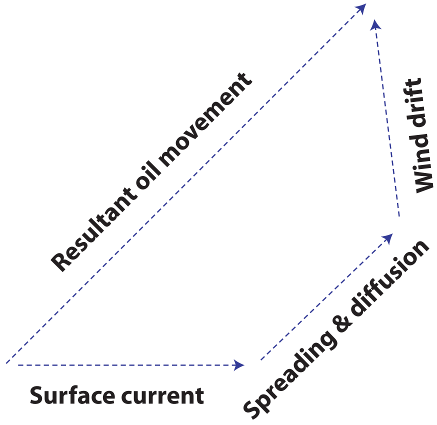
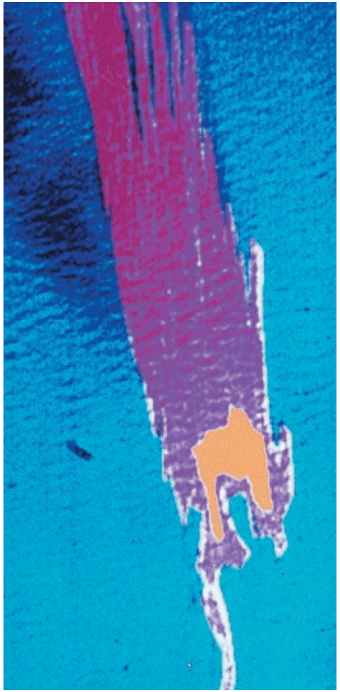


Oil Transport

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).



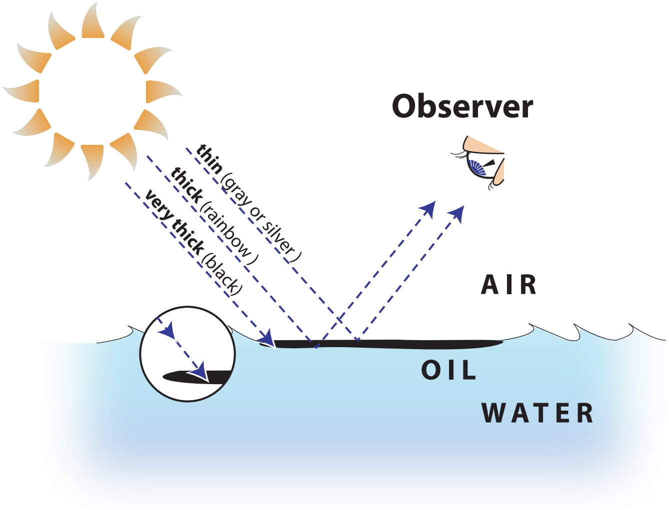
Color-enhanced image of a test spill (<50 barrels).

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

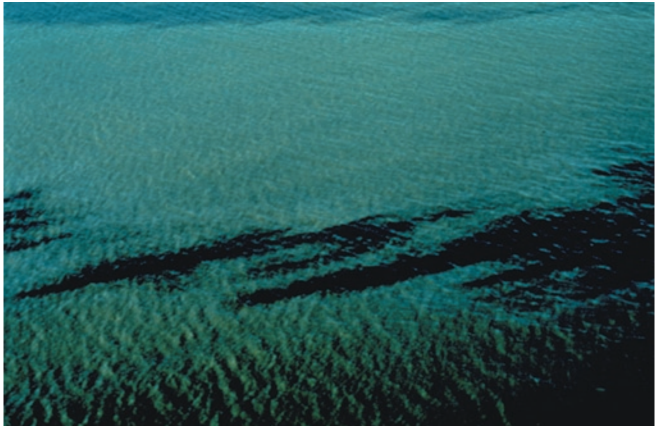
Wind speed	Waves
0 to 5 knots	Round or sinusoidal shape
5 to 10 knots	Trochoid shape (peaks are pointed)
10 knots	Breaking waves
15 knots	Tops are coming off the waves
20 knots	Streaks of foam trailing behind waves
>20 knots	Difficult to observe surface oil

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,



Windrows

Wind Drift

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.

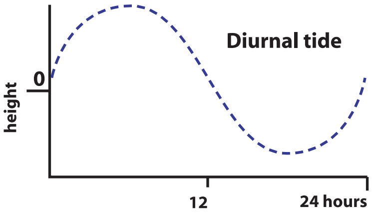
It should be noted that wind direction is commonly reported as the direction *from* which the wind is blowing and the surface current is reported as the direction *toward* which the water flows. This means that a north wind and a southerly current are moving in the same direction.

