OIL SPILL SCIENCE

SEA GRANT PROGRAMS OF THE GULF OF MEXICO

DEEPWATER HORIZON: WHERE DID THE OIL GO?

— UPDATED 2021 —

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During the Deepwater Horizon oil spill, approximately 200 million gallons of oil flowed from the Macondo well. Of this, responders recovered 17% directly from the wellhead, resulting in 172 million gallons of oil entering the Gulf of Mexico. Due to the size and scope of the spill, people wanted to know where the oil traveled in the environment. Some oil accumulated at the shoreline, on the ocean's surface, and in an underwater plume. A portion of the oil also found its way to the seafloor.

Oil floats on the surface during the Deep Horizon oil spill. (NOAA)

After the Deepwater Horizon (DWH) oil spill, Gulf residents wanted to know the oil's probable path and its potential impacts on the marine environment. Understanding where oil is likely to go in the environment during or immediately following a spill allows emergency responders to take the necessary actions to combat the spill.[1] Due to DWH's massive size and the fact that the oil released at great depth, it was more challenging to track the oil compared to past spills.[2]

In 2010, a group of scientists came together and developed an oil budget calculator to estimate what happened to the oil and to provide a status update to **Incident Command**.[3] Since that time, scientists have continued to expand their understanding of where the oil went (**Figure 1**). None of the mechanisms—natural or human-made—listed below completely remove oil from the environment but move it somewhere (evaporation), transform it

THE SEA GRANT and GOMRI PARTNERSHIP

The mission of Sea Grant is to enhance the practical use and conservation of coastal, marine, and Great Lakes resources in order to create a sustainable economy and environment. There are 34 university-based Sea Grant programs throughout the coastal U.S. These programs are primarily supported by the National Oceanic and Atmospheric Administration and the states in which the programs are located.

In the immediate aftermath of the Deepwater Horizon spill, BP committed $500 million over a 10-year period to create the Gulf of Mexico Research Initiative, or GoMRI. It is an independent research program that studies the effect of hydrocarbon releases on the environment and public health, as well as develops improved spill mitigation, oil detection, characterization, and remediation technologies. GoMRI is led by an independent and academic 20-member research board.

The Sea Grant oil spill science outreach team identifies the best available science from projects funded by GoMRI and others, and only shares peer-reviewed research results.

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(biodegradation), or both (burning). Researchers used the following categories researchers used to describe the fate of the spilled oil:

- **Recovered at the wellhead** – Oil captured directly from the wellhead using special equipment.[3]
- **Skimmed** – Thin layers of oil removed from the surface using skimmers.[3]
- **Burned** – Freshly spilled oil set on fire on the water's surface.[3]
- **Chemically dispersed** – Chemicals applied to break the oil into small droplets that will remain below the surface of the water in smaller concentrations.[3,4]
- Evaporated – **Volatile organic compounds (VOCs)** in the oil evaporated into the atmosphere when it reached the surface.[3]
- **Dissolved** – Oil compounds dissolved in the water as they made their way to the surface.[3]
- **Physically dispersed** – Natural mixing, such as via waves, formed oil droplets that mixed into the water.[3]
- **Photooxidized** – Certain compounds in oil broke down by directly or indirectly reacting with sunlight causing the behavior of the oil to change, such as to **emulsify**.[5]

BIODEGRADATION

Oil seeps occur naturally in the marine environment, so microorganisms in the ocean have evolved to be able to consume, or eat, oil. In the Gulf of Mexico, a region with many natural oil seeps, hundreds of species of microbes such as bacteria, archaea, and fungi break down oil through a process known as biodegradation. Biodegradation can reduce the overall environmental impact.[12,13] During DWH, scientists found species of oil-eating microbes in a variety of environments in the Gulf—in the water, on the seafloor, and along the coast in wetlands and on beaches.[2]

