



OIL SPILL SCIENCE

SEA GRANT PROGRAMS OF THE GULF OF MEXICO

OIL SPILL MODELING: PREPAREDNESS AND RESPONSE

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Oil spill modeling has benefited in the last 10 years from research funded by the Gulf of Mexico Research Initiative and others. Following the Deepwater Horizon blowout, scientists from government, industry, and academia collaborated to share best practices and research results. These scientific developments have helped to improve oil spill modeling, a key part of oil spill response.

OIL SPILL MODELS: WHY THEY MATTER

Oil spill models are tools used to simulate what might happen, what is happening, or what did happen in a given spill situation. They predict the movement of oil and also help scientists understand how oil **weathers** when exposed to the environment. Predictions are based on other computer models that

forecast ocean circulation, winds, waves, the physics of oil movement, and the **biochemistry** of its degradation. These models usually focus on a brief time period—hours to weeks—after an oil spill.

Oil spill models can guide response decision making and planning, analysis of oil industry **infrastructure** impacts on the environment, and assessment of damage after an oil

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.



spill. When used for spill response, models can help identify the potential harm oil can cause as well as the usefulness and impacts of possible response actions. Since the goal of spill response is to limit the impacts of oil, emergency responders need to be aware of the type of oil, the environment the spill occurred in, and the organisms that the oil can harm (**Figure 1**).^a To learn more about oil spill response, read the Sea Grant publication *Oil on the water: Insights into oil spill response*.

Oil spill models can estimate the potential amount and likely locations of oil so that response equipment and assets, such as booms, skimmer vessels, and aircrafts can be deployed effectively. To be useful, oil spill models need to be specific to the location and the environment

NOAA's oceanographer Amy MacFadyen explains how NOAA creates oil trajectory maps to former Department of Commerce Secretary Gary Locke during the Deepwater Horizon oil spill. (NOAA)



that the spill occurred in so that the model can accurately show where the oil is moving.^a

Oil spill models rely heavily on several components, known as inputs. Inputs may consist of observational data or outputs from other models, such as oceanographic circulation and atmospheric models. If the input is not accurate, the oil spill models will also not be accurate. Oceanographic circulation models provide an estimate of ocean currents, water properties, waves, and river flows at a specific time and place. When oil reaches the surface, these models help identify how these factors will influence the movement of oil. Atmospheric/meteorological models provide weather forecasts, including the surface winds that can move and evaporate floating oil. Fate models predict the chemical and physical changes the oil will undergo once it is released into the environment. The oil spill modeling process follows a series of steps that help gather information, evaluate the information, and inform responders (**Figure 2**).^a Operational oil spill modeling faces the challenge of providing 24/7 modeling results that must be available for use by emergency responders, natural resource managers, and other decision makers during active spills.

The Gulf of Mexico Research Initiative (GoMRI) supported a variety of research that improved oil spill modeling, including an assortment of studies that ranged from individual oil droplet scale to full three-dimensional and time-dependent ocean models for response and planning (**Figure 3**). Results from laboratory studies were essential in developing, calibrating, and testing models; developing new and improved models for specific purposes; and further expanding integrated oil spill models. Integrated models rely on data

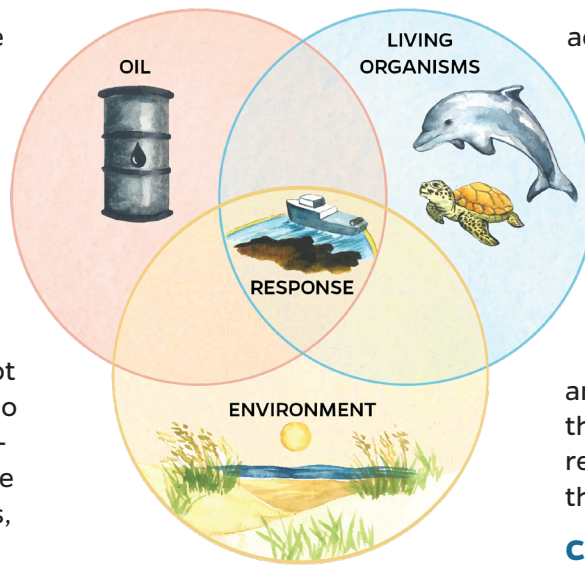


FIGURE 1. Oil spill response requires knowledge about the type of oil spilled, the environment in which it spilled, the organisms that are impacted, and best actions to take to clean up the oil.^a (Adapted from Barker et al., 2020)

