birds and, when oil collects in these areas, it can pose a significant threat. Strong and persistent convergence zones also collect great deals of other flotsam such as driftwood, floating kelp, and styrofoam. When this material gets mixed with oil it may complicate the recovery and clean up considerably. It is really impossible to do an initial trajectory analysis without an understanding of the current speed and direction but if the divergence and convergence of those currents are not know then it is equally impossible to understand how the spill trajectory will proceed and where the oil will end up or how it will look when it gets there. The first part of this problem seems well understood, but the second part is less widely recognized and numerous spill models have used statistical or non-coherent derivations for current patterns (such as from a ship drift atlas) which may have significant errors in the divergence fields. Extended trajectories using these methods occasionally lead to peculiar results that are very difficult to interpret. All in all, this is a tough problem and I know of no computational procedures that can fully handle the difficulty, even if the largest available computers were brought into the effort. It seems, for the present, that careful resolution of bathymetry and analysis algorithms that strictly conserve mass will help reduce obvious errors, but observational and empirical input are required for satisfactory operational results.

Ocean waves affect the movement and spreading of oil spills in several different ways and the relative importance of these processes change as the pollutant weathers. Initially, as the oil spreads to form a thin film, short gravity waves are absorbed by the film. This is the reason that an oil film is called a "slick". It looks smooth compared to the water around it. The thinnest transparent films are really only distinguishable by this change in surface roughness. It is a bit like looking at the difference between cotton and corduroy. In any case, as these waves are absorbed by the oil film, there is momentum transferred from the waves to the film. This has two effects. The first is that, as waves approach from a dominant direction, they tend to push the oil film or slick along. This means that floating oil films will actually be moving over the top of the water that they are floating on. This differential oil-water velocity has been measured a number of times at spills and turns out to be between 0.7% and 1.4% of the observed wind speed. Note that although this is a wave dependent phenomena it correlates pretty well with the wind since it is the wind that generates these small waves.

The second effect that small waves have on oil films is that even though there is a dominant wave direction, some small number of waves come from all directions around the slick and as these transfer momentum to the oil there is a slight compressional stress that tends to inhibit the slick from spreading. Although there are a number of other processes that seem to override this effect, there have been occasions in many spills, particularly when the winds are light, where a patch of oil will resist spreading and move for extended periods of time as a single large pancake. This wave/oil-film interaction will tend to be significant as long as the oil continues to make a slick. It will be reduced somewhat as the oil breaks into streaks and streamers. As the oil weathers and forms tarballs this wave stress and momentum transfer becomes negligible.

A third transport mechanism that is associated with ocean waves is that for short, relatively steep, waves there is a slight current generated. This is usually referred to as Stokes drift and will actually result in a small surface current that will move the oil along in the dominant wave direction which, once again, is really in the direction of the observed winds since it tends to generate these type of waves.

A fourth process that is associated with waves is dispersion, which has already been mentioned in the previous section. This process is related to the turbulence created by the waves and is thus not so much dependent on the general wave field, but rather on that fraction of the waves that are breaking. As waves break the plunging water that results creates turbulence and can carry particles of oil down into the water column. If the resulting particles are small enough then their rate of re-floating is so slow that they are essentially removed from the surface and are "dispersed". For larger particles these excursions below the surface are only temporary and they can be thought of as only spending some fraction of their time away from the surface. When there are large breaking waves present, oil particles or tarballs can be driven some distance below the surface; this process is often referred to as overwashing. As larger fractions of the oil particles are driven below the surface the actual spill becomes progressively more difficult to observe from the air. Under these conditions it is not uncommon for reconnaissance flights to report that the spill has dissipated, only to find that it has returned to be very much in evidence when the weather gets a bit better. This disappearing act and the fact that from a boat it is often possible to observe a tarball below the surface has led to reports at nearly every major spill that the oil is sinking. During the *Ixtoc I* spill in the Gulf of Mexico, divers were used to collect information on the subsurface distribution of tarballs and it was found that the concentration distribution had a similar pattern to what is seen in dust distributions over the ground. Under strong wind conditions the tarballs extend deeper into the water and during quiet conditions they move back towards the water surface. It appears that oil sinks in the same way that dead leaves fly from the ground. Actual sinking, in the sense that oil is removed from the surface for good, only occurs if the density of the pollutant is greater than the water or the pollutant has been mixed with enough sediment; these are relatively rare events.

It is commonly understood that wind has a significant effect on the movement and spreading of oil spills. This is true, but the effects are not direct, but rather through other processes that the winds cause, which in turn effect the movement of the pollutant. The wave processes that were mentioned above are examples of this indirect wind forcing. As we have seen, it is not the wind that is interacting with the oil, but rather the waves which, in turn, are well correlated with the observed winds. Therefore, from an algorithmic point of view, the winds become one of the primary prediction parameters.

