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Simulation of the Landfall of the Deepwater Horizon Oil on the Shorelines of the Gulf of Mexico

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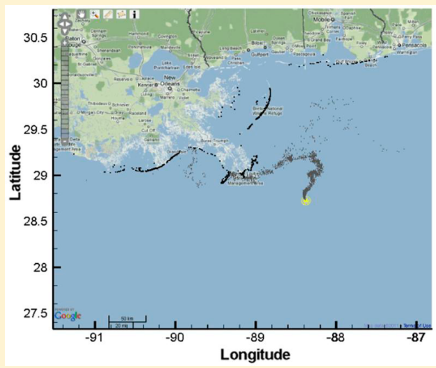
S *Supporting Information*

ABSTRACT: We conducted simulations of oil transport from the footprint of the Macondo Well on the water surface throughout the Gulf of Mexico, including deposition on the shorelines. We used the U.S. National Oceanic Atmospheric Administration (NOAA) model General NOAA Operational Modeling Environment (GNOME) and the same parameter values and input adopted by NOAA following the Deepwater Horizon (DWH) blowout. We found that the disappearance rate of oil off the water surface was most likely around 20% per day based on satellite-based observations of the disappearance rate of oil detected on the sea surface after the DWH wellhead was capped. The simulations and oil mass estimates suggest that the mass of oil that reached the shorelines was between 10 000 and 30 000 tons, with an expected value of 22 000 tons. More than 90% of the oil deposition occurred on the Louisiana shorelines, and it occurred in two batches. Simulations revealed that capping the well after 2 weeks would have resulted in only 30% of the total oil depositing on the shorelines, while capping after 3 weeks would have resulted in 60% deposition. Additional delay in capping after 3 weeks would have averted little additional shoreline oiling over the ensuing 4 weeks.



INTRODUCTION

The Deepwater Horizon (DWH) well blowout in the Gulf of Mexico (GOMEX) released oil from April 20th until capped on July 15th, 2013. The amount of oil released was estimated at around 5 million barrels.[1] Despite the considerable resources and effort marshaled to prevent the oil from reaching the shorelines, the spill contaminated around 500 km of shorelines (Figure 1) in the categories of heavy and moderate.[2,3] Impacts that included damage to wetlands and the fishing and tourist industries were highlighted in a recent report.[4] This paper addresses only the deposition of oil on the shorelines, because near shore open waters and shorelines constitute highly productive regions both ecologically and economically and, because oil tends to persist in shorelines in comparison to open water,[5−8] which tends to prolong the impact on the economy and ecology of shorelines. The persistence of oil also increases the remediation cost by orders of magnitude in comparison to oil intercepted at sea. Thus, it is important to develop a better understanding of the movement of oil and its deposition onto the shorelines.

There are numerous works on the modeling of the hydrodynamics and transport in the GOMEX.[9−19] Paris et al.[16] predicted the movement of oil from 1200 m deep using a detailed three-dimensional (3D) fate and transport that focused on the subsurface transport. Le Hénaff et al.[18] complemented the work by Paris et al.[16] by focusing on oil transport on the water surface and found that the wind played a major role in advecting the oil to the northern GOMEX. Kourafalou and Androulidakis[17] conducted a rigorous study for the 3D transport of oil near the Mississippi Delta and evaluated the influence of the river diversion conducted to minimize oil intrusion inland.[4,20] Barker[15] conducted Monte Carlo simulations consisting of 500 individual oil trajectory scenarios using historical data of water currents and winds. The results by Barker[15] indicated that, in approximately 75% of the scenarios, oil would be transported out of the GOMEX by the Loop Current. This means that the actual trajectory of oil from the DWH falls in the 25% of scenarios.

Our goal herein is to quantify the amount of oil that reached the shorelines. We make two major assumptions in our investigation. First, we assume that the only source of oil to the shoreline is the oil that reached the surface immediately above the wellhead (known as Mississippi Canyon 252, MC252 for short). This assumption is justified by the fact that the main part of the plume that rose to the surface occurred within 1.5 km of the well head projection on the water surface.[21] In addition, as the subsurface plume migrated 200 km horizontally at an approximate depth of 1200 m, it became diluted and density stratification prevented it from rising to the surface.[22] In

