Trajectory Analysis Handbook

National Oceanic and Atmospheric Administration • NOAA Ocean Service

Office of Response and Restoration • Hazardous Materials Response Division

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
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Hazardous Materials Response Division

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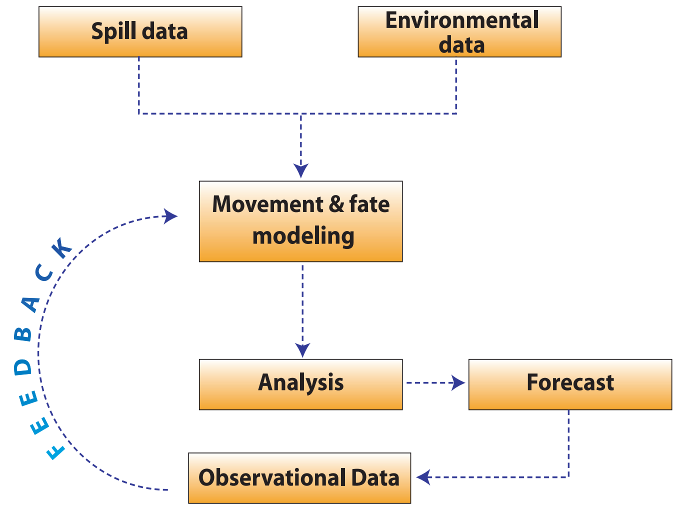
NOAA's Hazardous Materials Response Division provides scientific support to the Unified Command for response to spills in the marine environment. For further information, please visit our website at http://response.restoration.noaa.gov. This guide was developed with support from the U.S. Agency for International Development.

“Where will the oil go?”

This is a critical question asked by the emergency responder during an oil spill. Knowing the trajectory of the spill gives decision-makers critical guidance in deciding how best to protect resources and direct cleanup. However, it is often very difficult to predict accurately the movement and behavior of an oil spill. This is due, in part, to the interaction of many different physical processes about which information is often incomplete at the start of a response. The modeler must thus continuously update predictions with new data and explore the consequences and likelihood of other possible trajectories, a procedure called “trajectory analysis.” The end product of trajectory analysis is often a map showing the forecast and probable uncertainty bounds of the slick movement.

This guide provides an overview of the physical processes that affect oil movement and behavior in the marine environment. Trajectory analysis is most often done using computer models to keep track of complex, interacting processes. Even without a model, you can estimate the time and length scale of an event using the information you'll find here. The guide can help the responder and planner understand physical processes and potential uncertainties as they incorporate trajectory analysis into the response.



Trajectory Analysis

Forecasting the movement of an oil spill is often hampered by insufficient input data, particularly in the first few hours of the release. Detailed **spill data** (location, volume lost, product type) are often sketchy and **environmental data** (wind and current observations and forecasts) are often sparse or unavailable. Nonetheless, the modeler must examine the data and attempt to understand the physics and chemistry that will likely affect the oil **movement and fate** of the particular spill .

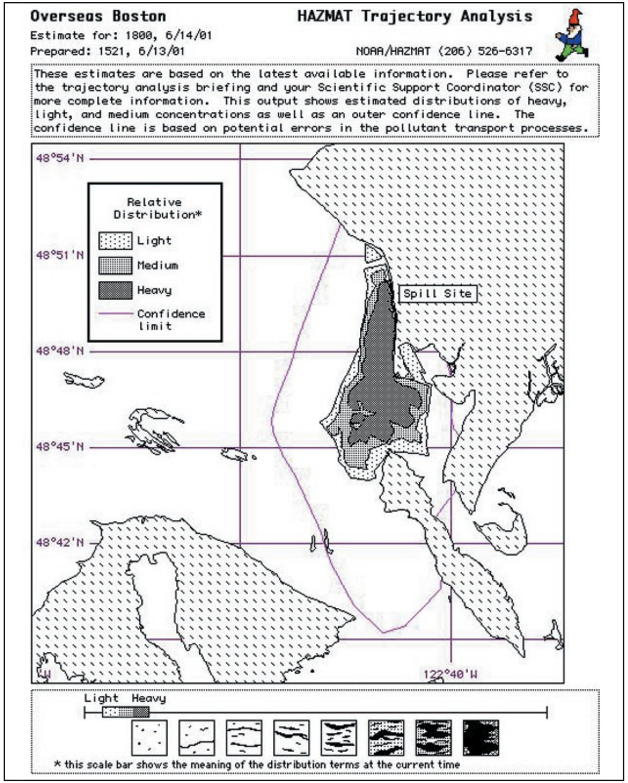
With an understanding of the physical processes, the modeler can provide an **analysis** to the Unified Command as a forecast. If the initial **forecast** is inaccurate, which can occur due to erroneous spill data (e.g., location and amount of oil released) and/or erroneous environmental data (e.g., weather forecast) and model limitations, the modeling team reviews the new information and refines the forecast. In general, as the spill unfolds, the forecast of oil movement and fate improves because the quality and quantity of the on-scene **observational data** improves (while initial spill data becomes relatively less important).

Uncertainty

Trajectory analysis should include not only the "best guess" of the oil movement and fate but also some representation of the uncertainty in the spill and environmental data used to make the forecast. The uncertainty in a trajectory forecast depends on the length and time-scale of the spill. The following table indicates the uncertainty for input data required by most oil spill models. It should be noted that model output uncertainty is not necessarily directly proportional to model input uncertainty.

