OIL SPILL SCIENCE

SEA GRANT PROGRAMS OF THE GULF OF MEXICO

ADVANCEMENTS IN UNDERSTANDING OCEAN CIRCULATION AND TRACKING THE MOVEMENT OF OIL

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In the aftermath of the Deepwater Horizon oil spill much remained unknown, including the rate that the oil flowed into the environment. This, along with the complexity of surface currents and lack of knowledge of near-bottom water currents and mixing, made it difficult to predict the movement of oil on the surface and underwater. In the past 10 years, researchers have learned more about the complex way oil moves around a marine environment and have used this knowledge to improve oil spill models.

SYNTHESIS SERIES

The purpose of this publication is to exclusively reflect findings from synthesis activities supported by the Gulf of Mexico Research Initiative (GoMRI). GoMRI synthesis documents are the primary references for this publication. The summary may also include peer-reviewed publications and other reports cited in the GoMRI synthesis activities that help to provide foundation for the topic.

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GULF OF MEXICO RESEARCH INITIATIVE

MOTION OF THE OCEAN

The ocean is a complex body of water with many interconnecting parts. Physical oceanography focuses on the physics of water movement occurring within a marine system. This field includes the study of physical conditions, such as **salinity**, **density**, and temperature, and how they are impacted by physical processes that include winds, currents, waves, and tides. These conditions affect the overall circulation of a body of water.

The circulation of the ocean can be broadly divided into two parts, the first one being wind-driven currents that flow mostly horizontal. The other kind of circulation is driven by the salinity and temperature of the water, termed the **thermohaline circulation**, involves deeper vertical overturning, which happens when surface water sinks and bottom water rises due to differences in

Fronts can be created when fresher water meets saltier water. They can be made visible by lines of white sea foam, as shown here, or by areas with high concentrations of floating material, such as *Sargassum* or oil. (CONCORDE)

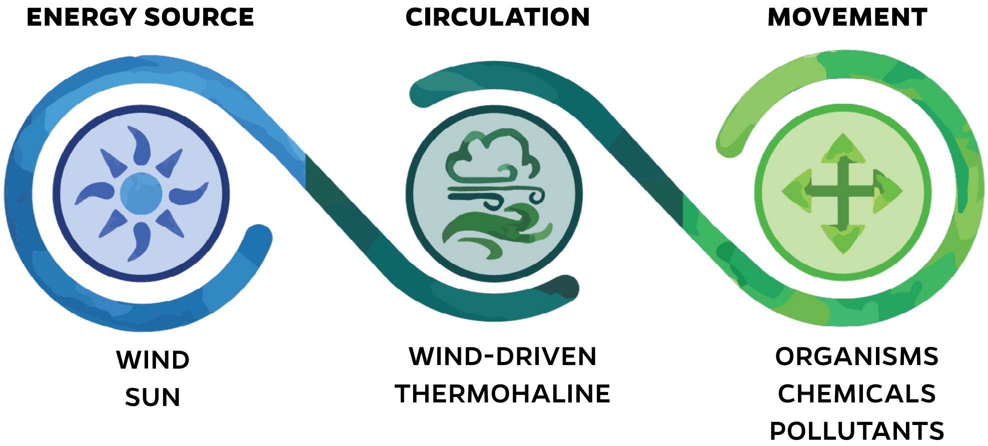

FIGURE 1. Energy sources like sun and wind affect the circulation in the ocean, which then impacts the movement of organisms, chemicals, and pollutants. These physical conditions and processes are all part of studying the physical oceanography of the ocean. (Anna Hinkeldey)

temperature.[1] Together these drive the movement and distribution of nutrients, **plankton**, chemicals, and pollutants (**Figure 1**). Increasing knowledge of how the circulation moves these materials on the water's surface and underwater helps us to understand the biological, geological, and chemical impacts of oil spills. Knowing how oil moves on and below the surface gives insight to the path pollutants may take and helps responders develop plans to minimize their impacts.

OCEAN CIRCULATION MODELS

Modeling circulation is complex. Water circulation is a combination of water movement patterns that operate across a wide range of distances (inches to miles) and time scales (seconds to centuries) (**Table 1**). Understanding these complex patterns requires a large number of measurements, including the speed and direction of currents, the surface and subsurface temperature, and the salinity throughout the **water column**.[a] Scientists conduct experiments, gather data, and use computer models to reproduce these patterns.