- **Biodegraded** – Multiple species of oil-consuming microbes that live in water, seafloor, and shoreline environments broke down compounds found in oil to varying degrees.[2,6]
- **Carried by deep-sea currents** – Gas and oil droplets formed a deep intrusion layer within the water approximately 3,600 feet below the surface, covering an area over 4,400 square miles.[2,7] Though low concentrations of oil and gas were detected in it, they were higher than would typically be found in the marine environment.
- **Sank to the seafloor** – Oil mixed with particles naturally present in the surrounding water. The mixture then sank and accumulated on the seafloor.[2,8] Oil and oil-derived carbon from the well polluted approximately 42,000 square miles of the seafloor around the well.[2] Recent research has shown that the deep-sea area impacted may have been up to 60 miles to the southeast of the wellhead.[9]
- **Reached the coastline** – Oil moved with the ocean currents and waves along the continental shelf off Texas and to the shores of Louisiana, Mississippi, Alabama, and Florida.[10,11]

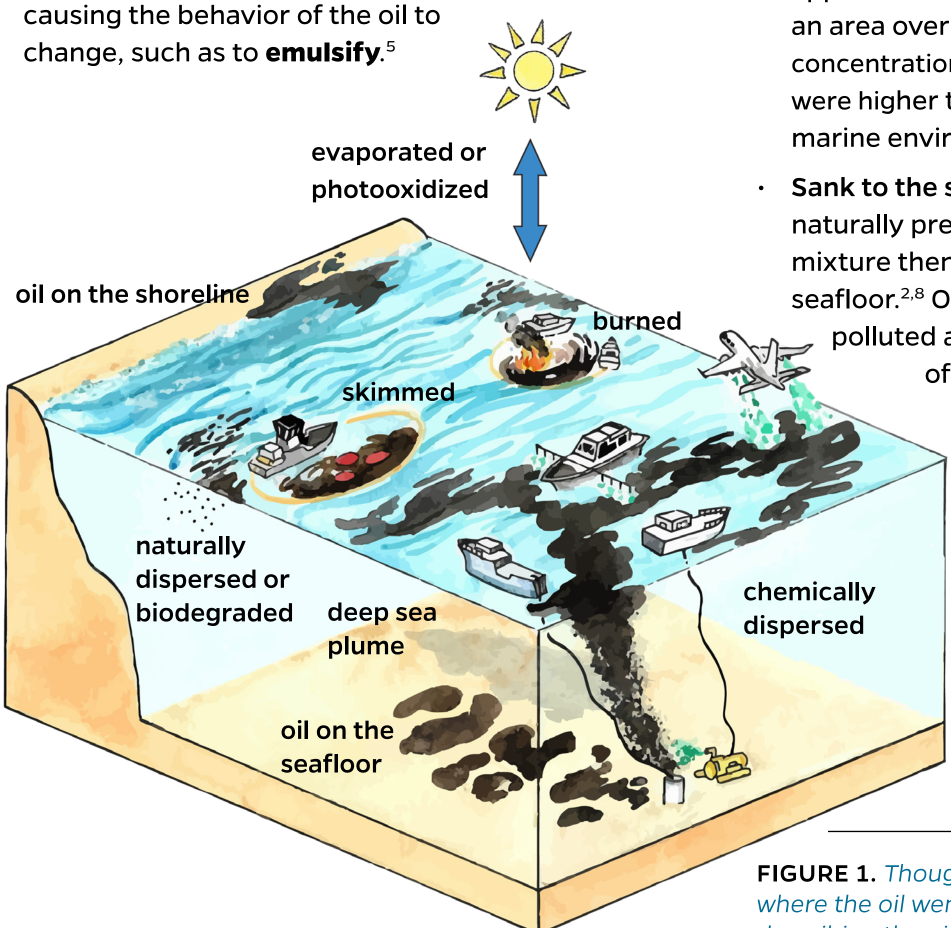

FIGURE 1. *Though it is difficult to fully understand exactly where the oil went, scientists have identified several categories describing the oil's fate. (Florida Sea Grant/Anna Hinkeldey)*