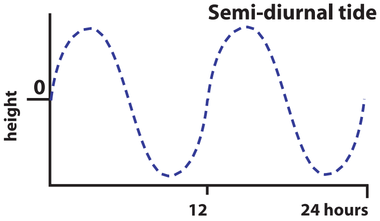
Drifters

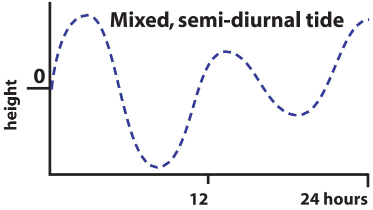
Currents

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





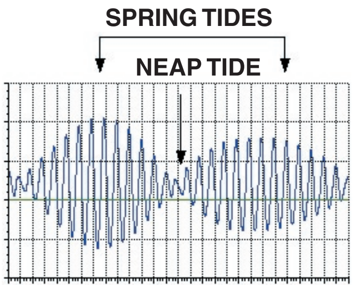


Tide Patterns

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.

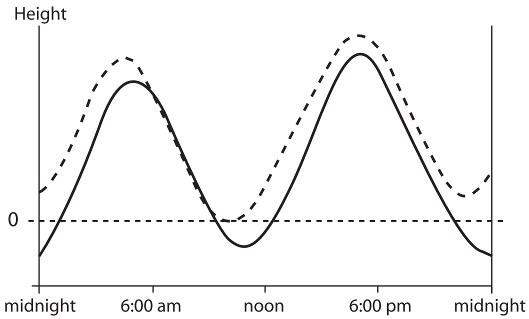
Tidal Currents

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

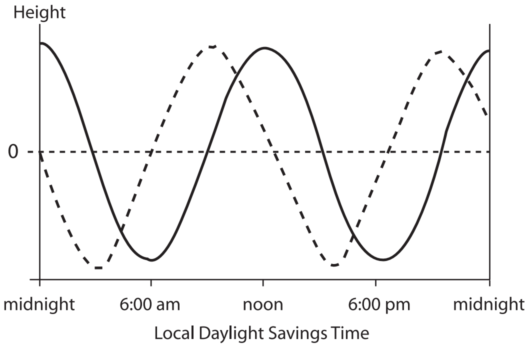
Currents in channels (i.e., entrances to bays and estuaries) are constrained to flow either up or down the channel. In open waters, the flow depends on the direction of the tide wave.

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)

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

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

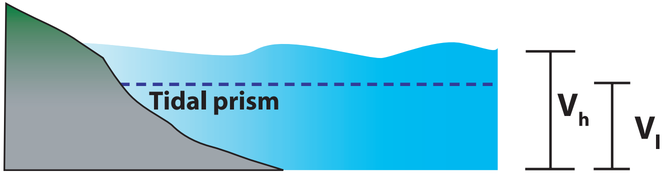
The trajectory analyst is often asked whether an offshore spill will move into a bay or estuary. To answer this question, one of the first things you should look at is the tidal excursion for the inlet. If the spill is anywhere near the extent of the tidal excursion, oil could move into the bay with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

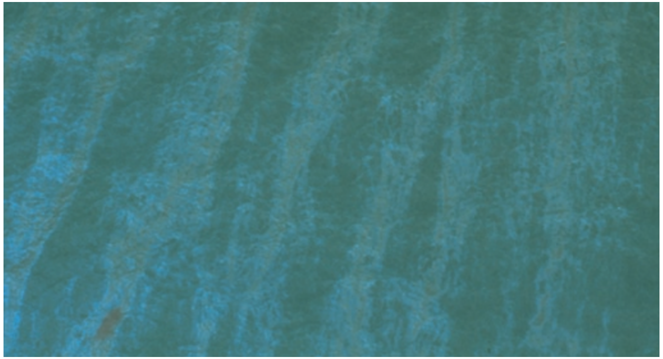
Oil spilled into water is subjected to turbulent flow. Oceanic turbulence is generated by winds and current, and by heating and cooling. Flow in the upper layers of water becomes more turbulent as the wind and current increases.