Uncertainty for input data required by most oil spill models

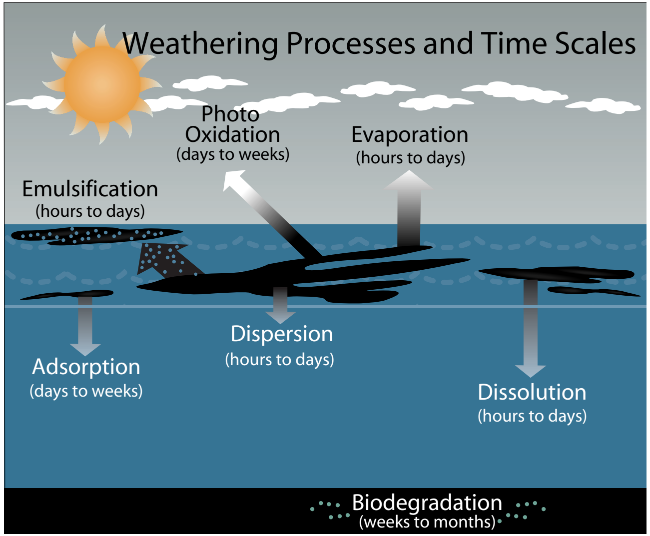
Category	Parameter	Uncertainty
Release details	Spill location	Low - Medium
	Time of release	Low - Medium
	Type of oil (density, viscosity)	Medium - High
	Potential spill volume	Low
	Actual spill volume	High
	Release rate	High
Oil weathering	Light refined products	Low
	Intermediate Fuel Oils (IFO 180, IFO 380, Bunker C, Fuel Oil #6)	High
	Heavily studied crude oils (Prudhoe Bay, Arabian, Ekofisk, Hibernia)	Low
	Crude oils	Medium - High
Winds	Observations	Low
	24- to 48-hour forecast	Low - Medium
	48- hour to 5-day forecast	Medium - High
	Wind drift (typically 1 to 6%)	Low
Surface currents	River	Low
	Tidal areas with current stations (unless currents are weak and variable)	Low
	Shallow-water lagoon	Low - Medium
	Shelf area (wind setup)	Medium
	Continental slope (e.g., Gulf Stream, California Current)	Low
	Abyssal Plain	High
Turbulence	Spreading	Medium
	Horizontal diffusion	Low - Medium



Sample trajectory analysis map.

Trajectory Analysis

Ideally, the trajectory is displayed in a format that is easy to understand. It should indicate both the forecast and the uncertainty. In this example, the forecast "best guess" of the oil movement is overlaid on a map of the shoreline. The forecast is presented as light, medium, and heavy contours. The scale at the bottom of the map represents the percent coverage of the surface oil within these contours. Plausible errors in the spill and environmental data were explored by the modeling team; the colored outer contour represents a 90% confidence bound. This provides an indication of the uncertainty in the forecast.



Weathering Processes and Time Scales

The physical and chemical characteristics of petroleum change almost immediately when spilled in the marine environment due to evaporation, dispersion, emulsification, dissolution, oxidation, sedimentation, and biodegradation. All of these processes interact with each other and are collectively referred to as *oil weathering*. The table following describes some of the weathering processes and the time scales of those processes important for emergency response.

Weathering processes and time scales important for emergency response

Weathering Process	What is It?	Why is it Important?	Time Scales
Evaporation	Conversion of liquid to a gaseous phase. The lighter fractions in the oil are lost first.	Major process that accounts for the loss of oil, particularly light oils. At 15°C, gasoline evaporates completely over a 2-day period, 80% of diesel fuel evaporates, 40% of light crude, 20% of heavy crude, and only about 5-10% of Bunker C.	< 5 days
Emulsification, or formation of mousse	Very small water droplets are mixed into the liquid oil. Water content often reaches 50-80%. Occurs on water, needs some wave action.	Can increase the amount of pollutant to be recovered by a factor of 2-4. Slows down other mixing processes.	Onset can be delayed for days but the emulsification process happens rapidly.
Natural dispersion	Breakup of an oil slick into small droplets that are mixed into the water by energy.	Removes the oil from the water surface.	< 5 days
Dissolution	Mixing of the water-soluble components of oil into the water.	The most water-soluble components of oil are most toxic.	< 5 days
Biodegradation	Breakdown of oil by microbes into smaller compounds, eventually to water and carbon dioxide.	Rate depends on oil type, temperature, nutrients, oxygen, and amount of oil.	weeks to months
Formation of tarballs	Breakup of slicks of heavy crudes and refined oils into small patches that persist for long distances.	Tarballs are hard to detect, so the slick appears to be going away though it is still a threat.	days to weeks

Percent evaporated over time for an instantaneous release of 100 barrels with winds at 10 knots and water temperature at 20°C

	% Evaporated	Hour
Gasoline	94	1
Lagomedio	38	18
Diesel fuel oil	37	18
Prudhoe Bay	28	70

Evaporation

Evaporation can be a major mechanism for removing oil. The amount evaporated depends chiefly on the oil properties, the wind speed, and the water temperature.

Generally, light refined products, like gasoline or jet fuel, evaporate faster than heavier products, such as heavy crude oil. From the table, you can see that most of the gasoline evaporates within a few hours. Lagomedio and Prudhoe Bay crude oils are more persistent in the environment and have much lower evaporation rates, 38% and 28%, respectively. After 120 hours, much of the product would be expected to remain on the water surface.

Dispersion

Breaking waves can drive small droplets of oil into the water column. If the droplets are small enough (diameters less than 50-70 microns) natural turbulence in the water will prevent the oil from resurfacing, just as turbulence in the air keeps small dust particles afloat. The smaller droplets that stay in the water column are considered dispersed.

Dispersion can be a mechanism for removing oil from the water surface. The amount dispersed depends on the oil properties (the viscosity and surface tension, in particular) and water conditions.

Oil products with low viscosity, like gasoline or kerosene, are more likely to disperse into the water with breaking waves than a high-viscosity oil, like an IFO 380 or Oficina heavy crude. Therefore, the dispersed fractions of gasoline or kerosene can be relatively large in heavy seas.

A possible treatment of oil spills is to spray the slick with chemical dispersant. Chemical dispersants enhance natural dispersion by lowering surface tension. This guide does not address subsurface oil movement because of the difficulty in developing a trajectory analysis of dispersed oil.