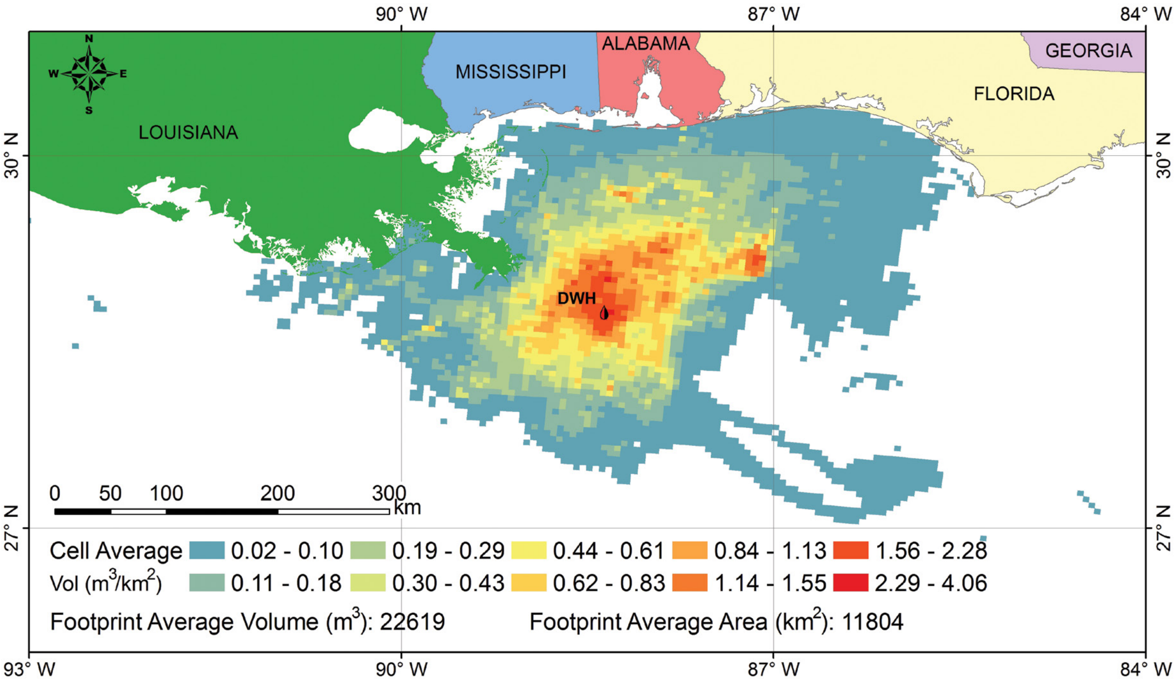

FIGURE 2. *During the Deepwater Horizon oil spill, the extent and amount of oiling on the sea surface varied across the Gulf of Mexico. Colors indicate the average volume of oil in each cell area, with the highest concentrations (red) occurring near the wellhead.[9] (Reprinted from MacDonald et al., 2010)*

OIL AT THE WATER'S SURFACE

Because oil is less dense than water, most newly-spilled oil floats on the water's surface. Currents, tides, river discharge, waves, and wind can move this surface oil, affecting where it winds up in the environment.[14,15]

Scientists also used satellite imagery to calculate the area affected by the oil flowing from the uncapped well. Results indicated surface oil reached a cumulative area of 57,000 square miles (**Figure 2**).[16] Scientists found that winds and high freshwater outflow from the Mississippi River kept a portion of surface oil offshore.[17] Though a small amount of oil made its way to a large **eddy** on the northern part of the **Loop Current**, the eddy remained stationary for several months, allowing the oil to disperse before reaching South Florida.[18,19]

EVAPORATION

Oil **weathers** over time as it interacts with the surrounding environment. The amount of weathering, the type of oil spilled, and the conditions during and after a spill influence where oil will move. Evaporation occurs when VOCs enter the atmosphere. It usually occurs on timescales of seconds to days and is an important part of the weathering process for most oil spills.[20-22] Typically, crude oils can lose up to 45% of their initial volume due to evaporation in the first few days following a spill.[22] A fraction of the DWH surface oil evaporated.[20,21]