In addition to forming waves, wind stress on the ocean drives a number of complex surface currents that will also contribute to the movement of floating oil. The actual dynamic processes of how the wind moves the water are very involved and require extensive non-linear mathematics to develop a reasonably complete theory. Fortunately, it is not necessary to understand all of these details, and, for the purposes of trajectory analysis, it is enough to use simple theories and settle for a description of the processes that we cannot technically predict. The primary current directly caused by the wind is the movement of a thin surface layer. In the original theories to describe this current the flow direction was at 45 degrees to the right of the wind, in the northern hemisphere. A more detailed analysis suggests that the deflection angle is considerably less than that and is more likely to be in the 10 degree range. As a practical response algorithm it is usually adequate to simply assume a wind driven surface current that has a velocity which is 2% of the wind speed and in approximately the same direction as the wind. (It should be remembered that when forecasted winds are being used for trajectory analysis, they are typically only specified by quadrant direction so that the errors associated with a few degrees are usually not significant.)

The 2% wind drift rule is a reasonably good approximation to the primary wind driven flow, but a closer look shows that the actual first order flow is unstable and tends to break up into more complex patterns called Langmuir cells. Langmuir cells are particularly important to floating oil because they result in surface convergences and divergences. As we have already seen, convergence zones can have a profound effect on the distribution of floating oil.

Langmuir cells begin to appear if the wind becomes stronger then a few knots. This flow is characterized as a series of alternating bands which are oriented in the direction of the wind. Within every other band the surface flow moves downwind and to the right or left. A small convergence line forms between adjacent bands where the flow comes together and divergence zones form at the boundary between bands where the flow tends to separate. At the convergence zones the water sinks and then returns moving still downwind, but with a crosswind component opposite to that at the surface. In some respects, it is as if the water were moving along a series of alternating right and left handed corkscrews which were laying in the surface and pointing in the direction of the wind. The distance between adjacent corkscrews, or convergence lines, varies from a few meters to some tens of meters. Obviously the surface flow is still generally downwind, but much more complicated in the detail.

A floating oil film will be effected by this current pattern and there will be a tendency for it to thicken and collect in the convergence bands. Between the convergence bands where the surface flow is diverging there will be a tendency for the oil film to rupture and form a banded gap. Putting these together it is likely that the presence of Langmuir cells will result in a distribution of floating oil that is banded, or in streaks and streamers oriented in the direction of the wind. We can note that this process is somewhat counteracted by the compressional wave stresses that are mentioned above so that the rupturing of an initial patch or film of oil is by no means a precise event. Under strong wind conditions oil slicks rupture and become banded quite quickly, often within minutes to hours, depending on the type of oil and the size of the spill.

There are some significant implications of floating oil distributions that break up into streaks and streamers under the influence of Langmuir circulation. It is often thought that oil spills form a more or less continuous layer of oil. Once it breaks into streaks and streamers this is obviously not the case and over any particular region the major portions of the oil may only cover a relatively small fraction of the actual water surface. Many clean-up procedures, such as applying chemical dispersants, suggest that it be applied at rates that depend on the thickness of the oil and the area covered. In this case it is not at all clear what area the oil covers and any spray application will certainly be treating primarily open water. This fractional surface coverage is also significant for many remote sensing attempts to observe oil. It may be that the oil extends over a very large area, but in the vast majority of that region it is present as streaks and bands such that a pixel footprint of the sensor is actually looking at mostly open water and a weak or ambiguous signal is returned.

Up to this point a number of different physical processes have been identified that are related to the observed winds; wave stress, wave compression, Stokes drift, dispersion, over-washing, surface drift and Langmuir circulation. It is quite common in spill trajectory simulations to lump all of these together into a wind drift factor which is usually taken to be 3% of the wind speed. This is an extremely useful approach, but it does simplify a great deal of what is going on. When the oil initially forms a film the wave stress, Stokes drift, and surface drift might add up to something closer to 4.5% of the wind speed. At the other extreme, as the oil weathers to tar balls and over-washing takes place, the oil may spend a significant part of its time away from the surface and out of the influence of most of the processes associated with the wind and an average drift factor of less then 2% of the wind might be more appropriate. More advanced algorithmic approaches should at least have the ability to treat wind drift factors as something more then a constant, but even with this there will still be the need for observational support and feedback during actual spill events. Once again, an understanding of these processes has some implications on spill response activities. A number of experiments have been carried out to try and design a buoy that will drift on the surface of the ocean in much the same way as oil so that it can be used as a tracking device during spills. Considering how varied the processes are that the buoy would have to replicate this is a difficult task. At the extremes; during the initial part of the spill it would have to act like an oil film and absorb wave stress like a slick, and during the later parts of the spill it would have to behave like a particle, perhaps being uncoupled from wind effects altogether for a fraction of the time. Dispite this, the approximate Lagrangian data from drifters has provided useful initialization information for planning reconnaissance flights to track moving oil slicks