Sample oil solubilities

Oil	Aqueous Solubility (mg/L)*
Unleaded gasoline	260.9
Diesel	60.4
Prudhoe Bay crude	20.5
Lagomedio	10.0

*Jokuty, P., S. Whiticar, Z. Wang, M. Fingas, B. Fieldhouse, P. Lambert, and J. Mullin. 1999. *Properties of crude oils and oil products.* EE-165. Ottawa, Ontario: Environment Canada.

Dissolution

Dissolution begins immediately and is likely to continue throughout the weathering process.

The loss of petroleum product from dissolution is minor when compared to the other weathering processes.

Less than 0.1% (very heavy oil) to 2% (gasoline) of the spilled oil volume actually dissolves into the water column. However, the components of the oil that dissolve into the water column are often more toxic to the environment.

Sample viscosities

Product	Viscosity at room temperature (cP)
water	1
diesel fuel	10
Prudhoe Bay crude	46
Prudhoe Bay crude after emulsification	250,000
Lagomedio	20
Lagomedio after emulsification	300,000
honey	10,000
peanut butter	1,000,000

Emulsification

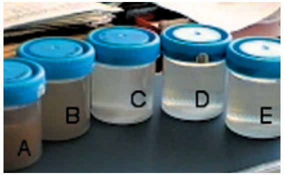
For many crude oils and some refined products, weathered oil is likely to reach a stage where water droplets are mixed into the oil, forming a water-in-oil emulsion, or "mousse."

The ability to form an emulsion depends on water conditions and the chemical properties of the oil. For example, oils with high wax and asphaltene content, such as Prudhoe Bay crude, emulsify easily if there are breaking waves. Once the oil has emulsified, the viscosity can increase enormously (see table).

Generally, oils must weather a certain amount before forming an emulsion. Although the onset of emulsification may take several days, the emulsification itself can occur within a few hours.

The emulsion can be 70 to 90% water so that the combined volume of oil and water mixture may be much greater than the volume of the original spill.

Emulsions are often classified by their stability. In unstable emulsions, water and oil separate easily under calm conditions with warm temperatures. In stable emulsions, water remains in the oil for weeks to months.



A) 10,000 g/m^3
B) 1000 g/m^3
C) 100 g/m^3
D) 10 g/m^3
E) 1 g/m^3

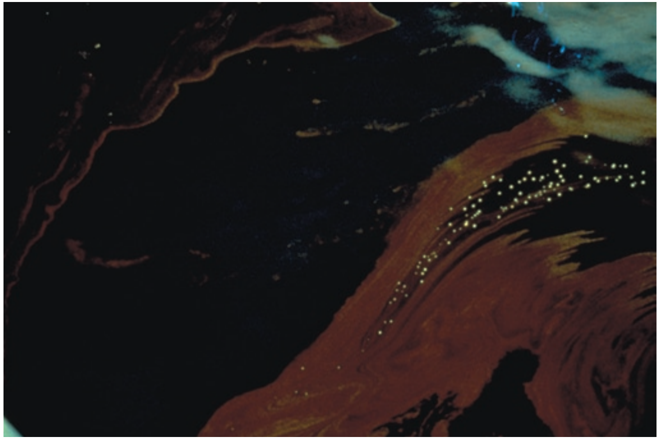
Different concentrations of fine dust in water.

Sedimentation

Sedimentation is defined as the adhesion of oil to solid particles in the water column. Oil can be sorbed onto sediments in the water column and may eventually be found in the bottom sediments.

Turbulent waters with high sediment load (~500 g/m^3), such as a fast-moving, muddy river, can move the oil through the water column within hours of the initial release.

Waters with low sediment load (< 5 g/m^3), as in the open ocean, will allow oil to remain on the surface much longer (weeks), spreading the slick over a wider area.



Photograph showing a large patch of weathered oil with a crusty, "skin" layer on the surface. The white spots in the picture are 3-inch by 4-inch drift cards cast into the water to help track the movement of the oil.

Photo-oxidation

Sunlight changes the spilled oil's chemical and physical properties.

This process is limited to the surface of the oil and can result in a thin, crusty "skin" on slicks and tarballs.

The "skinning" of the oil is thought to limit evaporation because the lighter oil components can no longer diffuse through the surface of the slick.

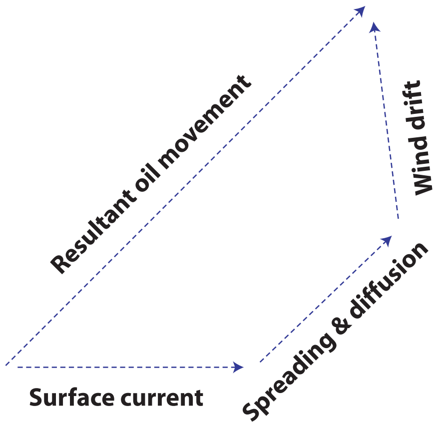
Photo-oxidation may increase the ease of emulsification and is considered a long-term weathering process taking weeks to months.

Kelp attached to weathered oil or "tarballs"

Biodegradation

The spill is finally removed when the oil biodegrades. The microbes that degrade oil occur naturally in the environment.

The rate at which the organisms degrade the oil depends on the properties of the water and the oil and microbial activity. This process is thought to occur over time scales of weeks to years.