from physical, chemical, and biological research to better predict oil spill releases, where the oil will go, how the oil will change, how it affects the environment, and how microbes—tiny organisms that sometimes feed on oil—react to it in a region of interest.¹

PLANNING AND PREPAREDNESS

When oil enters the marine environment, it immediately begins to change and move. The movement and fate of oil depend on the environment where the spill occurs. To plan for a potential oil spill response, responders need to estimate where the oil might travel in a particular region. One of the products of oil spill models is predicting the pathway, or trajectory, of the oil. Running models with different input conditions that may occur in a region produces hundreds of potential trajectories. These trajectories are then analyzed and laid over maps to develop response plans. Using these trajectories, responders can prioritize response

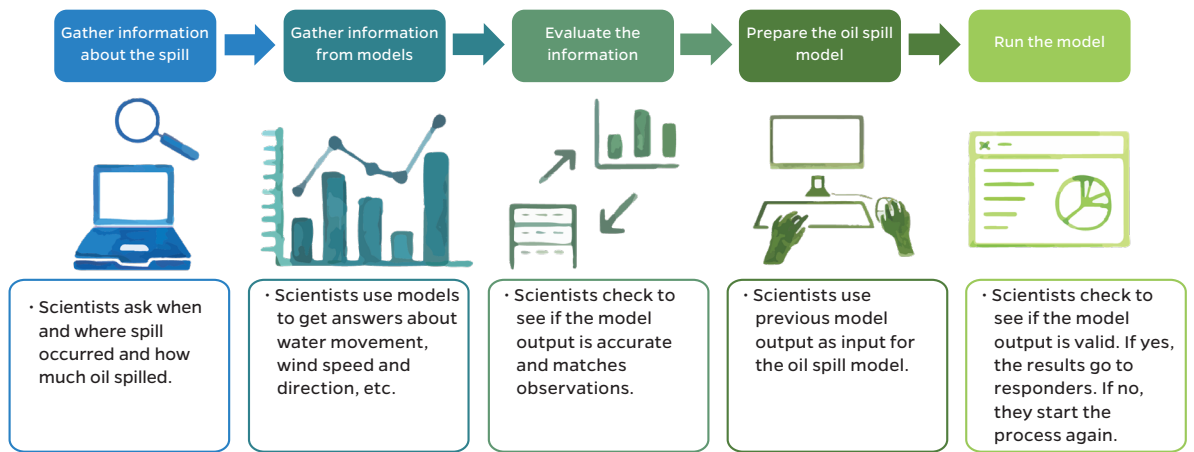
actions for different time periods after a spill and coordinate moving response supplies to the appropriate locations. This process can help evaluate the effectiveness of different response methods as well as their advantages and disadvantages. It also gives responders an idea of how quickly they need to organize and mobilize to minimize damage to the environment and socioeconomic resources in the likely path of the oil that may be at risk.^a

COUPLING OF MODELING SYSTEMS

It is essential for oil spill models to accurately represent the connection between the ocean and atmosphere. However, that requires consideration of many interacting factors. For example, in shallow water near the coastal zone, waves tend to move towards the shore, potentially making them responsible for moving oil onshore. However, not all waves move oil equally. Waves created by distant hurricanes can cause much greater movement of oil than typical local wind-driven waves.