OIL ON THE SHORELINE

During the DWH oil spill, wind and ocean currents moved a portion of the floating oil towards the shore. The coasts of all five Gulf states experienced shoreline oiling to different degrees (**Figure 3**). The oil impacted approximately 1,313 miles (37%) of the Gulf of Mexico coastline.[10]

While the shorelines of all five Gulf states received some oil (**Table 1**), Louisiana received 64% of the oil that made it to shore. The two shoreline habitats with the greatest impacts were coastal wetlands (52%) and beaches (46%). The remaining 2% included all other shoreline types.[10] Once the oil reached the shore it began to weather by multiple processes, including biodegradation, the rates of which varied depending on the environment. However, it was visible for weeks to months in some areas.[23]

TABLE 1. *Number of miles of shoreline oiled by state.[14]*

State	Miles of oiled shoreline	Percent of total oiled shoreline
Texas	35	3%
Louisiana	847	64%
Mississippi	158	12%
Alabama	95	7%
Florida	178	14%
Total	**1,313**	**100%**

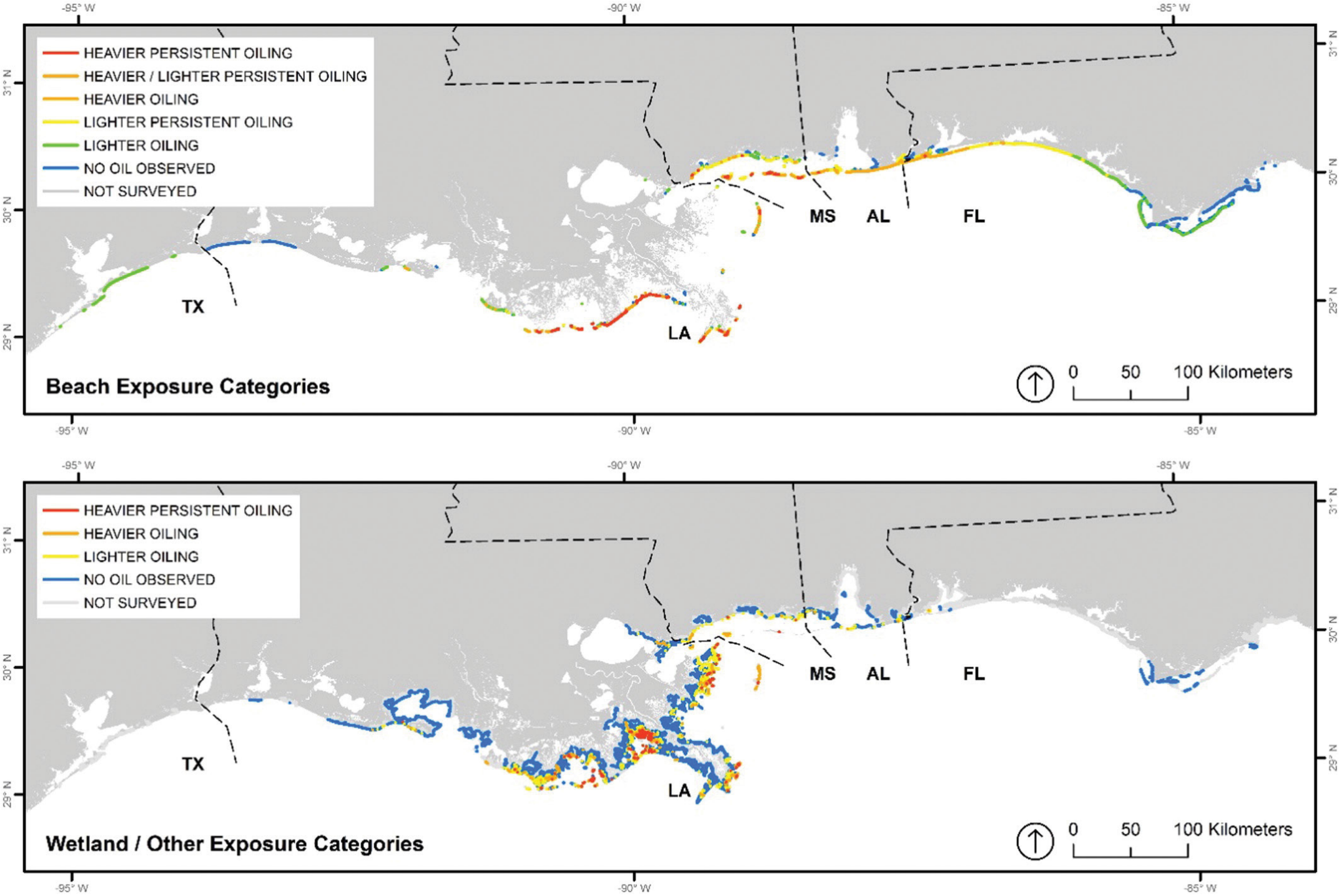

FIGURE 3. *Varying amounts of oil reached the shorelines and impacted beaches (top) and coastal wetlands (bottom). (Reprinted from Nixon et al., 2016)*

OIL BELOW THE SURFACE WATER

Approximately one month after the spill began, scientists found evidence of an oil plume under the water's surface, called a subsurface plume or deep intrusion layer.[24] More than 22 miles in length, the subsurface plume was not a river of oil floating under water but water containing low concentrations of oil.