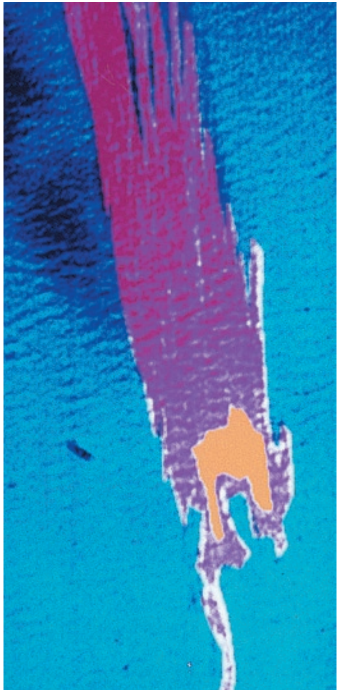


Oil Transport

Two major processes transport oil spilled on water: spreading and advection. For small spills (<100 barrels), the spreading process is complete within the first hour of the release.

Winds, currents, and large-scale turbulence (mixing) are advection mechanisms that can transport oil great distances.

In general, the oil movement can be estimated as the vector sum of the wind drift (using 3% of the wind speed), the surface current, and spreading and larger-scale turbulence (diffusion).



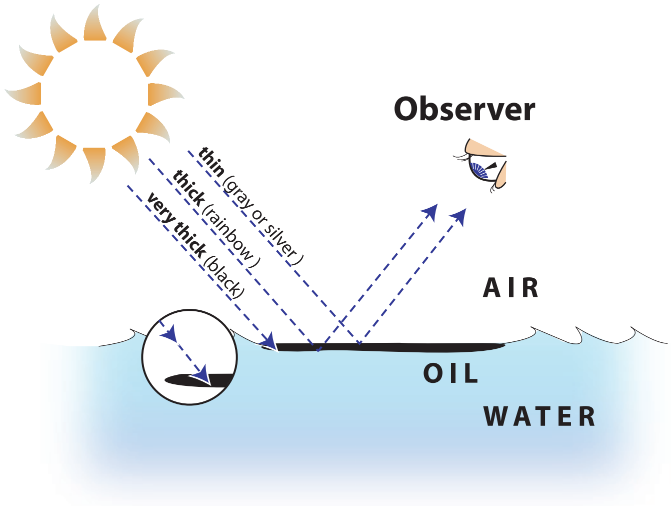
Color-enhanced image of a test spill (<50 barrels).

Oil Spreading

The spreading process occurs quickly and, for most spills, mostly within the first hour. In the open ocean, winds, currents, and turbulence will quickly move the oil.

Spreading will occur quicker for lighter and for less viscous oils in warm water temperatures and for warm oils.

The slick does not spread uniformly but will often have a thick part surrounded by a larger, but thinner sheen. The figure shows a color-enhanced image of an experimental spill. The orange portion is the thick part of the slick and the pink area, sheen. Note that about 90% of the oil is found in 10% of the slick area (the orange portion of the figure).



Very thin films: no phase shift or reflection and all frequencies reflected back (gray or silver)

Intermediate films: phase shift depends on wave length or color and distance traveled through the oil (rainbow)

Thick films: light is absorbed (brown or black)

Trajectory analysis does not typically provide good information on oil thickness.

Oil Thickness

Oil slicks form very thin films on the open water and, depending on the product, the thickness can range from a tenth of a micron to hundreds of microns. Since 1929, oil spill researchers have studied the relationship between oil thickness and the color of the film.

When direct light from the sun contacts a very thin oil film (<0.1 micron; µm), much of the light is reflected back to the observer (see diagram) as gray or silver sheen.

If the film is thicker (perhaps 0.1 to 3 µm), the light passes through the film and is reflected off the oil-water interface and back to the viewer. The observer will then see a film that can range from rainbow to darker-colored sheens.

For very thick films (> 3 µm), the light is absorbed and the slick will appear dark- colored (i.e., black or brown) to the observer. However, the viewer can no longer determine film thickness based on color. If the slick is dark-colored, the observer cannot tell whether the film is 3 µm or 100 µm thick.

Because sun angle, glare, sea state, view angle, and viewing through plexiglass windows can affect the appearance of the slick, estimating film thickness based on color is unreliable. Calculating oil volume also requires estimating the percent oil coverage, a very difficult task.

Wind affects on oil trajectory

	Wind Speed	
	LOW <5 knots	**HIGH>25 knots**
evaporation	increases	→
dispersion	increases	→
patchiness	increases	→
convergences	natural	Langmuir →
observability	good	poor →

Winds

Winds affect the trajectory in three major ways:

1) oil weathering
2) surface effects on the water
3) direct transport

Estimating Wind Speed From Helicopter

Wind speed	Waves
0 to 5 knots	Round or sinusoidal shape
5 to 10 knots	Trochoid shape (peaks are pointed)
10 knots	Breaking waves
15 knots	Tops are coming off the waves
20 knots	Streaks of foam trailing behind waves
>20 knots	Difficult to observe surface oil

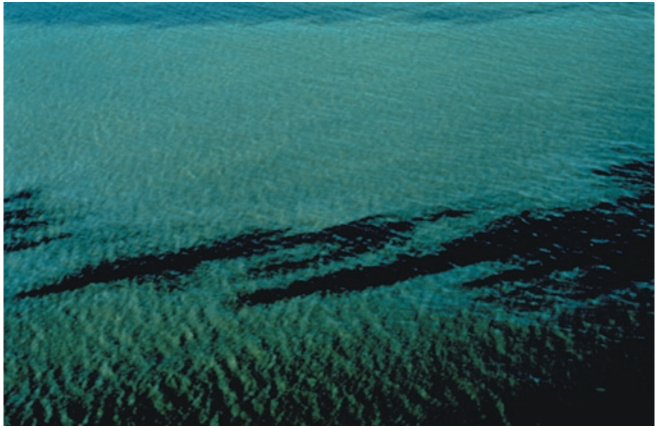
Wind Speed Scale

The Beaufort Wind Scale is named after Admiral Sir Francis Beaufort, who developed the scale in 1805 to estimate wind speed from observing the sea state. The table at left provides an alternative approach to estimating wind speed, particularly useful if you are observing from an aircraft. The following table shows the Beaufort Wind Scale for wind speed and the corresponding sea characteristics.