As oil approaches the coastline it becomes a threat to the beach face or intertidal area. In many spills this threat and/or the actual oiling of the beach becomes a major issue and the focus of most of the spill response activities. As is often the case a number of different processes interact to control how, or if, the oil actually impacts the shoreline. To start with, ocean currents cannot actually bring the oil in contact with the beach face unless there is some kind of flow that actually penetrates the coast, such as percolation into a marsh or mangrove swamp. The reason for this is that as currents approach the coast, the volume of water is deflected from the normal to the beach and the flow must elongate along the beach face. Large scale currents never run into the beach, but rather turn and run along the beach. Along a relatively exposed beach the small scale processes associated with flow in the surf zone also become important. Wave transport and possibly wind drift will transport oil through the surf to within the swash zone. In this area, alongshore currents develop as a result of the wave transport and these will advect the oil parallel to the shore between the surf zone and the beach face. "Rip currents" develop when these alongshore currents build up to something on the order of a knot. These rip currents extend perpendicular to the coast and out through the surf zone to a distance of several hundred meters offshore. Putting this all together it, as oil approaches the shore it moves laterally through the surf zone to be re-injected outside the surf zone by the rip current process, where the process starts again. The net result is that as oil approaches the coast it seems to change directions and spread out parallel to the beach over a longer section of coast than would be suggested by its angle of approach.

The actual beaching of oil occurs when there is a component of the wind that is onshore. This allows the floating oil to actually be pushed against the shoreline. If the wind is very weak or is offshore then essentially no beach impacts are seen. An additional factor that greatly increases or decreases the amount of oil stranded is whether the tide is rising or falling. Heavy oiling takes place with onshore winds and falling tides. While the tides are rising or winds are calm, steady coastal oiling is greatly reduced. One of the consequences of this mechanism is that most oil is stranded in the upper intertidal zone. From a statistical analysis of this process, about 75% of the oil should strand within the upper half of the intertidal region; observations certainly tend to support this.

Once oil has stranded on the shore it will start to wet the surface and may soak into the interstitial spaces in the beach. Subsequent high tides and a wind with an offshore component will tend to wash some portion of the oil back into the water and may act like a secondary source to the trajectory analysis problem. The amount of re-washing that takes place will depend on the type of oil and the character of the beach face. For example, rocky headlands may release most or their oil over a few tidal cycles and protected marshes may retain heavy oil concentrations for years.

Oceanographic and Meteorological Factors

It will not be possible to outline all of the physical oceanographic and meteorological processes that are relevant to the pollutant transport problem in the ocean in this paper, but an attempt will be made to point out some of the most important factors and consider their relative scales of significance.

Nearshore the strongest currents are often associated with the tides. The ebb and flow of the water in bays and inlets will certainly carry pollutants back and forth, it is always useful to have some idea about how important these might be. Assuming that the tides are simple harmonics, with a major semidiurnal component, then the total movement over a tidal cycle will be given by;

$$\text{excursion} = 12.4 \times V_{max}/\pi$$

Where V_{max} is the maximum expected flood current. In other words the tides are likely to move the oil back and forth nearly 4 times the maximum velocity. (For a 1 knot current the excursion will be about 4 nautical miles over a 12 hour period.) This gives a quick estimate of the relative importance of the tides in the trajectory problem. If this distance turns out to be less then needed, or expected, accuracy of the estimates it may not be necessary to include detailed tidal current analysis in the considerations. There are a lot of regions where tidal current velocities are not accurately known, particularly in small inlets. For this type of region an alternate scaling estimate can be obtained by calculating the volume of the tidal prism (area of the bay * rise in tide) and divide that by the cross sectional area of the inlet mouth. Once again this kind of estimate can be used as an initial screening for the decision of whether to include a tidal analysis as part of the trajectory problem. Both of the estimation procedures mentioned will only give an indication of the current at the mouth of a bay. What is actually needed is a pattern of the currents as they fan out both inside the bay and outside the mouth. To solve this problem it is absolutely essential that the analysis include a realistic representation of the bathymetry. For this type of detail, local data is needed, but once this is available, a relatively simple numerical procedure can give quite satisfactory estimates of the tidal displacements within a bay and the region of influence ("inhale distance") from which a pollutant might be pulled into the inlet on a tide cycle.