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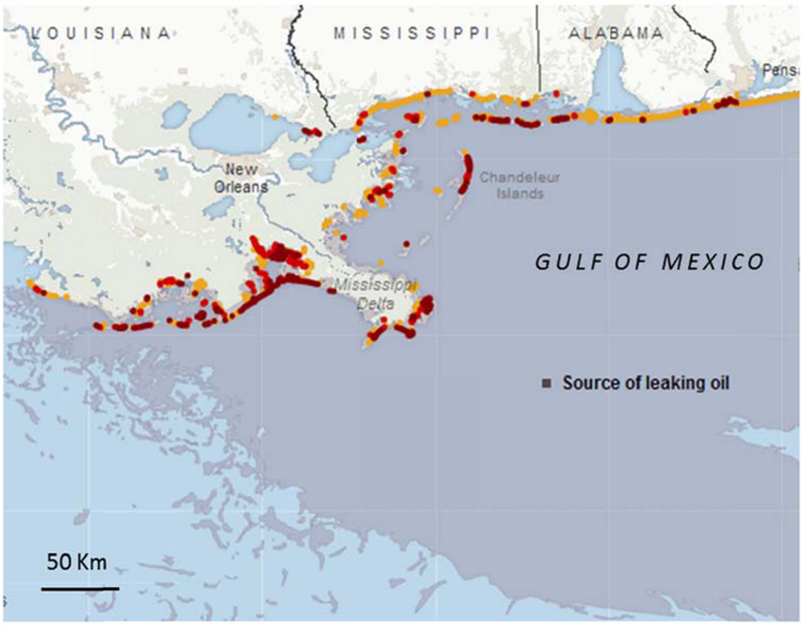

Figure 1. Map of region of shorelines affected by the actual spill (http://www.nytimes.com/interactive/2010/05/27/us/20100527-oil-landfall.html). The darker red indicates heavier shoreline oiling. The gray region shows the suspected satellite-derived surface oiling over the entire spill period.

addition, droplets that were small enough to be advected in the deep plume have a rise time to the surface varying from weeks to months,[21] a time scale over which biodegradation could play a major role.[23,24] Second, we assume that response efforts (skimming, burning, and dispersant application) did not alter the spatial distribution of the oil reaching the shoreline but only reduced the amount of oil reaching the shorelines; because of the large size of the spill, it was not possible to set aside resources to protect a particular area of the shoreline. Rather resources were marshaled to intercept oil whenever it was found. This second assumption is needed because detailed data on the amount of oil removed at particular locations are difficult to compile and evaluate. Considering the uncertainty in oil trajectory, this assumption is plausible.

■ BACKGROUND

Oil on the water surface becomes transported by winds, waves,[25−27] and sea currents. These processes are simulated succinctly in the National Oceanic and Atmospheric Administration (NOAA) General NOAA Operational Modeling Environment (GNOME), which moves Lagrangian elements, labeled "splots" on the water surface based on input of sea currents obtained from hydrodynamic models (structured or unstructured grids) and wind models. For the latter, GNOME requires a "windage factor", which reflects the surface water movement as a percentage of the wind speed. The windage factor is typically around 3% of the wind speed and is usually less than 6% of the wind speed.[28] The GNOME model also assigns a turbulent diffusion coefficient to represent turbulent mixing.

During the DWH blowout, the Environmental Response Division (ERD) of the Office of Response and Restoration at NOAA relied on six available hydrodynamic models to predict the movement of oil, as reported by MacFadyen et al.[29] On each day, the NOAA ERD selected the hydrodynamic model that matched best the observations obtained from satellites and overflights[29] (see Tables S1 and S2 of the Supporting Information). The wind data were derived from the National Weather Service gridded products.[29] The NOAA ERD simulated the oil for 72 h and initialized the oil distribution twice a day in the first few weeks of the spill and later daily.[29] The initialization was performed on the basis of observations.

■ METHOD OF APPROACH

Our goal was to simulate the continuous release of oil at the water surface and its subsequent transport and fate on the water surface until it reached the shorelines, including barrier islands. The overall oil spill evaluation is modeled as follows: In our simulations, we released 500 splots at the water surface daily until the date of well capping. These splots represent the average amount of oil released to the water surface per day. These splots were then tracked throughout the GOMEX until landfall (or beaching). The number of splots released to the water surface immediately above the wellhead does not represent any particular oil volume; it could represent 33 000 barrels per day (bpd), as estimated by Barker,[15] or only 1000 bpd. The main thrust of this investigation is to evaluate the portion of the released oil at the sea surface that reaches the shorelines (including the barrier islands). We used the parameter values and the water current and wind input used by NOAA ERD during the DWH spill. This information was retrieved from the database of the NOAA ERD archives.

GNOME has an option for the landfall (i.e., beaching) and resuspension of oil. We considered the deposition only, because (1) the net movement of floating materials on beaches is landward,[30] (it is thus unlikely for a large portion of the deposited oil to move seaward if it becomes resuspended) and (2) the accuracy of the hydrodynamic models used in this study deteriorates in the coastal zone because of coarseness of the grid and the fact that these models were developed primarily for offshore hydrodynamics and transport. Therefore, there was no justification for a detailed mechanistic model of deposition and resuspension of oil on the shorelines. Le Hénaff et al.[18] assumed that oil becomes deposited when it is within 3 m from the bottom, and they did not consider resuspension of oil after deposition.