Wind Scales and Sea Descriptions (From Willard Bascom, *Waves and Beaches*, 1980)

Beaufort Scale	Seaman's description of wind knots	Velocity (knots)	Estimating wind velocities on sea	International scale sea description and wave heights
0	Calm	<1	Sea like a mirror	Calm, glassy 0 foot
1	Light air	1-3	Ripples, no foam crests	
2	Light breeze	4-6	Small wavelets, crests have glassy appearance and do not break	Rippled, 0-1 foot
3	Gentle breeze	7-10	Large wavelets, crests begin to break. Scattered whitecaps.	Smooth, 1-2 feet
4	Moderate breeze	11-16	Small waves becoming longer. Frequent whitecaps.	Slight, 2-4 feet
5	Fresh breeze	17-21	Moderate waves taking a more pronounced long form; mainly whitecaps, some spray.	Moderate, 4-8 feet
6	Strong breeze	22-27	Large waves begin to form extensive whitecaps everywhere, some spray.	Rough, 8-13 feet
7	High wind (moderate gale)	28-33	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind.	Very rough, 13-20 feet
8	Gale (fresh gale)	34-40	Moderately high waves of greater length; edges of crests break into spindrift. The foam is blown in well-marked streaks along the direction of the wind.	Very rough 13-20 feet,

Wind Drift


Windrows

Observations of actual oil spills and controlled experiments indicate that the wind drift can range from 1 to 6% of the wind speed (most modelers use an average of 3%). The lower windage value of 1% reported may be due to some of the oil droplets being submerged by waves. Langmuir circulation can also result in wind drift variability. The oil within the windrows may move up to 5.5% of the wind speed. This hypothesis would account for the higher windage value of 6% reported at spills.

While oceanographic theory predicts an angle between the surface current and the wind speed, observations of oil slick trajectories suggest that the actual angle is less than 10°. Wind direction predictions are typically not this accurate and few modelers include a rotation angle in their calculations.

Most modelers use wind speeds measured at 10 meters above the water surface. Observations at other heights are adjusted by standard techniques to the standard 10-m height.

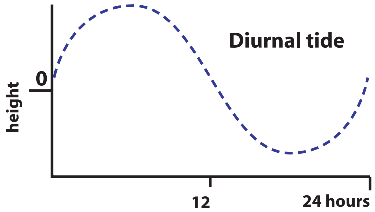
It should be noted that wind direction is commonly reported as the direction *from* which the wind is blowing and the surface current is reported as the direction *toward* which the water flows. This means that a north wind and a southerly current are moving in the same direction.

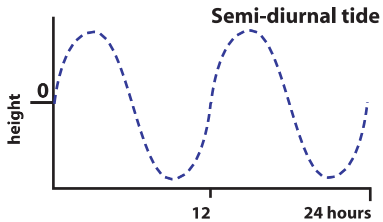
Drifters

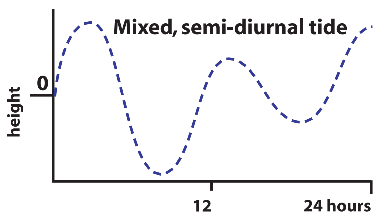
Currents

The surface current is a mechanism for transporting oil. Currents are an important factor in determining the length and time scale of a spill.

- Ocean circulation can transport oil for thousands of miles in months to years
- Ocean coastal flow can transport oil for hundreds of miles in weeks
- Estuarine circulation can transport oil tens of miles in days
- Rivers can transport oil tens of miles in hours to days





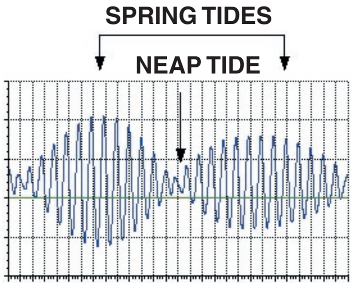


Tide Patterns

In a few coastal areas, there is a pattern of one high tide and one low tide per day. This tidal pattern is called a diurnal tide.

The dominant tidal pattern in most of the world's oceans is two tidal cycles where the high water-low water sequence occurs twice a day. If the highs and lows in a semi-diurnal tide occur at different levels, the tide is referred to as a mixed, semi-diurnal tide.

The predicted astronomical tidal pattern is often modified by other factors. Winds acting on the sea surface and atmospheric pressure can modify the sea level. These types of events can be particularly important in shallow-water areas. Strong coastal storms can markedly modify the tidal patterns for a particular area.

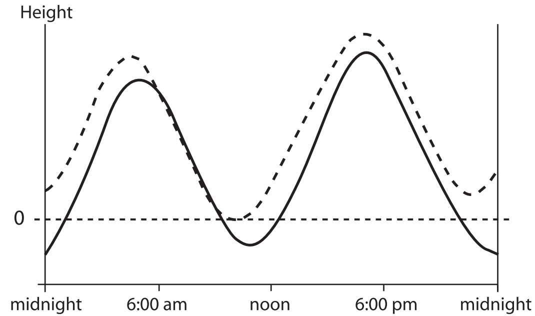


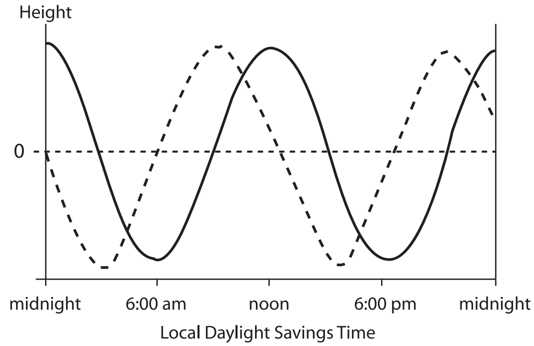
Spring and Neap Tides

Spring tide is the very highest and very lowest tide, which occurs twice a month when the moon is either new or full.