Some oil spill models are computer models that can help predict the movement of oil, which makes them an extremely useful tool before, during, and after an oil spill. To learn more about computer models and how scientists use them to track oil, read the Sea Grant publication *Predicting the movement of oil*.

Funding and response activities after the Deepwater Horizon (DWH) oil spill drove rapid advances in the modeling of oil movement. After the spill, scientists needed more information about the near-bottom currents along the **continental slope** of the Gulf of Mexico to enhance observations of the deep-sea plume and its significance during DWH.[b] As models got more complex, they were able to improve and more realistically represent near-field processes (such as movement of oil near the wellhead) in far-field models (models that determine where the oil will end up far from the wellhead). Scientists have come together to share how they modified existing models and developed and compared several new models to track the distribution of oil since the spill. Advances in oil spill science, including better understanding of oil droplet formation and fate, have improved models for forecasting oil spill dispersal. The oil industry, government, and academia have all focused on developing numerical models to simulate the intricacies of deep-water spills like DWH.[b]

TABLE 1. Complex patterns make up ocean circulation.

Type of Circulation	Examples of the Type of Circulation	Length Scale	Time Scale
Micro-scale	Droplets and bubbles	0.05 inches to 3 feet	A few seconds to minutes
Small-scale	Turbulence, coastal mixing, waves, and near surface "mixed" layer	30 to 300 feet	2 to 15 seconds (waves) Minutes to hours (mixing)
Submesoscale	Fronts, convergent/ divergent flow, **ageostrophic** eddies	0.5 to 50 miles	Days to months
Mesoscale	Larger **quasi-geostrophic** eddies	~50 miles	Weeks to months
Large-scale	Circulation driven by large ocean currents (example, Loop Current)	50 to 500 miles	Months to years

FRONTS

Fronts are marked boundaries where two water masses with different salinities, temperatures, and/or densities meet. Where the water masses come towards each other, they converge. Where the water masses move away from one another, they diverge or separate. Depending on how the water masses move, these areas can cause floating material or pollutants to gather in higher concentrations and possibly sink, or they can cause them to disperse or scatter (**Figure 2**).

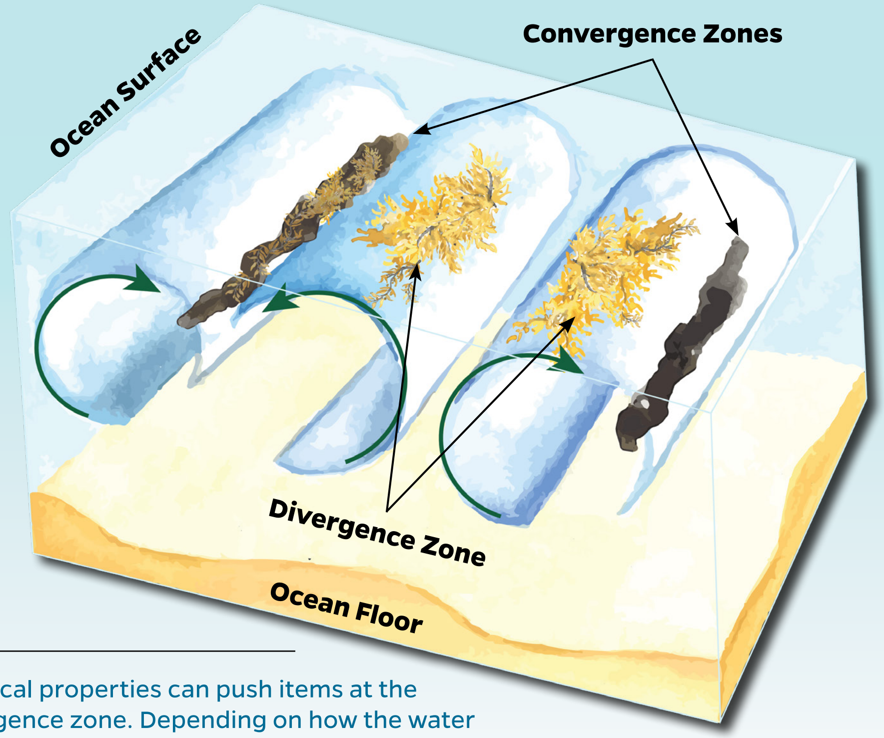

FIGURE 2. Two water masses of different physical properties can push items at the surface such as oil or *Sargassum* into a convergence zone. Depending on how the water masses are moving, fronts can also create divergence zones that push surface items away from each other. (Anna Hinkeldey, adapted from AE Nieblas, CSIRO)