There are other transport processes associated with tidal currents that are much more difficult to estimate, but which may be very important in the trajectory analysis problem. These are the eddies and horizontal mixing that are caused by the shear in the tidal flows. In particular, during strong ebbs and floods the movement of pollutants is pretty well specified by the simple considerations that are outlined above. As the currents approach slack water, however, the currents don't actually stop, but rather tend to break up into a series of eddies. These swirls make a significant contribution to the cross-channel mixing and spreading of pollutants, but the details are virtually impossible to model using presently available procedures. The solution which has been useful in operational forecasts is to increased diffusion, or mixing coefficients in the formulations and use care in the interpretation of the results.

Another tidal process that may be significant for oil spill problems is the flows that are associated with internal tides. In some stratified areas a tidal wave forms on the interface between lighter surface layers and the more dense lower layers. The currents that result from these tides are generally weak, but they may create surface convergences that can collect the floating oil. Like other convergence phenomena these will control, at least locally, the distribution of the pollutant. Internal tidal flows can be calculated numerically, but it is a significant effort and is usually not done for spill response. In present day operations it is more typical that a trained observer will recognize the process and include descriptions of it in the trajectory analysis briefings.

After the tidal considerations are settled, the residual, or background current is of interest. Unfortunately, the residual currents can be made up of a staggering array of dynamic possibilities including estuarine flow, geostrophic shelf currents, mesoscale eddies and all sorts of shelf waves. To try and put these in perspective is properly in the domain specialty of an experienced physical oceanographer. At this point we will not try and make any attempt to sort this dynamic zoo, but we can note that the oil spill trajectory analysis problem is essentially related to floating oil. This means that the most useful computational or analysis procedures will be the ones that concentrate on the surface currents. It turns out that these are typically also the most technically accessible so, with not quite the conviction of a rule, it is certainly advisable to start out with simple approaches and add complexity only at the demand of operational necessity. This advice may seem to be counter to the so called "state of the art" capabilities of modern computational oceanography, so some sort of a discussion of the spill response environment is in order.

The initial alert associated with a spill is typically in a data starved situation. It is not uncommon to only have a vague idea where the spill took place. The amount of product that was spilled is hardly ever known during the initial response and a significant fraction of the time multiple cargoes may be involved in unknown ways. With this much uncertainty the one thing that is sure is that additional information will be required and, as the spill goes on, the best source of data will be the details of the Lagrangian experiment and field test that is going on, i.e. the spill itself. It has been demonstrated over and over that it is useful to have relatively simple computational procedures which can be quickly reinitialized as new data becomes available. These more basic approaches (provided that their limitations are known and factored into the final trajectory analysis), are invariably preferable to more complex and complete dynamic simulations that cannot be supplied with real time boundary conditions. It is also clear that any successful trajectory analysis support activity will require an immediate tie-in with the actual response operation, preferably with trained observers from the trajectory analysis team as part of the response.

In the face of all the complexity and difficulties that are associated with understanding the oceanographic and meteorological processes that are required to support operational trajectory analysis it is tempting to think that a good deal of the setup and description of the wind and flow fields could be done before the spill occurs and the idea of a model based on climatology has been proposed a number of times. In this case, a most probable statistical representation based on past history would provide the input for a quick response model. Although this idea has considerable merit for planning and training models, it is a conspicuously bad choice for a response model. If you were trying to plan an office picnic for next spring it would be useful to know that May is generally a dry month. On the other hand, if you were trying to decide whether to go for a picnic this afternoon you would look out the window; the average conditions are not of interest. Similarly, climatological data will be of some use in spill response and planning to establish the range of possibilities that one might expect, but, even as vague as it usually is, the initial spill notification will do more to establish where the spill is in terms of geophysical situation space than relying on an unguided statistical guess.

In previous sections, the importance of surface convergence zones has been stressed. These oceanographic processes have a profound effect on the outcome of most spills and it is worthwhile to consider the oceanographic conditions that lead to their formation. Within the ocean, divergences occur at all scales from the smallest ones associated with surface waves and Langmuir cells to basin wide phenomena such as in the Sargasso Sea around Bermuda. For most spill response activities we are specifically concerned with the intermediate size convergences; these are typically associated with two particular processes.