Neap tides are the opposite of the spring tide: the tidal range between high and low water is smallest and occurs near the time of the first and last lunar quarters.

Spring tides may be important for spill response as oil beached during this time is likely to remain stranded on the upper portion of the shoreline until the next spring tide (about 14 days) or storm event. If there is a storm surge during a spring tide, the oil can remain stranded for a much longer period.





Tidal Currents

Strongest tidal currents are found in shallow-water areas or through narrow channels that connect large bodies of water.

Currents in channels (i.e., entrances to bays and estuaries) are constrained to flow either up or down the channel. In open waters, the flow depends on the direction of the tide wave.

Along the outer coasts, the tidal currents and heights are more closely in phase (progressive wave).

Tidal currents are generally out of phase with tide heights for stations inside an enclosed bay (standing wave). Phase change can also be caused by bottom friction.

Tidal currents and heights at the entrance to Galveston Bay. Solid line is tidal heights and the dashed line is tidal currents. (top)

Tidal currents and heights at the entrance to Portland Harbor, Casco Bay, Maine. Solid line is tidal heights and the dashed line is tidal currents. Note max flood is about 3 hours earlier than high tide. (bottom)

$$\text{Tidal excursion} = V\frac{T}{\pi}$$

To calculate the tidal excursion, let

T = Time from low slack to low slack (high slack to high slack)

V = Maximum tidal current velocity

Tidal Excursion

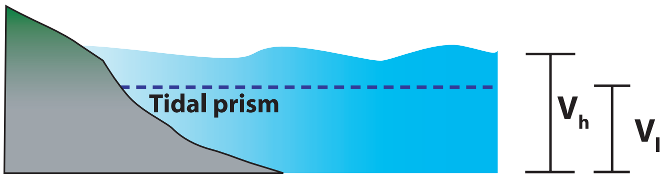
The trajectory analyst is often asked whether an offshore spill will move into a bay or estuary. To answer this question, one of the first things you should look at is the tidal excursion for the inlet. If the spill is anywhere near the extent of the tidal excursion, oil could move into the bay with the tide.

It is important to keep in mind that the tidal excursion is very much dependent on the bathymetry. In areas where the bottom is very broad and flat, the tidal influence will drop off quickly. In long, narrow channels, the tidal influence could be much larger.

Flushing

The volume of water exchanged between an estuary and the open sea during a complete tidal cycle is often called the tidal prism. In the figure, the difference between the volume of water at low tide (below the dashed line) and high tide (below the curved line) is the tidal prism.

The tidal prism method for estimating flushing assumes that the water entering on the flood tide is fully mixed with the water inside the estuary. It also assumes that the volume of river water and sea water during the flood tide equals the tidal prism.



Vertical profile of a simplified shoreline. Area between the curving and dashed lines indicates the tidal prism.

To calculate the flushing time, first measure the area of the estuary from a map. Second, calculate the volume of the estuary at low water, by selecting a depth that best represents the estuary. Third, calculate the volume of the estuary at high water, V_h. Finally, the flush time can be calculated from $f_t = \left(\frac{V_h}{V_h - V_l}\right) t_c$

where t_c is the time of one tide cycle (from low tide to low tide) and V_l is the volume of water in the estuary at low tide

This is a general approach, but the method may underestimate flushing time due to incomplete mixing; fresh water at the head of the estuary may not move through the mouth of the estuary in one tide cycle and some water that escaped on the ebb is returned on the flood. Underestimating flushing times may mean that the oil remains in the estuary longer than predicted.

***Exxon Valdez* oil spill**

Turbulent Mixing

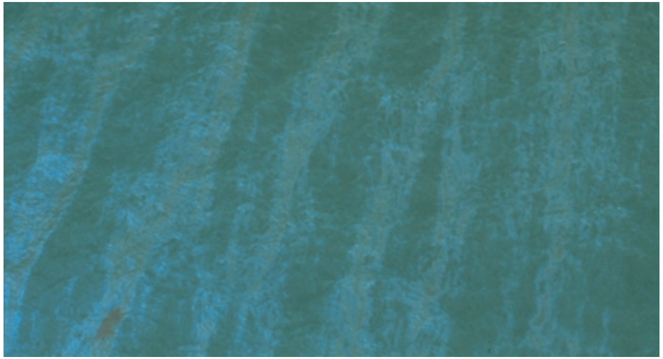
Oil spilled into water is subjected to turbulent flow. Oceanic turbulence is generated by winds and current, and by heating and cooling. Flow in the upper layers of water becomes more turbulent as the wind and current increases.

Turbulent diffusion, caused by random bulk movements of water, tears oil slicks into smaller patches that are distributed over a wider area.

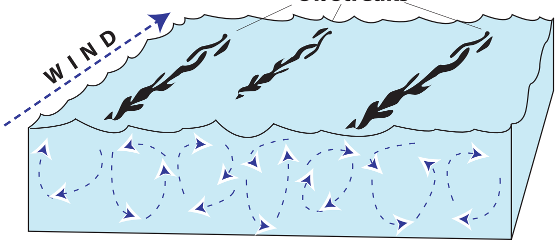
The diffusion of oil occurs mainly in the horizontal direction. Horizontal diffusion of the surface water ranges from 100 to 1,000,000 cm^2/s.

Diffusion in the vertical direction is much smaller by orders of magnitude than horizontal diffusion and generally decreases with depth.

Turbulent diffusion is not to be confused with mechanical dispersion (i.e., mixing caused by breaking waves).



Oil in widrows, or Langmuir cells.



Langmuir cells in the mixed layer depth.