UNDERSTANDING OCEAN SURFACE CIRCULATION

When oil from a subsurface spill reaches the surface, it is impacted by ocean currents, wind, waves, and sunlight. Therefore, understanding these dynamics is essential for estimating where pollutants might have come from and where they will go. Scientists have conducted several experiments and developed new techniques to learn how these processes interact in nature. Data from these experiments is used to evaluate the accuracy of ocean circulation models.[c]

Scientists have gathered robust datasets using a variety of new instruments created to capture currents near the surface.[c] One of these new instruments is a biodegradable drifter.[4] Drifters survey ocean circulation patterns by providing real-time information about how surface currents move. They float on the surface of the water and contain global positioning systems (GPS) to track their position as they move. Scientists deployed and tracked thousands of surface drifters that allowed them to observe the speed and direction of the water's motion over distances of feet to miles. The motion of the water causes drifters to both scatter over a region but also sometimes to converge into clusters. By studying how the drifters scatter or cluster in the water, scientists can identify where **fronts** occur and pollutants can gather.[a] To learn more about drifters and other technology used during oil spills, read the Sea Grant publication *In the air and on the surface: Technology used to investigate oil spills*.

Drifters have other advantages too. They are cheap and can rapidly be deployed directly on top of a spill. They also collect data during the day or night and in adverse weather conditions. As an example, scientists released drifters near the DWH region during the summer and winter months in two different experiments. After release the drifters spread across the entire Gulf of Mexico within three to six months. Scientists learned how the changes of the seasons and winds at the surface affected the movement of water and pollutants. The amount of data available from the drifters allowed scientists to evaluate the accuracy of models and improve model simulations and forecasts.[c]

Scientists studied water motion on multiple scales—from a couple of feet to a quarter of a mile—using different types of instruments, such as **drift cards**, boats, drones, and **aerostats** (**Figure 3**).[a] For the first time, scientists measured small scale currents at different depths to within half an inch of the water's surface.