The first of these is where a barotropic current moves over a change in depth. In this case we can think of a column of water that moves in a horizontal direction. As it encounters deeper water the length of the column must stretch so that it extends from the surface to the bottom. Since the volume of the column cannot change (water is incompressible at this scale), the vertical elongation must be compensated for by a horizontal compression. Oil floating on the horizontal surface will of course also compress and thicken. A common form of these convergence zones is referred to as "tidal rips" and they are often semi-permanent features of coastal and estuary regions, at least during some stage of the tidal cycle. This particular type of convergence zone depends on relatively simple dynamics (barotropic flow) and detailed bathymetric data. As such, it is often possible to calculate or predict where and when these convergence zones will occur and factor them into the overall trajectory analysis.

The second type of intermediate size convergence is associated with density variations in the water and occur in conjunction with sources of fresh water, either from large estuaries or where rivers meet the ocean. The mechanism that leads to the convergence is that a relatively light layer of water will spread out as a thin layer or wedge. As horizontal currents run into this layer they will typically slide under them, the surface where they meet forms a convergence zone. The common oceanographic description of this type region is a front. This type of convergence zone is quite difficult to predict since they fundamentally depend on baroclinic processes and small scale turbulence as well as upper ocean dynamic processes. The usual operational approach for factoring these into trajectory analysis is to observationally map them during the initial reconnaissance phase of a spill. There are some areas where this type of convergence zone, or front is a semi-permanent feature. Good examples of this type of convergence can be seen in Lower Cook Inlet, at the mouth of the Columbia River and along the Louisiana Coast. It should be noted that in some respects these fronts often act as a trap that holds the oil offshore and thus protects beaches and coastal areas (this configuration. however is still a significant threat to sea birds). The most pressing trajectory analysis problem is to try and determine under what conditions the density front will break down and release the oil, thus threatening the beaches. Breakdown of a density front can occur when there is major wind mixing, like tropical storms, or when the tidal velocities through an inlet are strong enough to provide the energy to mix the stratification, such as at the mouth of Galveston Bay. These occurrences are technically very difficult to handle and the typical results of trajectory analysis on this class of problem are not particularly impressive.

Trajectory analysis requires a description of the wind field distribution for at least as long as the desired forecast period and, in many cases, this is what sets a practical limit on how long into the future a projection can be carried out. Detailed forecasts are difficult to make, particularly in coastal areas that may have sparse reporting stations and significant localized effects such as sea breezes, or drainage winds. In carrying out a trajectory analysis it is essential to compare forecasts with observational data so that accuracy estimates and potential variability can be factored into the overall uncertainty analysis that goes with the trajectory forecast. As the required forecast period extends farther into the future more uncertainty is inevitable and, eventually, a fallback to climatological statistics is about the only practical option. Obviously the presentation of the analysis results and the technical briefing that goes with it must make the degree of uncertainty clear.

Modeling Procedures and Error Analysis

At the core of many trajectory analysis procedures are a series of computational algorithms or numerical look-ups into databases. These are usually referred to as trajectory models and, for many people in spill response, it is assumed that these models are totally responsible for the trajectory analysis process. For the present this view is naive. There are really no available systems that can be used as stand alone, or turnkey trajectory analysis components in an operational spill response and, if experienced personnel are not available to set up and interpret results, then there is a significant chance of getting results which are of marginal use, or perhaps even misleading. In spite of the fact that computational systems cannot answer the entire trajectory analysis problem they are still a substantial help and it is worthwhile to consider some of the computational features of algorithms that have proved useful in a number of practical models.

In previous sections it has been mentioned that trajectory analysis must be able to handle variable scale resolution because most significant spills start off small (usually from a point source) and become large. To handle this numerically, all major spill models have gone to a mixed Eulerian/Lagrangian formulation where the oil is represented as a number of particles that are embedded in a series of vector fields that represent the advective processes due to winds and currents. Each of these particles represents some amount of oil and can have associated with it attributes that describe its age, type, weathering state, beached status, etc.. The actual distribution of the oil is then represented by clusters or swarms of oil particles. This type of formulation has proven extremely powerful and is free from the numerical dispersion that would be a problem from small sources in a purely Eulerian formulation. There are some facets of this approach that are limiting. The first is that as the pollutant particles move and spread, the spacing between them may become large and, for any particular area, the oil may be represented by a small number of particles. Such distributions are clearly patchy and it is not clear how to interpret or describe the results. One solution to this problem is to let large initial particles partition into numerous smaller particles, but that typically only puts off the problem. A statistical presentation is often appropriate but, to get useful statistics, it is sometimes necessary to use a large number of particles and, as usual, the briefing or description of what the model is showing must be carefully prepared. The models that are presently in use typically represent spills using between several hundred to several thousand particles. Using the higher numbers it is possible to talk meaningfully about distributions around the fringe of the spill that are in the few percent range, but none of the presently available models are reliable for details below this limit.