Further, the presence of an oil slick on the surface can actually affect the way that air moves across water, changing the way that the wind drives the waves. This is because oil slicks modify both evaporation at the water's surface and modify the force the wind puts on the water. Oil also acts as a physical barrier on the surface of the water. This barrier keeps water vapor from passing through, so less water will evaporate in areas that have oil on the surface. The decline in evaporation reduces **heat flux**, causing the temperature of the water to increase, which then can also alter the surface winds, waves, and oil movement.² Oil also reduces the friction on the water's surface, which causes the near-surface wind speed to increase but the

FIGURE 2. Operational oil spill modelers use many types of data to help them produce the most accurate predictions possible during an oil spill. A simplified series of steps helps to gather information, evaluate the information, and inform responders. (Anna Hinkeldey)



force applied by the wind on the water’s surface to decrease. Observations have shown that surface winds respond to changes in surface temperatures. Modeling studies have shown that this response can happen very quickly, and the ocean then responds to this change in winds.^a

MODELING CHALLENGES AND IMPROVEMENTS

One challenge operational modelers had during the Deepwater Horizon (DWH) oil spill was working with a number of circulation models for the Gulf of Mexico, which often gave different and sometimes conflicting results.³ The problem is similar to the saying, “A person with one clock knows what time it is; a person with two clocks is never quite sure.” This situation also applies to oceanographic models. Since the spill,

scientists have worked on standardizing the modeling procedures and data formats used in these models to reduce such differences. However, other challenges remain.^a

To inform critical decisions, operational models need to balance accuracy and reliability against the amount of time and computer memory it takes for a model to calculate results, as well as ease of use by responders, especially during the early stages of a response. Model results can be compared with data collected in the first few days of a response to reduce uncertainties. However, this step can lead to response decisions based on incomplete early information, if not much data have been gathered. An ideal model therefore allows for frequent updates as new data become available.^a

Dispersants are chemical mixtures sometimes used by emergency responders that can help break large surface oil slicks into small oil droplets. Before the DWH oil spill, responders had never used dispersants at great depths below the surface. Whether or not to use subsea dispersant injection (SSDI) is now an important emergency response decision during a deep-water oil release. Studies on the simulations of oil fate with and without dispersants was extended after the DWH oil spill. Such simulations help responders weigh the environmental, health, and safety tradeoffs involved. To evaluate tradeoffs of SSDI use, simulations must incorporate predictions of oil droplet size and the amount of oil trapped and broken down at depth, which affect the subsequent surfacing of oil and its evaporation into the atmosphere. Numerical simulations of a hypothetical deep-water blow-out suggest that the effectiveness of SSDI is greatest when the method is implemented as soon as possible.¹

The size and distribution of oil droplets (referred to as Droplet Size Distribution, or DSD) created by turbulence near a wellhead plays an important role in the trajectory