[25] They discovered the plume using **colored dissolved organic matter (CDOM) fluorometers.** Certain chemical compounds in oil are detectable by **fluorescence** techniques. Scientists found elevated levels of CDOM at water depths greater than 3,280 feet and as far as eight miles from the wellhead. They then took water samples from areas with elevated levels of CDOM and also found relatively higher levels of **polycyclic aromatic hydrocarbons (PAHs)** compared to the surrounding area.[24,26] The PAH concentrations confirmed that the elevated levels of organic matter (CDOM) were related to DWH oil contamination.[24]

Using similar techniques other scientists analyzed over 5,000 water samples to track the subsurface plume. In addition to looking for oil droplets, they searched for other evidence of contamination at the plume depth, including elevated concentrations of PAHs and dissolved gas, fluorescence, and lowered dissolved oxygen levels. Water samples containing oil droplets were found as far as 96 miles from the wellhead. However, samples collected as far as 256 miles from the wellhead showed elevated fluorescence and low dissolved oxygen signals, suggesting the presence of oil (**Figure 4**).[27]

Scientists confirmed the presence of the subsurface plume between depths of 3,380 and 4,265 feet in late May and early June of 2010.[25] Some estimates suggest that as much as 50% of the spilled oil was within the subsurface plume.[26,28-30] Scientists estimate that biodegradation removed up to 60% of oil from the plume.[2]

OIL ON THE SEAFLOOR

Although oil normally floats on the surface, it can take many different pathways to make its way to the bottom