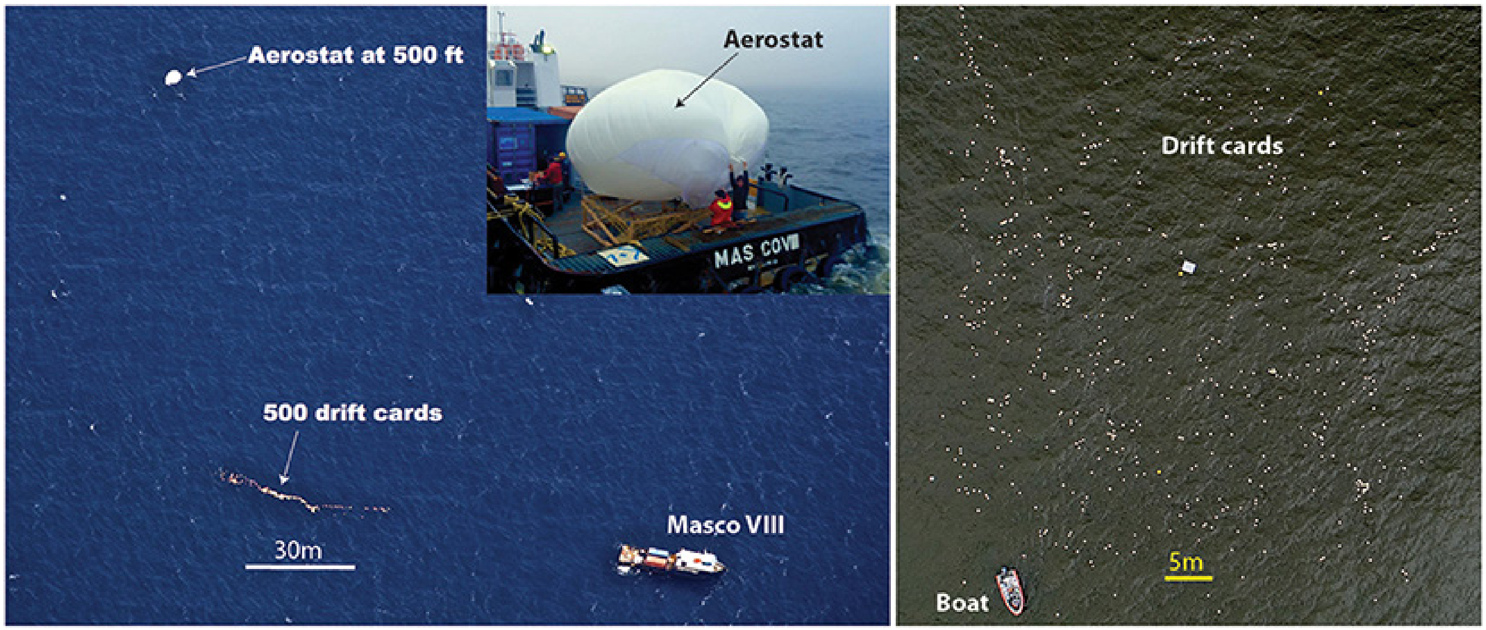

FIGURE 3. Scientists used boats, drift cards, and an aerostat to capture the movement of the surface currents.[4] (Reprinted from Özgökmen et al., 2018)

Water current speeds in the upper half inch of the ocean are an average of four times faster than those of the upper 30 feet of the ocean, implying that winds have a great effect on the current speeds very close to the surface. The difference in speeds between the surface currents and those deeper in the water can quickly separate pieces of **marine debris** that vary in size or **buoyancy**. These new findings can improve the understanding of how marine plastics and oil move on the surface of the ocean.[c]

Submesoscale motions in the ocean can range in size from about half a mile to 50 miles and occur on time frames of days to months. An example of a submesoscale motion would be fronts. Using the data gathered by drifters, scientists found that these particular processes can influence how oil moves in three ways: 1) enhance oil dispersion, 2) divergent fronts can act as natural booms at the surface, and 3) accumulate oil at convergent fronts and move it to below the surface.[c]

By installing radar instruments on ships, scientists measured water speeds that identified such ocean circulation features. The radars monitored the speeds at about every 100 yards, and these measurements agreed with the drifter data collected in the same area. The data from the radars identified the submesoscale fronts as well as how they changed with the seasons, which makes radars an excellent tool to detect circulation features.[a]

Scientists also used fixed-wing airplanes equipped with infrared cameras able to sense differences in temperature to locate surface currents and fronts. These experiments also demonstrated the importance of submesoscale motions and their effect on the distribution of oil.[a]

River fronts occur when fresh water from the river meets the salty water of the ocean. Depending on how strong the river water flows, the fronts can be spread well into the interior of an estuary or ocean. The flow from a strong river like the Mississippi or Atchafalaya creates a front that marks the boundary where the lighter freshwater is stirring into the heavier, saltier Gulf of Mexico. Model simulations of the river outflow show that the water at these fronts converges and sinks, which can impact how floating material is distributed.[a] These river fronts can act as a barrier and keep surface oil floating offshore, away from coastlines.

DEEP SEA OIL AND PLUME

Whether oil is released from a natural oil seep or from a wellhead, once it enters the water it undergoes a series of natural processes as it rises to the water's surface. The main force driving the release of oil is usually the high pressure in the underground oil reservoir.[d] As oil emerges from a source, such as a wellhead, it mixes with seawater and forms a highly buoyant and turbulent jet, rather like that from shaking a soda can and popping the top. This pressure causes the oil and gas to rapidly break up into small bubbles and oil droplets as they leave the wellhead. The way oil is distributed in the water depends on the size of the oil droplets and associated gas bubbles.[b] The size of the oil droplet and the amount of mixing in the water column determines where the droplets will go. Larger, more buoyant droplets rise to the surface and then move with the surface waters. Smaller, less buoyant droplets spend much more time deeper in the water column, moving with the deep-sea currents.[a]

During the DWH oil spill, a large amount of oil reached the surface. However, a significant amount of oil remained confined underwater within deep subsurface plumes or **intrusion layers**.[d,e] The largest subsurface oil plume was found at a depth of between 3,000 and 4,000 feet in late May and early June of 2010.[2] Researchers estimated that these deep-sea plumes trapped nearly 50% of the oil discharged from the wellhead.[3] The plumes are not a river of oil floating underwater but are volumes of water that have elevated amounts of oil-based chemicals, including **polycyclic aromatic hydrocarbons (PAHs)**, compared to surrounding water.[2] As the oil droplets and gas bubbles made their way out of the wellhead, the currents around the wellhead transported them until their density matched the density of the water. After that, they were carried by the deep ocean currents downstream and developed into a horizontal deep-sea plume.[b] A multiphase plume of oil droplets and gas bubbles in the water could have multiple intrusion layers that depend on the speed at which the individual liquid droplets and/or gas bubbles rise. The oil plume observed during the DWH formed in this way.[d]

The intrusion layers near the DWH wellhead travelled horizontally at depths of about 4,000 feet along the continental slope (**Figure 4**).[b,e] Since the discovery of the deep plume in 2010, substantial progress has been made towards understanding and modeling the movement, change, and fate of the oil trapped within it.[b] The way oil and gas move in the water, the formation of oil droplets and bubbles, and the movement of oil in the deep sea are complex processes and not well understood.[d]

To better understand the water movement, chemistry, and fate of oil droplets in the water, scientists studied oil jets and plumes in a number of laboratory experiments.