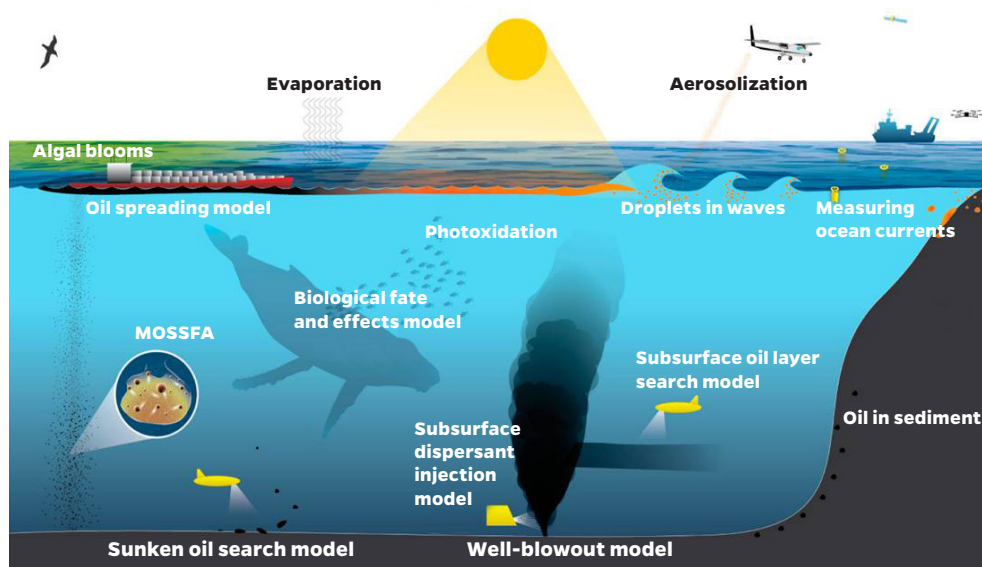


FIGURE 3. Oil spill modeling has benefited from studies funded by the Gulf of Mexico Research Initiative that addressed a wide range of topics related to oil and dispersants present in an ocean environment, as depicted in the above image.^a (Adapted from Barker et al., 2020)

and fate of oil. Large droplets rise rapidly to the surface, whereas small droplets rise very slowly and remain below the surface for a longer period of time, allowing ocean currents to move them horizontally. The use of dispersants can affect how the oil moves because it changes the size of oil droplets. Therefore, models must accurately estimate DSD in scenarios with and without dispersant use to inform decision makers as they select a response method. Before DWH, most research to estimate DSDs was based on surface water conditions, which were unsuitable to be used as input for deep-water plume models.^a The ability to make better field observations of oil droplets, bubbles, and **particulates** came from the use of a silhouette camera system. This system uses backlighting to create silhouettes of particles suspended between the light and the camera. Such observations provide valuable data for model input, particularly when the system automatically detects particles in the water.⁴

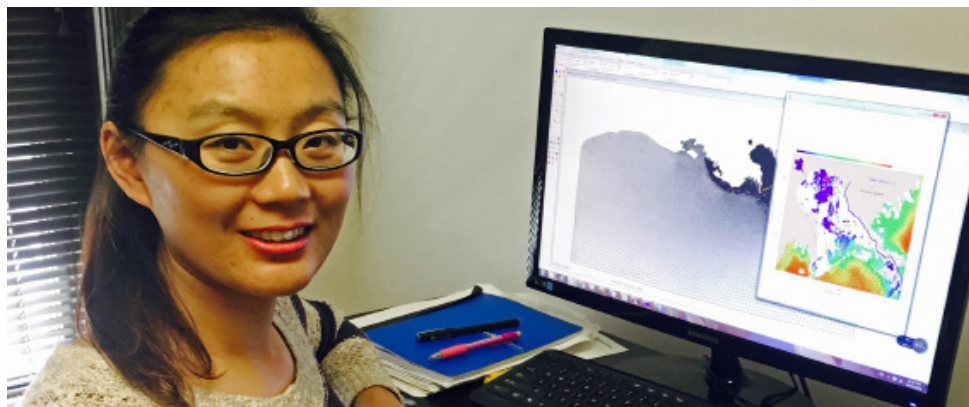
Laboratory experiments also helped to determine DSD in simulations of subsurface oil plumes. These experiments, conducted under a variety of conditions, provided data that researchers and response modelers use to adjust their models for real conditions during an oil spill.⁶

REPRESENTING IMPORTANT PROCESSES THAT IMPACT OIL'S FATE

Once oil is released into the environment, it undergoes a number of changes. Understanding these changes is important when models predict what is happening to the oil and where it will end up.

Underwater processes

Dissolution occurs when water soluble compounds in oil dissolve into the surrounding water. These compounds can be used for food and



Linlin Cui creates a movie using particle tracking to determine if freshwater diversions impacted the salinity of Barataria Bay. (GoMRI/Provided by Linlin Cui)

energy by organisms but can also be toxic to some of them. Dissolution is particularly critical in a **deep-sea plume**, but it also plays a role in the transformation of oil at depth and the surface. Dissolution of lighter oil components, often omitted in earlier response models, is beginning to be included in response models because it may be able to offer better answers to questions about potential effects of response actions.^a