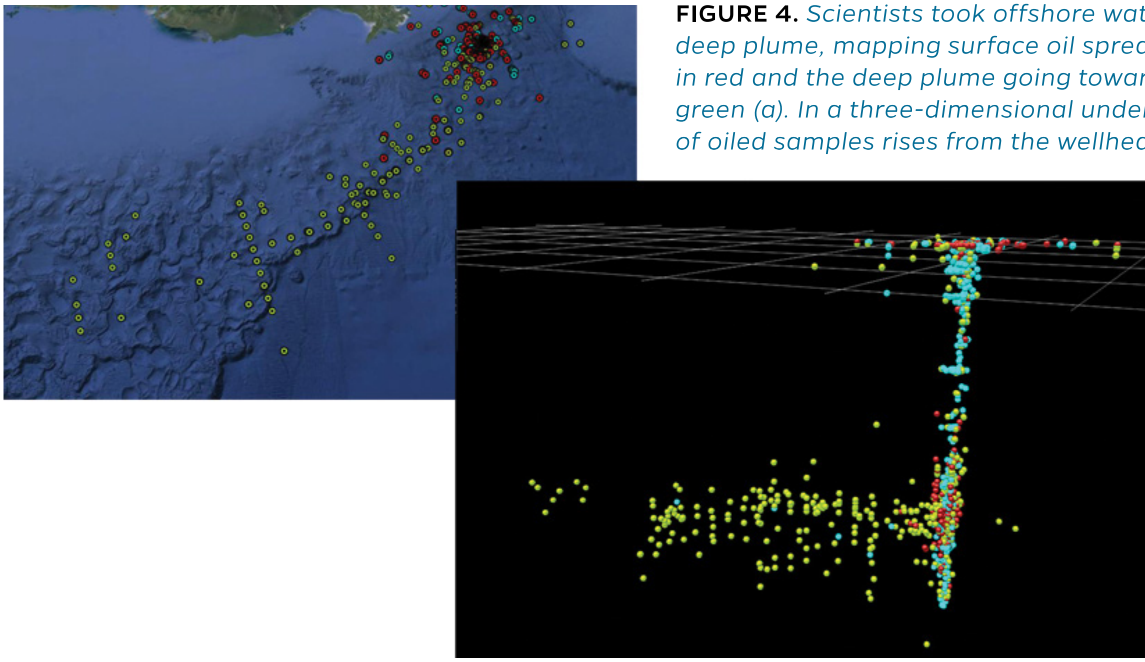

FIGURE 4. *Scientists took offshore water samples to track the deep plume, mapping surface oil spreading out from the wellhead in red and the deep plume going towards the southwest in yellow/green (a). In a three-dimensional underwater model (b), a column of oiled samples rises from the wellhead to the surface while the deep plume extended 256 miles southwest from the wellhead. Colors relate to the phases of each sample's oil—samples with Deepwater Horizon oil droplets (red); dissolved oil without oil droplets (blue); or containing poorly defined oil fingerprints but with other evidence of oil such as dissolved oxygen or fluorescence (yellow/green).[16] (Adapted from Payne and Driskell, 2015)*

(**Figure 5**). **Sedimentation** occurs when the oil attaches to other, heavier particles in the water and sinks to the seafloor.[31] Rivers flowing into the Gulf, such as the Mississippi River, can introduce sediment and small particles that the oil can attach to.[32,33] Sedimentation is also affected by currents and the shape of the seafloor.[9]

Certain biological processes may also form sticky particles, called marine snow, that can capture the oil droplets and cause them to sink. Marine snow may contain tiny algae, microbes, web-like threads of mucous, pieces of small decaying animals, feces, and other bodily waste that can carry contaminants from the surface to the bottom.[34] During the DWH spill, oil along with residue from on-site burning became part of marine snow. This process has been termed Marine Oil Snow Sedimentation and Flocculent Accumulation (MOSSFA).[35,36] These processes transported approximately 20% of the oil floating on the water's surface onto the seafloor.[2] Recent modeling studies suggest that the sinking rates of marine snow particles played an important role on how far they traveled from their point of origin. Particles with fast sinking rates reached the seafloor within 5 to 15 days and settled within 0 to 20 miles from their origin, those with slow sinking rates settled within 68 miles from their origin, and those floating in the water possibly traveled over 205 miles from their origin.[37]