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

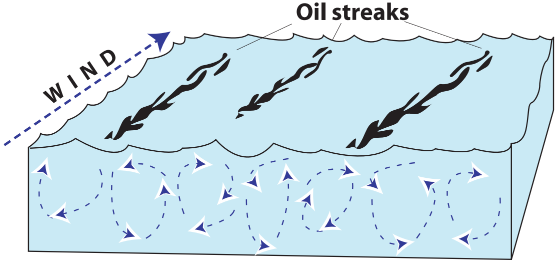
The diffusion of oil occurs mainly in the horizontal direction. Horizontal diffusion of the surface water ranges from 100 to 1,000,000 cm^2/s.

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.



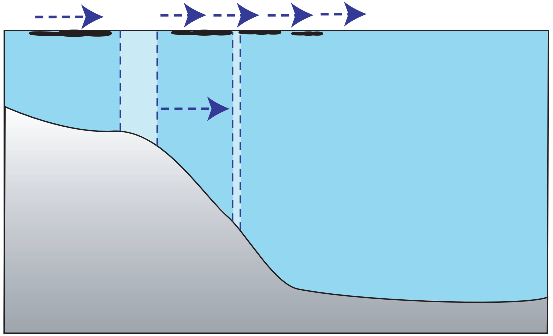
Langmuir cells in the mixed layer depth.

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

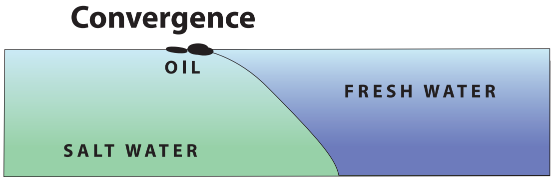
Convergences are natural collection areas for oil, especially tarballs. Because they are close together, the tarballs in a convergence may coalesce and form a cohesive slick.

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 with oil sheen moving into the convergence.

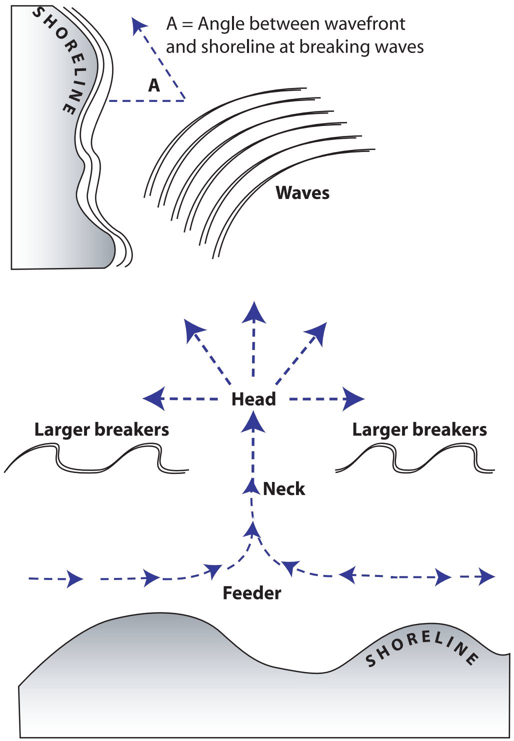


Freshwater-saltwater Interface

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.



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

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.

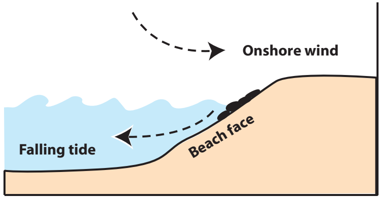
Oil in marsh.

Oil streaks moving parallel to the shoreline.

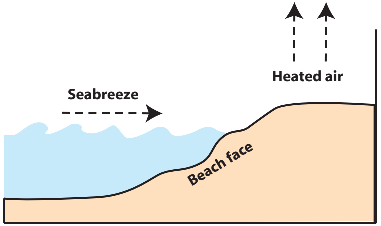
Land/Sea Breeze

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.

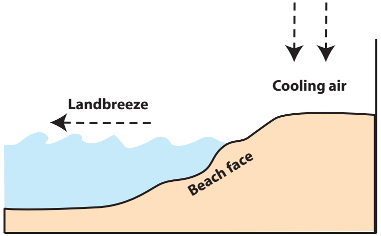
The land and sea breeze cycle occurs in many coastal areas and is caused by heating of the land during the day and cooling at night (see second and third figures). In some areas, the land and sea breeze can extend many miles offshore.



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.