Biodegradation is another process that impacts the fate of oil. One of the most important understandings that came from GoMRI-funded research was that under certain conditions, biodegradation occurs quickly enough to compete with other weathering processes known to be important within the first weeks after a spill. Prior to DWH, it was thought that biodegradation was a slow process that did not have a significant impact until after oil had been in the environment for at least a week, so it was often left out of response models. DWH provided an opportunity to study biodegradation on a large scale. Now biodegradation models based on droplet size are beginning to make their way into operational models.^{5,6}

Sedimentation occurs when particles (or sediment) suspended in a liquid settle and get deposited on the bottom. The interaction of sediments,

oil, and biological material (marine snow) can cause oil to sink and impact the seafloor marine ecosystems. In the months following the DWH oil spill, scientists discovered that a **Marine Oil Snow Sedimentation and Flocculent Accumulation (MOSSFA)** process had occurred and continued several months after the wellhead had been capped.

This MOSSFA event carried a large amount of oil (about 7% of the total amount spilled) to the seafloor.⁸⁻¹⁰ Though much has been learned from the study of MOSSFA, future improvements to models might include how oil, sediments, and marine snow in the water interact and change over time. Such a model could then be combined with models that simulate water movement, allowing scientists to reproduce how both oil and marine oil snow move through the environment.^a

To prevent potential damages, the response community should be aware of the possibility of a MOSSFA event forming. However, prior to DWH, oil spill models did not include this type of event because MOSSFA processes had not been widely observed or studied. To learn more about marine snow, read the Sea Grant publication *Microbes and oil: What's the connection?*

Improvements are also needed for the representation of **bottom boundary layers**, which are critical in pre-

dicting the movement of marine oil snow and buoyant oil leaking from deep spills and damaged underwater structures.^a

Surface processes

With the continuous improvement of environmental forecasting systems, the accuracy of oil spill model trajectories has improved. However, forecasting winds and currents at a fine scale required remains challenging, particularly in coastal areas where the **topography** of the seafloor and the shoreline may not be well represented or may change due to human modification or large storm events.^a

To plan an oil spill response, decision makers need to know the volume of oil released and its properties. Weathering processes can change both of these factors. The key processes in weathering are evaporation, dissolution, biodegradation, **emulsification**, spreading, and **photooxidation**. Some of these processes are well understood and are already included in operational models. However, the interactions between evaporation, dispersion, dissolution, and spreading at the surface are not as well understood. Current operational models do not necessarily capture how much of the oil evaporates, rather than dispersing or dissolving.^a

Entrainment occurs when oil is broken up into tiny droplets that can stay suspended under the water's surface. Multiple improvements were needed in existing modeling methods to better capture how oil is entrained and transported through the water. Scientists made these improvements possible by expanding the range of oil types they modeled and including the effects of dispersant application. Based on this work, scientists have now developed updated surface entrainment models to include in operational models.^a

Emulsification is the process of small droplets of water mixing with the oil causing the volume of the mixture to increase, much like whipping cream. In addition to the increased volume, an oil emulsion has very different physical properties than the original oil, causing it to move differently and requiring different response equipment. Though this information is important for responders, currently no operational models can predict emulsification well based on oil chemistry and environmental conditions alone.¹⁰

Photooxidation has long been considered to be a longer-term effect in the fate of spilled oil, so it has not usually been included in response models.¹⁰ However, research since DWH has indicated that this process may also happen rapidly (hours and days), can affect a substantial portion of the oil at the surface, and is important in the formation of emulsions. Scientists have established photooxidation as an important factor in oil's fate that must be considered early in a spill, especially under conditions with high ultraviolet light exposure.¹¹

MODEL LIMITATIONS AND UNCERTAINTY

In order for responders to rapidly and correctly respond to an oil spill, they must have access to accurate models, but they must also understand the limitations of those models. A trajectory model that is not adjusted and regularly updated with field observations will not be accurate after the initial days of a spill. The DWH deep-sea blowout created additional challenges because observations in deep waters are sparse, resulting in fewer inputs to models and making it more difficult to determine the degree of uncertainty.^a