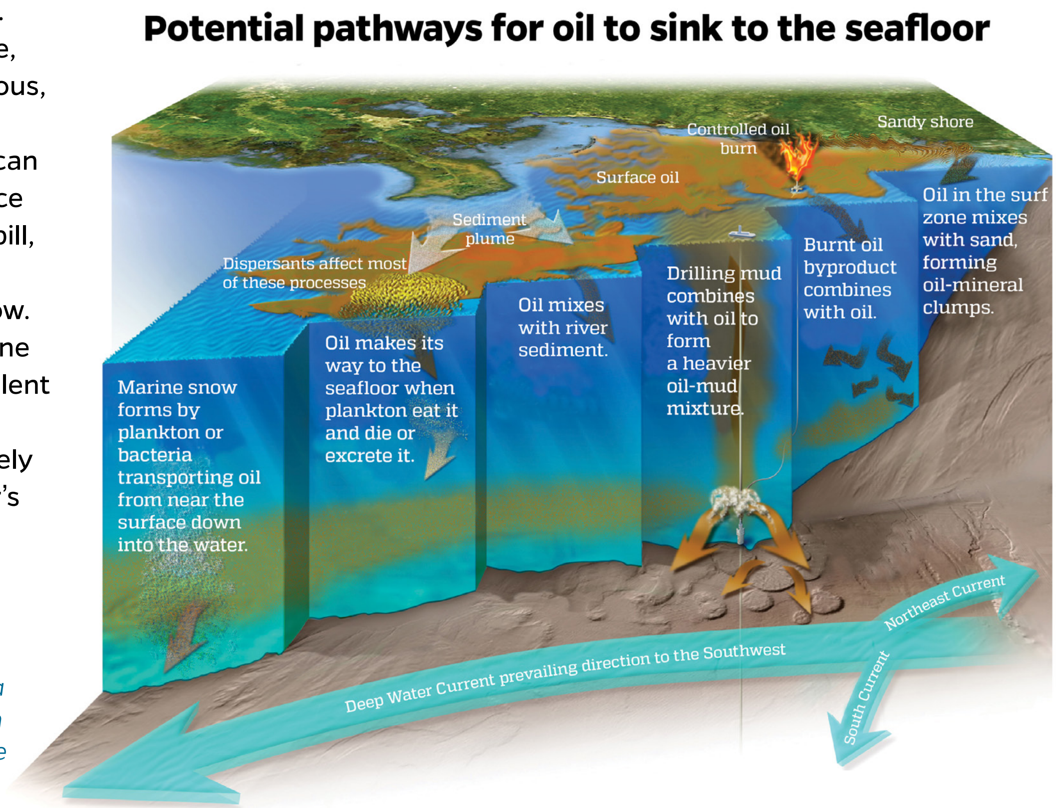

FIGURE 5. *Oil can take many paths to reach the ocean floor. (Florida Sea Grant/Anna Hinkeldey, adapted from Deepwater Horizon Natural Resource Damage Assessment Trustees)*