Langmuir Circulation

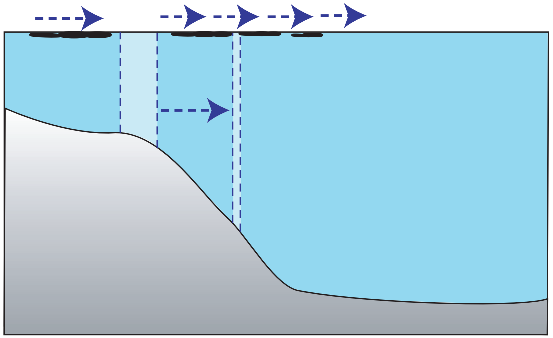
Langmuir circulation is the result of the interaction between wind-driven surface currents and surface waves. Though Langmuir circulation may be present in weak or no-wind situations, it is most often seen when the wind speed is 1.5 m/s or greater. Langmuir circulation is a major mechanism for breaking the slick up and may be important for transporting oil droplets into the water column. Predicting the onset and strength is difficult at best, but we do know the following:

1) The windrows, or streaks, tend to last from 5 to 30 minutes, then dissipate and reform.

2) The surface current, stronger in windrows, can be up to 5.5% of the wind speed.

3) Downwelling (vertical) speeds at convergence range from 5 cm/s to 20 cm/s.

Reference: Special Issue Langmuir Circulation and Oil Spill Modeling. *Spill Science and Technology Bulletin Vol. 6*



Water column moves from shallow water to deeper water.

Tidal Convergences

Convergences are natural collection areas for oil, especially tarballs. Because they are close together, the tarballs in a convergence may coalesce and form a cohesive slick.

Tidal convergences can be formed by water moving from shallow to deeper water (ebb tide) that is stretched. To conserve mass, the surface velocity decreases.

Flotsam, rafting birds, and oil can collect in these areas.

Under weak winds, the oil may not cross convergences. Strong winds may rupture the convergence. However, tidal convergence can appear consistently in the same general area during ebb tides.

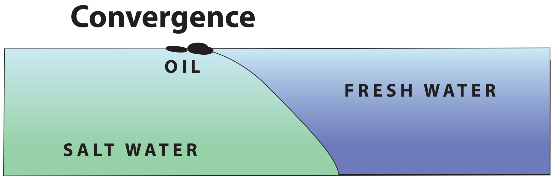
Freshwater-saltwater Interface

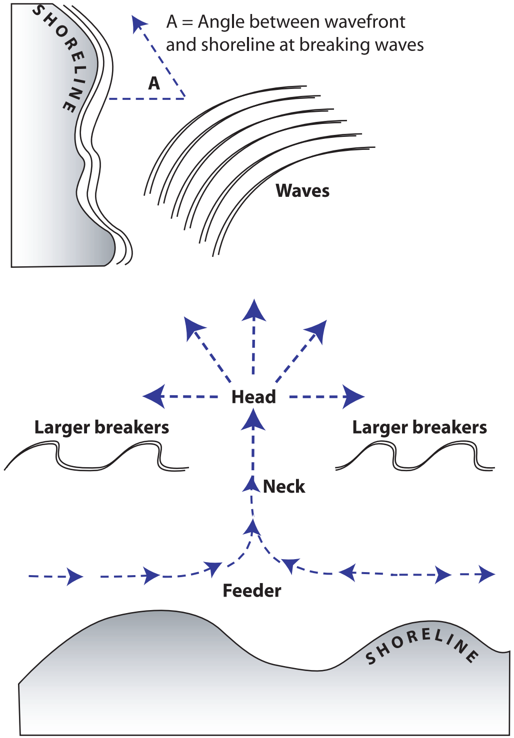
As with tidal convergences, the freshwater-saltwater interface is also a natural collection area for oil. However, this type of convergence is formed by river water flowing into the sea and spreading out over the seawater.

The fresh water is less dense than the seawater, creating a convergence at the surface.

Strong winds can rupture these convergences.

Freshwater-saltwater interface with oil sheen moving into the convergence.





Formation of longshore currents

Longshore Currents

Longshore currents are produced by waves approaching, at an oblique angle, a coastline having a gently sloping beach.

Speed and direction of the longshore current increase with wave height and with an increase in the angle of the wave front.

Typical speeds of longshore currents range from 0.3 m/s to 1.0 m/s.

As the current approaches 1.5 m/s, a jet often forms that returns flow seaward in the form of rip currents.

This type of current is very important for trajectory purposes as it provides a mechanism for transporting oil in nearshore areas beyond the breakers and offshore.

Reference: Horikawa, K. 1978. *An Introduction to Coastal Engineering*. New York: John Wiley and Sons. 403pp.

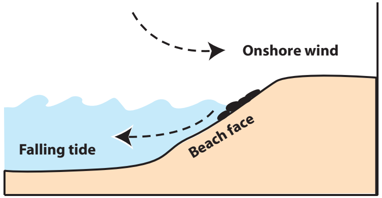
Beaching/Refloating


Oil in marsh.

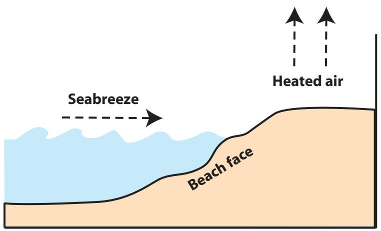

Oil streaks moving parallel to the shoreline.

Ocean currents cannot actually bring the oil into contact with the shoreline unless there is some kind of flow that penetrates the shoreline (e.g., marshes and mangroves). The first photograph shows an oil spill moving into a marsh on a flood tide.

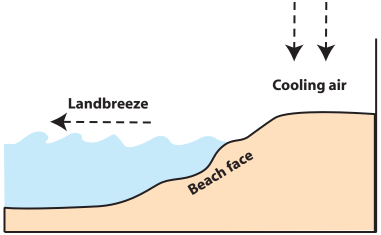
The second photograph shows streaks of oil moving along the shoreline. For the oil to beach, the wind must typically be blowing onshore.



Oil beaching with a falling tide and onshore wind.



Heating of the land and a sea breeze (from sea to land) during the day.