A second implication of representing the pollutant distribution as a cluster of points is that oil density data is not directly available. This mean that algorithmic processes that are non-linear in terms of the oil distribution cannot be directly represented. Considering the accuracy to which background geophysical fields are known and the overall computational sensitivity of the trajectory analysis process, this is not a serious handicap for the forecasts of the pollutant distribution. The same is not necessarily true for looking at the implications of the spill as it interacts with sensitive resources. For example, to determine the impacts of oil on sensitive coastal resources it is often desirable to have an estimate of the actual oil density. There are several ways to go from a Lagrangian point distribution to a Eulerian density distribution and many models provide for some mechanism to do this as part of a post-processor step that displays the data. The simplest way to do this is to divide the domain into cells and count the number of particles in each cell, then present the results as a rastor map. This is a very fast routine but has the weakness that it becomes patchy around the fringes and the answer will depend, to some extent, on cell size. An alternate approach is to partition the point distribution domain into Thiessen polygons and a triangular mesh. This is computationally more difficult but provides a continuum and contourable representation of the pollutant density data.

In most trajectory models advection processes, which include currents and wind drift factors, are handled as external data that is calculated, or entered as though they came from an independent procedure. Computationally, they can be thought of as functions that any Lagrangian particle can call, with position and time as parameters, and an advective displacement is returned. In its most general form, these are multi-dimensional look up tables which could be handled by very large databases or interactive programs, but a number of simplifications are possible and, in general, they seem to provide sufficient accuracy to be operationally useful. An example of this is to use a separation of variable approach, where a spatial pattern is modulated by a separate time dependent amplitude function. Then combinations of patterns and modulation functions are added together to represent complex flows. Models that handle up to a dozen alternate advective patterns usually provide enough flexibility to represent at least as much of the flow complexity as is understood at the time of the trajectory analysis.

For anything except solid objects that float in the ocean there will be small scale shear effects caused by turbulence and unsteadiness in the currents, or wind. Because of this, any collection of particles will tend to spread out and the mean distance between them will increase with time. This process in independent of convergence zone effects and acts in a way that is opposite to them. For small convergences, these turbulence effects will tend to dominate and, even though the oil distribution might remain banded in Langmuir cells, the convex hull of the oil distribution will continue to increase in area with time. For large scale convergences, turbulence effects will tend to be overshadowed and the oil distribution may be compressed into quite narrow zones. The standard approach that is used to simulate these turbulence processes is to use a Monte Carlo representation of the diffusion operator. This amounts to applying a statistical random walk algorithm to each of the Lagrangian particles for each time step. The size of the random step is usually adjusted to simulate observational data as soon as it is available. Prior to observational input, nominal standard oceanographic values give acceptable results. There are cases where some improvement in the model results may be possible by using anisotropic dispersion step sizes, or shear dependent scaling, but in general the potential improvement in model results would be insignificant compared to the other uncertainties and a simple uniform random walk is adequate.

There are a number of processes that are associated with the local winds and most models represent them with a simple wind drift factor. As has been pointed out, this collection of processes will depend somewhat on the sea state, age, and weathering stage of the oil. Since the oil is represented as particles that can have attributes which may include much of this information some of this variability can easily be included into the algorithms. A relatively simple and yet operationally useful approach is to specify a range of wind drift factors (typically 2% - 4.5% of the wind speed) and then use a Monte Carlo procedure for applying this as an advective process to each Lagrangian oil particle. A slight advance on this approach is to modify the drift factor based on the individual mass, or age of the particles.

As oil weathers its physical characteristics alter significantly and, subsequently, the processes that affect its movement and spreading change. To represent these effects the weathering algorithms must be applied to individual Lagrangian oil particles. There are a number of different approaches that have been used for these computations, but generally they are simple and tend to concentrate on mass balance considerations such as evaporative loss and dispersion into the water column, rather than physical properties of the remaining oil such as emulsion formation. It is safe to say that this is an area where operational needs are not met by presently available models and a number of research projects are looking at ways to make improvements in the algorithms. Several stand-alone oil weathering models are being tested and compared with various forms of data and this may be a case where the restriction on non-linear algorithms in the mixed Lagrangian/Eulerian formulation leads to some limitations.

Oil beaching processes can be modeled using wind and tidal data. Typical algorithms exclude the possibility of currents beaching the oil, but strand it if the winds are onshore and the tides are at a neutral, or falling stage. Lagrangian oil particles that are beached are flagged as such and then subject to refloating algorithms that depend on the shoreline characteristics and whether the tide is at such a stage that the individual particles are in the water. Obviously, oil that strands on a spring tide may not even get an opportunity to refloat for a two week period and the computational procedures should consider this possibility.