The deep plume from DWH was different from natural oil seep plumes. Natural oil seeps occur when oil and natural gas flow through cracks in the earth at a slow rate. The plume from DWH had extremely high concentrations of **methane**, because the oil and gas mixture exited the wellhead at an enormous pressure and a very high temperature. When hot oil containing gas under high pressure comes in contact with much colder water, the water becomes **supersaturated** with gas. As the DWH oil and gas moved away from the wellhead, it began to dissolve into the surrounding water and tiny organisms, such as bacteria or fungi, who can use hydrocarbons for food, began to break it down. Oil droplets also tend to rise in the water column. As they do, they may attach to other particles of sediments and biological debris in the water that can cause them to become more dense and sink to the seafloor.[b]

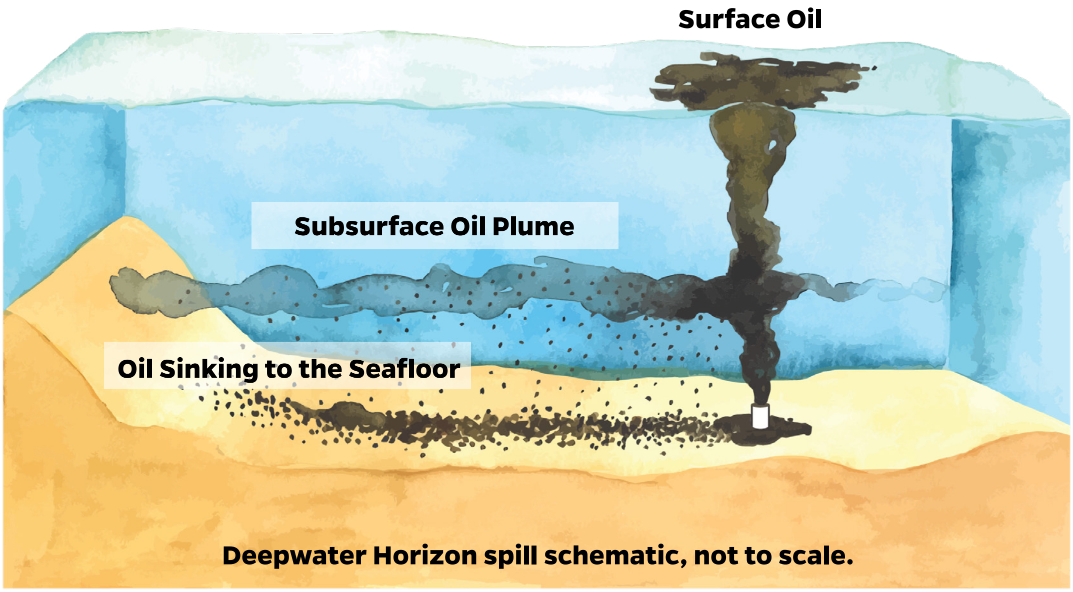

FIGURE 4. As the oil escaped from the wellhead, some of it made its way to the surface while some of it stayed in the deep subsurface plume or made its way to the ocean floor. The subsurface plume and oil on the seafloor were not rivers or mats of pure oil; the graphic is drawn this way to visualize oil drops spreading within the water. (Anna Hinkeldey, adapted from Jack Cook, Woods Hole Oceanographic Institution)

As liquid and gas flow out of a pipe, the flow pattern depends on how fast they are being released. In laboratory experiments scientists found that when the gas content of the oil flow is moderate to high, turbulent churn flow is likely to occur. When this happens, the gas and liquid no longer flow together but tumble separately within the pipe. The size of the orifice, or pipe opening, can also have an impact on the size of oil droplets. These laboratory observations provide data that can be used to improve models and verify their accuracy.[d]

WHAT REMAINS TO BE LEARNED?