It has historically been difficult to locate and track oil that is moving beneath the water's surface, either

as individual droplets that can float or rise or as heavy oil (determined by its density) that eventually sinks to the bottom. Scientists improved the Subsurface Oil Simulator (SOSIM) model for finding submerged oil. Water forms different layers in the ocean based on its **density**, which depends upon its salinity and temperature. The SOSIM model follows oil droplets along layers of water density, rather than at a single depth. For oil that has sunk, the model includes options for tracking oil along the deep contours of the continental shelf. Combining these methods will improve oil spill trajectory modeling as production and transportation of heavy oil products, which can sink when spilled, increase.^a

Model limitations become sources of error and uncertainty in forecasts. Limitations that affect model performance include model resolution, accuracy of the input to the models, and the ability to correctly represent physical processes such as winds, waves, and currents. Improving these limitations and uncertainties will advance model prediction capabilities. Understanding both the predictions made by numerical models and their potential errors are very important in operational modeling.^a

Uncertainties exist in ocean circulation models and oil spill models,



NOAA biologist Gary Shigenaka goes out on a helicopter to assess a spill. (NOAA)

meaning some things may not be known accurately or in great detail. In ocean circulation modeling and forecasting, the main source of uncertainty will vary depending on location and particular processes. For example, in coastal areas the primary source of uncertainty comes from the complex topography, water depth, and river outflow rates. In deep water, uncertainty is often due to the variations in the depths of different density layers, like the **thermocline**.^a

Oil spill models have similar uncertainties. The greatest sources of uncertainty in operational oil spill modeling are the drivers, such as the source and quantity of oil, DSDs, and forecasts of winds, waves, and currents. If not corrected, these uncertainties are passed along to the oil spill models. Because of these and other sources of uncertainty, operational oil spill forecasting is only conducted for short amounts of time, typically from 12 hours to two days. Using multiple models allows for output comparison that can improve the quality of the predictions to the weekly time scales.¹² Uncertainty is limited by combining observations of the oil and

meteorological and ocean conditions for each new modeling cycle.^a

Reducing uncertainty

To help reduce model uncertainty in the future, additional steps need to be taken: Research and development are needed to improve the accuracy of the chemistry, physics, and ocean dynamics being represented by the models. Creating multiple models and combining them to produce improved results should become more common for ocean circulation modeling to reduce uncertainty and to improve operational ocean and oil spill modeling. Uncertainties of the ocean, meteorological, and wave modeling should be determined, and well visualized, to be better communicated to those using the models. User-centered design would help non-modeling experts, including responders and the general public, to better understand both the basic information about oil spill trajectories and their corresponding uncertainty levels.^a

FUTURE OUTLOOK

Going forward, exploring new model advancements and methods will help to improve oil spill response modeling.

Since the majority of oil exploration sites are located across the **continental shelf** and coastal environments, a modeling approach that integrates these areas is important for improving ocean model simulations and forecasts. High-resolution modeling is needed to advance understanding of the processes related to estuaries and deltas, river plumes, nearshore waves, and coastal upwelling.^a

To improve the outcome of oil spill response, the forecasting tools need to stay current with research, which needs to continue to address key questions. After years of work to improve environmental data used to inform models, gathering sufficient data in a timely manner remains a serious challenge. Models are run by a number of institutions with no central server. It would be beneficial to set up an operational server for models that would either copy the data from different specialized models or install and run forecasting systems developed by academia or the public sector.^a