Use Strategies For Trajectory Models

When most people think of trajectory analysis or trajectory modeling they assume that the modeling activity will forecast the future distribution of the pollutant based on the initial or present distribution of the oil. In this sense the models are used in much the same way as a standard weather forecast model. In fact, this is the most common first request that comes in during operational spill responses. However, this is only one of the potential ways to use trajectory models or analysis techniques. Forecasts of where the oil will go are very useful for immediate response activities, but they are limited by the length of time that weather forecasts are available. Most significant spills will last a great deal longer than that. For major spills it is necessary to carry out advanced planning that covers contingencies well beyond the time scales that are reliably covered by direct forecasts. To provide information for this longer range planning several other modeling and analysis techniques are available.

One alternate trajectory analysis approach is to focus attention on the locations of high value resources, rather than the oil distribution. This technique is referred to as receptor mode analysis. In this approach, a high value target, such as a sensitive environmental region, is identified and the problem is formulated in terms of where the oil or pollutant could come from such that it might impact the target. To solve this problem the transport processes are reversed and the spill is hypothesized to come from the target. If the results are done in a statistically correct way the output is a joint probability distribution map that gives the probability that oil coming from any particular point could move to the target. In essence this is a threat zone map. As oil moves into the threat zone it starts to represent a threat to the high value target and some protective response may be called for. It is also possible to use this same inverse modeling procedure to overlay minimum time of travel contours on the threat zone map so that response personnel can estimate not only whether a threat is developing but also how long they may have to respond to it. During large spills it is generally a good idea to look in a "down stream" direction for the spill movement and carry out receptor analysis for all major high value targets. This then turns out to be very useful for staging equipment and committing scarce resources only to threats that have a significant probability of developing.

A third type of trajectory analysis is based on a statistical use of climatological distributions for transport processes. In this statistical analysis a particular weather forecast and current regime is replaced with a sequence of wind and current patterns that represent a statistically accurate synthetic climatology. Since each realization is independent, the resulting distribution is a probabilistic representation of an ensemble of spill centroids. The correct interpretation of this representation is that it presents an envelope of the potential locations that may be threatened by the spill. It is a composite of all the places that might need protective consideration during a spill.

Obviously either of the two previous analysis techniques could be done prior to the spill and thus equally well contribute to contingency planning for spills. If they have not been done as part of a planning activity they should of course be carried out as part of the package of analysis techniques that are used to compile the overall spill response recommendations from the trajectory team.

During any complex spill response the focus and degree of concern within the activities will shift from place to place and encompass more or less detail. Modeling and analysis procedures will need to be flexible and easy to use. It is absolutely essential that any models must have the capability to quickly assimilate any new data that may become available so that they can re-establish their initial conditions. In operational response this requirement is typically far more important then trying to include progressively more complex representations of dynamic processes that may give a better explanation of the physics but cannot be supported with real time data corrections. It is important to remember that the very best full-scale representation of the spill process is the actual spill itself. If the trajectory analysis techniques cannot recognize this fact and take advantage of it, then the results will be substandard no matter how complex the algorithmic representations and colorful the data presentation turn out to be.

As important as it is to take full advantage of the information that is gathered during actual spill events, a good deal of care must be exercised to make sure that the information that is used in the analysis is self consistent. For example, current pattern observations that do not conserve mass must be re-analyzed or the extraneous convergences or divergences will destroy the usefulness of any analysis results. In addition, during any major spill literally hundreds of observers will report oil position data from overflights. Many of these observers are untrained and may not have very much experience in looking at oil floating on the sea. Under these conditions a surprising number of false positive sightings are reported. If all reports are used to correct model output the results will be chaotic at best. Under these conditions, there are statistical analysis techniques that make it possible to identify and classify variations between predicted and observed results. In many cases it is quickly possible to divide the discrepancies into physically inconsistent cases, which are likely to be false positives and errors in the transport processes, which can be used to update and calibrate model results. The small number of remaining ambiguous discrepancies can usually be easily investigated in future reconnaissance fights by experienced observers.