The physical drivers of the ocean (winds, waves, currents, and differences of pressure, temperature, salinity, and density of the water) play an important role in the movement of oil on the surface, pollutants, oil droplets, and gas bubbles. Having a better understanding of the effects of these drivers can greatly improve the working knowledge of the behavior of oil once it is released. During the past ten years, great advances have taken place in developing tools, improving collection methods, analyzing and synthesizing data, and connecting coastal models to those of offshore oil movement.[e] However, the enormous range of scales of time and space involved make it difficult to observe and model all the important processes. Other research priorities that would improve the ability to predict the fate of oil and its impacts can be found in **Table 2**.

TABLE 2. Scientists studying the Deepwater Horizon oil spill have suggested these research priorities for future work in oil spill science.[b,d]

Research Topic	Research Priorities
Ocean circulation	• Understand how currents move through time and space very close to the surface of the water and at the bottom. • Understand how water mixes between layers of different densities.
Physical and circulation models	• Develop models to represent key components that connect the estuaries and coasts to the ocean. • Improve representation of the realistic motions of the ocean **bottom boundary layer**. • Use of multiple models at different scales to better represent and connect multiscale processes.
Oil spill models	• Improve estimates on how the distribution of sizes of oil droplets is impacted by different environmental conditions and oil spill response tactics. • Use data and observations to help improve existing models (especially very close to the surface).
Fate of oil and gas at depth	• Improve modeling accuracy of how quickly or slowly oil breaks down, chemically and biologically. • Improve understanding of the role of physical processes on **biodegradation**. • Obtain more measurements that describe the way the plume moves and how oil droplet and gas bubble size affect distribution at various distances from the plume.
Impacts of oil and methane in the deep sea on larger marine animals	• Improve estimates and tracking of large marine animals near drilling sites.

GLOSSARY

Aerostat — A tethered helium-filled balloon used to monitor air quality changes.

Ageostrophic — Not caused or affected by the Coriolis force, a force that results from the Earth's rotation.

Biodegrade (-ation) — The natural breakdown of a substance, especially by bacteria.

Bottom boundary layer — The layer of water flowing along or near the ocean floor.

Buoyancy — The tendency of a less dense object to float or rise when submerged in water.

Continental slope — The slope of the seabed between the continental shelf and the deep ocean floor.

Density — Describes how much space an object or substance takes up in relation to its mass.

Drift cards — Biodegradable floating materials released into the ocean that follow the movement of water right at the surface and show the direction of ocean surface currents in a particular region.

Fronts — Boundaries between distinct water masses with sharp differences in temperature and/or salinity. Fronts can be convergent (both water masses are moving towards each other) or divergent (water masses are moving away from each other).

Intrusion layer — A layer formed when an oil/water mixture reaches a depth where it can no longer rise and begins to move horizontally along with the layers of water.

Marine debris — Human-created waste that has been deliberately or accidentally released into the ocean.

Methane — A colorless, odorless hydrocarbon gas that is the main component of natural gas.

Plankton — Microscopic organisms that drift or float in bodies of water.

Polycyclic aromatic hydrocarbons (PAHs) — A chemical group found in many sources, including but not limited to oil, tar, ash, coal, car exhaust, chargrilled animal fats, and smoke from burning oil or wood.

Quasi-geostrophic — Flows where the pressure difference across the water's surface is almost in balance with the Coriolis force.

Biodegradable drifters, which float on the water to measure surface currents, wait to be deployed. (CARTHE)

Salinity — The average concentration of dissolved salts in a body of water.

Submesoscale — Ocean processes that occur on a spatial scale of 1 to 100 kilometers and time scales of days to months.

Supersaturated — Having too high a concentration of a substance to remain dissolved.

Thermohaline circulation — Circulation that is driven by differences in the salinity and temperature (and hence the density) of the water. Density differences are created by surface heating and freshwater flows.

Water column — A vertical column of water that stretches between the surface of a body of water and the seafloor.

REFERENCES

Publications resulting from the GoMRI-supported synthesis activities serve as the primary references for this work. Additional supporting literature, either cited in GoMRI synthesis papers or necessary for foundational information about the subject, is also included.

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The GoMRI Research Board established Synthesis & Legacy committees to review 10 years of oil spill science findings. Look for Sea Grant extension publications on these GoMRI synthesis topics:

- Observing and modeling oil plumes and circulation
- Combined ecosystem modeling
- Combined oil spill modeling
- How oil weathers and degrades
- Ecological/ecosystem oil spill impacts
- Human health and socioeconomic oil spill impacts
- Microbiology, genetics, and oil spills
- Dispersant-related impacts from oil spill response

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