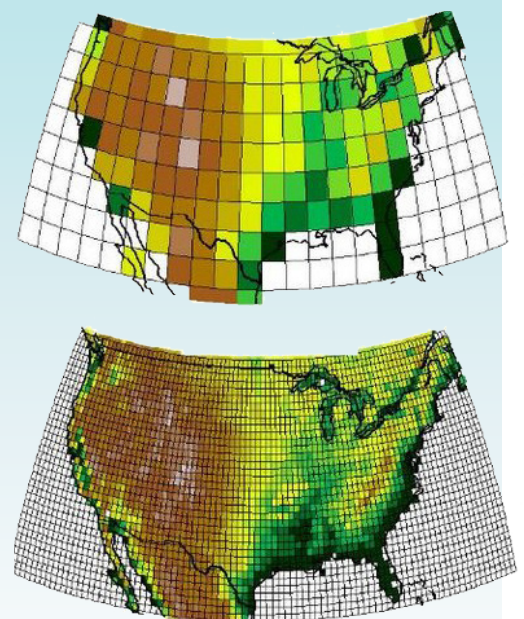
Integrated models are key to preparedness and planning for oil spills. They provide an overview of the development of oil spills and their likely

MODEL RESOLUTION

Model resolution refers to the number of grid cells used to cover a certain area. Grid cells are similar to pixels in a picture. The fewer the pixels in a picture, the lower the resolution. This causes the picture to look a bit blurry since not as much detail is provided. The opposite is also true. When there are more pixels the resolution and detail increase, making the picture clear and crisp with sharp lines.

The same goes for model grids; lower resolution means fewer grid cells and fewer details about the modeled area. The more grid cells used, the higher the resolution, allowing modelers to get a more complete picture of the area. However, higher resolution also means using more computational power, time, and space. Not all models have the same resolution, which can cause a mismatch when trying to use the output from one model as input for another, such as an oil spill trajectory model.

Lower to higher grid cell resolution represent the same map of the U.S., with higher resolution giving more detail.¹³ (Reprinted from Gettelman and Rood, 2016)



consequences, and include resource information to assist responders in selecting response options. They also provide a view into the future evolution of oil spills, so that responders can decide which techniques will be most effective.^a

The scientific results over the past 10 years and the variety of new models developed should improve preparedness and understanding of potential oil spill impacts. This legacy of model development and improvement should help future researchers and

responders continue improving oil spill modeling to inform response decisions. As the science builds upon the work of GoMRI, oil spill modeling groups will be able to leverage advancements to better support oil spill response all over the world.

GLOSSARY

Biochemistry — The study of the chemicals that occur in plants, animals, and microorganisms and the changes they undergo.

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.

Continental shelf — A shallow undersea plain of varying width forming a border to a continent and typically ending in a comparatively steep slope to the deep ocean floor.

Deep-sea plume — A volume of water that has elevated amounts of oil-based chemicals, such as polycyclic aromatic hydrocarbons (PAHs), when compared to surrounding water.

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

Emulsify (-ied, -ication) — Occurs when water and oil combine, with one being suspended in the other. For crude oils, it refers to the process where sea water droplets become suspended in the oil by mixing due to turbulence.

Heat flux — A flow of energy per unit of area per unit of time.

Infrastructure — The basic physical and organizational structures and facilities needed for operation, such as buildings, roads, and power supplies.

Marine Oil Snow Sedimentation and Flocculent Accumulation (MOSSFA) — An event during oil spills where

biological material falling from the surface waters combine with oil droplets in the water, sink, and settle on the seafloor.

Particulates — Small suspended materials in the water that can include living organisms and organic or non-organic particles.

Photooxidation — Sunlight causing a chemical transformation of oil into new, oxygen-containing compounds.

Sediment — Naturally occurring material that is broken down by weathering and/or erosion and transported by wind, water, or ice. It can consist of rocks, boulder, sand, and /or the remains of plants and animals.

Thermocline — A steep temperature change in a body of water, such as a lake or ocean, marked by a layer above and below, each with different water temperatures.

Topography — The representation of the natural and artificial physical features of an area.

Weather (-ing, -s, -ed) — A collection of physical, chemical, and microbial processes that alter and break down oil. It includes processes such as oil spreading, evaporation, dispersing, biodegradation, and photo-oxidation. These processes are influenced by many factors (for example, type of oil being weathered, temperature, bacteria present).

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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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ABOUT THE GOMRI/SEA GRANT SYNTHESIS SERIES

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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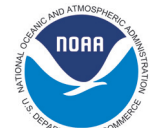
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