Conclusions

The major physical processes that affect the movement and spreading of oil have been outlined. In addition, a number of trajectory analysis procedures and possible model use strategies have been discussed. At some stage it becomes necessary to consider how to put these components together so that they can be used to support operational spill response activities. Clearly, the results should be packaged in such a way that they relate to required operational decisions and realistic response options. In general the product of trajectory analysis is a focused, detailed briefing to response personnel. Wonderful explanations of subtle oceanographic process may thrill the trajectory analyst but have no place in the operational briefing unless they relate to the questions at hand. Various data and graphic components, model output, etc. may be used; but these are component parts and tools, and individual pieces can never carry out the important synthesis that views the data in terms of the overall response activities. An important component of any briefing that the trajectory analyst must consider is the processes that are not represented and the potential errors that might occur. In can't be overstated that whenever trajectory models are used it is at least as important to know what they cannot say as it is to know what they do say. Responders absolutely want to know how much they can count on the analysis results and what the potential unresolved questions may be. A detailed briefing should also be ready to suggest additional investigations that might help resolve outstanding questions if they become critical.

It is important to remember that trajectory analysis is more then just a map of where the oil may go. Physical process data has many uses throughout the response. Weather forecasts are important for planning field operations. Current data is critical for designing boom placement and mooring strategies. The sensitivity of recommendations to possible errors in the scenario description and input data should be a standard part of the analysis procedures and the results of these uncertainties should be part of the briefing package. Models should be run forwards and backwards and statistically. The implications of uncertain input data should be explored and the error bounds mapped through to the final recommendation. In some respects trajectory analysis could be thought of as a task which tries to explore all potential situations that result from the release, movement and spreading of pollutants. This task is, of necessity, interactive because each new view of the spill as it develops changes it initial reality and requires a new round of investigations and synthesis.

Given all the pieces and components that go into trajectory analysis the ultimate usefulness of the information will depend on how relevant the advice that is generated is to the actual response. It is clear that more than just trajectory models, oceanography and meteorology are required for successful trajectory analysis support. An understanding of the spill response options and available tools is also critical. In addition, it is very important to understand operations in an environment that is initially data sparse, and driven by truly phenomenal pressures to respond immediately. Many formal and very powerful computational and analysis procedures are simply not available because the required input information is not known and could not be obtained in time to be applied to the problem. The fragments of information that are available may have high uncertainty and any projections into the future, with regard to forecasted environmental conditions or the arrival of needed response equipment will also be uncertain. In the face of all this the response community must sort out what is known, grab what can be had, in terms of equipment, and get it to the places it might do some good. While this is going on hundreds of non-responders - in government, industry, private groups and the press - are forming their own opinions based on sparse and possibly wrong data. These opinions quickly get translated into advise, or demands to the response personnel and the stage is set for the general cacophony that characterizes most large oil spills. This process seems unavoidable in a free country with an active press. The question turns out to be; is there anything that trajectory analysis can do to help guide the response, to make sure that what gains in environmental protection are possible can actually happen, and, to keep the deflection of critical attention and resources from focusing on false positives.

In some way the above situation sounds like the description of a small war, and people who have been through it at least think of it as a battle. This gives a cue as to where to look for additional analysis tools. In particular, the Navy has developed a number of procedural techniques that are referred to as operational research and operational analysis. These components are directed at the task of collecting information on how to respond to situations that have many of the characteristics that are found in the spill scenario that is described above. Of particular interest is some applications of what is called "Game Theory". In any game where chance plays a part, the player can take all of the information available and try and respond so that they will achieve a "maximize win". This would provide the best chance of maximizing their return. An alternate and generally different, game strategy might be appropriate if the player is protecting very high value resources. In this case the player would attempt to "minimize regret" rather then "maximize win".

In spill response it seems like the inherent uncertainties in understanding the spill situation and its potential to unfold into the future suggest that trajectory analysis should be aimed at supporting a "minimum regret" rather then a "maximum win" strategy. To put this into context; a " maximum win" strategy would be one where the very best estimate of winds, currents and initial distribution of the pollutant were collected and the resulting forecast taken as "the" threat that needs to be responded to. This is where a trajectory model, or analyst would "give it their best shot" and come up with a most probable scenario. A "minimum regret" strategy, on the other hand, would use whatever analysis techniques are available to investigate the sensitivity of various estimates to errors in the input data and explore the implications of alternate, plausible scenarios in the geophysical forcing functions. For example, what is the significance of an atmospheric frontal passage six hours before the forecasted time of arrival. Or, is there any historical data that suggests a coastal current reversal this time of year and if so what would the trajectory look like then. As this type of analysis takes place the investigator is exploring situation space and the briefing documents can then provide the response organization with the "best guess" and at the same time cover alternate possibilities that might present a significant threat. The major difference between these two approaches is that the second one can identify less likely, but extremely dangerous or expensive, scenarios that may require the development of alternate protection strategies. These might include the set-up of monitoring or reconnaissance activities and the identification of reserve supplies of equipment or personnel should the need arise.

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