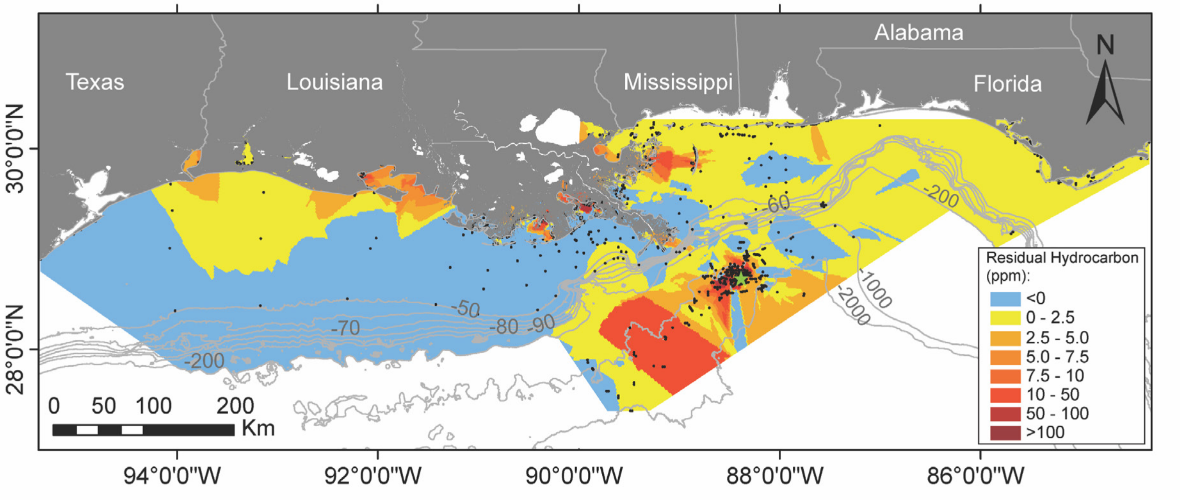

FIGURE 6. *This map shows oil concentrations from coastal to deep-sea areas in 2010 and 2011. Gray lines show bathymetry, green star is the location of the deepwater horizon well site, and black dots indicate study sites.[41] (Reprinted from romero et al., 2017)*

Estimating the total amount of oil that made its way to the seafloor is difficult. Deep-sea currents moved the deposited oil, causing it to accumulate in dips and depressions on the seafloor. Marine animals that live on the bottom can bury, move, and change the oil's location. Scientists estimated that an area of approximately 1,235 square miles around the Macondo well had been polluted with different amounts of oil and **oil-derived carbon** from the spill. While oil on the seafloor had not been included in the original oil budget, studies showed that about three to five percent of the oil discharged from the well made its way to the seafloor.[38-40]

In another study, scientists analyzed data from a large area (approximately 75,000 square miles) in the Gulf of Mexico. Results identified weathered oil from DWH deposited in approximately 56% of the studied area. This number equates to an area of approximately 42,471 square miles, from coastal to deep sea areas, and as far as 321 miles from the wellhead (**Figure 6**).[41] A more recent study found that residues on the seafloor from the DWH oil spill changed over time between 2010 to 2018. Currents moved large quantities of sediment down-slope to areas where sediments accumulate in the deeper parts of the Gulf of Mexico. Results indicated that oil residue could be found up to 60 miles to the southeast of the wellhead. This finding suggests that a much larger area was impacted with DWH oil than previously reported.[9]

The Gulf of Mexico Research Initiative (GoMRI) funded multiple studies into the movement, placement, and degradation of oil that can be found on GoMRI's website at ***http://gulfresearchinitiative.org***. To access other oil spill-related products, visit the program website at ***www.gulfseagrant.org/oilspilloutreach***.

GLOSSARY

Colored dissolved organic matter (CDOM) — Dissolved organic matter in the water that consists of broken-down plant parts, such as leaves, algae, or phytoplankton.

Eddy — A current having a rotary or circular motion.

Emulsify — 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.

Fluorescence — A substance absorbing light re-emits the light as a different color.

Fluorometer — An instrument used to measure re-emission of light by a substance.

Incident Command — An organized system that consists of government, industry, and private sector parties. It provides a common structure for managing emergency and non-emergency events and to ensure a fast and efficient emergency response.

Loop Current — A warm ocean current that flows northward between Cuba and the Yucatan Peninsula, moves north into the Gulf of Mexico, loops east and south before exiting to the east through the Florida Straits and joining the Gulf Stream to flow between Florida and the Bahamas.

Oil-derived carbon — Oil-derived chemicals from weathering, microbial degradation, and ingestion of oil by marine organisms.

Oil seeps — Areas where oil and natural gas flow up naturally through cracks in the earth at a slow rate.

Polycyclic aromatic hydrocarbons (PAHs) — One of the many chemical groups found in oil, tar, smoke from burning oil, coal, wood, or decaying vegetation; used to identify oil in the environment.

Sedimentation — Occurs when particles (or sediment) suspended in a liquid settle and get deposited on the bottom.

Volatile organic compounds (VOCs) — Gases that evaporate from certain solids or liquids, such as oil. Inhaling these compounds for a long period of time can be harmful to one's health.

Weather (-ed, -ing, -s) — 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 photooxidation. These processes are influenced by many factors (e.g., type of oil being weathered, temperature, bacteria present).

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