Cooling of the land and a land breeze (from land to sea) during the night.

Land/Sea Breeze

A falling tide with an onshore wind greatly increases the amount of shoreline oiling (see first figure). A sea breeze may strand the oil on the shore.

The land and sea breeze cycle occurs in many coastal areas and is caused by heating of the land during the day and cooling at night (see second and third figures). In some areas, the land and sea breeze can extend many miles off-shore.

Summary

To develop a trajectory "picture," the analyst must look at the components considered in any model and consider the proceses outlined in this guide. The major components of any model will be:

Spill Data

- location of spill
- type of oil
- volume lost
- time/type of loss (instantaneous or continuous? stationary? moving?)

Environmental Data

- wind
- currents (large-scale, tidal, river flow, etc.)
- tidal heights
- diffusion

Some of the processes in this guide are typically not modeled well and the modeler must account for these in the uncertainty included in the final trajectory analysis:

- oil thickness
- convergences
- local variations on astronomical tides
- small-scale currents (i.e., around piers, small groins, or jetties)
- small-scale meteorology

Beaching oil that comes ashore

Biodegradation breakdown of oil by microbes into smaller compounds, eventually to water and carbon dioxide

Convergence areas where surface waters "come together." They are natural collection areas for oil, especially tarballs.

Diffusion large-scale turbulence that mixes spilled oil

Dispersion breakup of the oil into small droplets that are mixed into the water by sea energy. If the droplets are small enough, they remain in the water column.

Dissolution mixing of the water-soluble components of oil into the water

Diurnal tide coastal areas with one high tide and low tide each day

Emulsification small water droplets or water mixed into the liquid oil, thickening it to a "chocolate mousse" consistency. Water content often reaches 50-80%.

Evaporation conversion of liquid to a gaseous phase

Flotsam garbage, or detritus, on the water surface

Flushing turnover of water from an estuary or harbor

Freshwater-saltwater interface type of convergence formed when river water flows into the sea and spreads out over the seawater. Like tidal convergences, this interface is a natural collection area for oil.

Langmuir circulation wind induced water movement that leads to windrows, or streaks, of oil that dissipate and reform. This is a major mechanism for breaking up the slick and may be important for moving oil droplets into the water column.

Longshore currents produced by waves obliquely approaching gently sloping beaches.

Mixed, semi-diurnal tide two tidal cycles where the high water-low water sequences occur twice a day at different levels

Movement and fate the direction in which the spill moves, and the physical/chemical changes that occur to the oil over time

Neap tide the opposite of spring tides: the tidal range between high and low water is smallest and occurs near the first and last lunar quarters.

Observational data on-scene measurements (winds, currents, and oil location)

Photo-oxidation changes made by sunlight to a spilled oil's physical and chemical properties

Progressive wave energy is transmitted through the water, but water particles move in an oscillatory manner.

Refloating oil that has come ashore and re-floated off the shoreline

Sedimentation adhesion of oil to solid particles in the water column

Semi-diurnal tide two tidal cycles where the high water-low water sequences occur twice a day at the same level

Spring tide the very highest and the very lowest tide, which occurs twice a month when the moon is either new or full

Standing wave as a tidal wave reaches the end of a bay or estuary, it is reflected back toward the entrance.

Surface tension tendency for molecules to stick together and present the smallest surface to the air

Tarballs weathered oil that has formed a pliable ball. Size may vary from pinhead to 30cm.

Tidal excursion degree of influence of the tides on movement of the oil

Turbulent mixing random bulk movements of water, caused by high winds and currents, that tear oil slicks into smaller patches that are distributed over a wider area

Uncertainty "confidence limits," or the degree to which the spill forecast may be relied upon to be accurate

Viscosity a measure of fluids resistance to flow

Weathering changes in physical and chemical characteristics of spilled oil due to evaporation, dissolution, oxidation, sedimentation, and biodegradation

Length

	cm	m	km	in.	ft	mi
1 cm	1	10^{-2}	10^{-5}	0.3937	3.281×10^{-2}	6.214×10^{-6}
1 m	100	1	10^{-3}	39.37	3.281	6.214×10^{-4}
1 km	10^{5}	1000	1	3.937×10^{4}	3281	0.6214
1 in	2.540	2.540×10^{-2}	2.540×10^{-5}	1	8.333×10^{-2}	1.578×10^{-5}
1 ft	30.48	0.3048	3.048×10^{-4}	12	1	1.894×10^{-4}
1 mi	1.609×10^{5}	1609	1.609	6.336×10^{4}	5280	1

Area

	m^2	cm^2	ft^2	$in.^2$
1 m^2	1	10^{4}	10.76	1550
1 cm^2	10^{-4}	1	1.076×10^{-3}	0.1550
1 ft^2	9.290×10^{-2}	929.0	1	144
1 $in.^2$	6.452×10^{-4}	6.452	6.944×10^{-3}	1

Volume

	m^3	cm^3	li	ft^3	in.^{3}
1 m^3	1	10^6	1000	35.31	6.102×10^4
1 cm^3	10^{-6}	1	1.000×10^{-3}	3.531×10^{-5}	6.102×10^{-2}
1 li	1.000×10^{-3}	1000	1	3.531×10^{-2}	61.02
1 ft^3	2.832×10^{-2}	2.832×10^4	28.32	1	1728
1 in.^{3}	1.639×10^{-5}	16.39	1.639×10^{-2}	5.787×10^{-4}	1

Speed

	ft/s	km/h	m/s	mi/h	cm/s
1 ft/s	1	1.097	0.3048	0.6818	30.48
1 km/h	0.9113	1	0.2778	0.6214	27.78
1 m/s	3.281	3.6	1	2.237	100
1 mi/h	1.467	1.609	0.4470	1	44.70
1 cm/s	3.281×10^{-2}	3.6×10^{-2}	0.01	2.237×10^{-2}	1

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