Oil is expected to disappear off the surface because of a variety of mechanisms, including evaporation, photooxidation, dissolution, emulsion, and biodegradation.[31,32] In addition, oil could deplete off the surface through entrainment into the water column as droplets (labeled as "dispersion" in the oil literature because the oil "disperses" into small droplets) because of waves[27] and Langmuir cells.[33,34] However, only oil that does not return to the surface should be considered as "disappeared" off the surface. This "lost" oil mass in the water column is usually made up of small oil droplets, typically less than 100 μm in diameter.[35] Furthermore, oil disappeared off the surface due to active removal by response activities that included skimming, dispersion, and *in situ* burning.[36,37]

The NOAA's ERD was interested in providing the "worst case scenario" for the response officials and was reinitializing the spatial distribution of oil every 24 h based on observations from satellites and overflights; it did not consider the depletion of oil from the surface.[29] However, oil depletion off the surface needs to be considered when simulating the continuous fate of oil during 3 months. Rigorously accounting for each of the aforementioned factors of oil weathering is not realistic because of the complexity and scale of the oil−water−atmosphere system. However, one could deduce the oil depletion rate off the surface based on empirical observation as follows.

Figure 2 depicts the areal coverage of oil based on satellite data obtained from the date of well capping (i.e., July 15th)

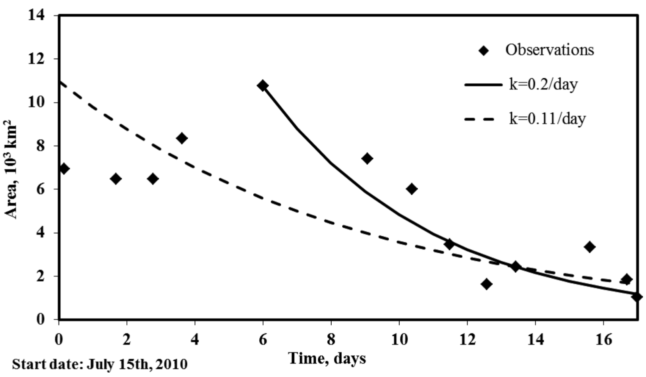

Figure 2. Observed areal extent of surface oil and two fitted exponential decay curves. The observed areal extent was obtained from NOAA/National Environmental Satellite, Data, and Information Service (NESDIS) (http://www.ssd.noaa.gov/PS/MPS/deepwater.html).

until July 30th. The areal extent fluctuated but a trend of decrease is obvious, resulting in complete depletion of the oil off the water surface. Obviously, patches of oil persisted for longer durations, but their areal extents and masses are negligible in comparison. The bulk of the oil slick was relatively far from the shorelines, as confirmed from satellite and simulation data between July 15th and August 5th. It is thus reasonable to assume that the disappearance of oil from the surface was not due to beaching but weathering and active removal by the response activites.

An expedient model for the depletion of fields (mass, surface area, etc.) is an exponential decay curve, used herein for the oiled area

$$\frac{\mathrm{d}A}{\mathrm{d}t} = -kA \tag{1}$$

where A is the area of oiled water surface (km^2) and k is a first-order rate (day^{-1}).

The model GNOME does not allow for depletion of mass; rather, it reduces the portion of components in a mixture of hydrocarbons. For this reason, the removal of a selected percentage (20% for $k = 0.2$ day^{-1} and 10% for $k = 0.1$ day^{-1}) of the splots was conducted as follows: (1) Run the model for 24 h. (2) Output the results (e.g., number and location of oil splots). (3) Postprocess the results to separate the splots that beached from those that remained on the water surface. (4) Use a uniform random generator to remove randomly the selected percentage of the splots off the water surface. (5) Use the beached splots and those that "survived" on the water surface as the initial condition for splots for a GNOME simulation for another 24 h. Note that beached splots do not deplete nor do they move, and the splots that survive continue their transport on the water surface unaffected. (6) Repeat the process until there are no splots on the water surface or for 3 weeks after capping, whichever occurs first.

■ RESULTS

Figure 2 shows that fitting eq 1 to the observed oiled area starting on July 20th, the largest oiled area after well capping, gave $k = 0.2$ day^{-1}, (i.e., the oiled area shrinks by 20% daily). The fit starting on July 15th (the date of the well capping) gave $k = 0.11$ day^{-1}, and we adopted $k = 0.1$ day^{-1} for simplicity. The fit giving $k = 0.2$ day^{-1} was better than that giving $k = 0.1$ day^{-1}. Nevertheless, we conducted simulations with $k = 0.2$, 0.1, and 0.0 day^{-1} (i.e., no depletion). For all of the simulations, we used the same windage factors used by NOAA ERD daily, which varied between 0 and 3%. We also used the same value of the horizontal turbulent diffusion coefficient as NOAA ERD, 10 m^2/s, because we found this value reasonable (see, for example, the study by Boufadel et al.[26] for a discussion on the horizontal diffusion coefficient).

Panels a, b, and c of Figure 3 report the simulated splots distribution on August 5th, 2010 based on $k = 0.2$, 0.1, and 0.0 day^{-1}, respectively. The oil deposition on the shorelines in Figure 3a ($k = 0.2$ day^{-1}) appears by far to have the closest resemblance to the observed oil deposition on the shorelines (Figure 1). Panels b and c of Figure 3 show considerable oil deposition west of longitude −91, which is in disagreement with observation (Figure 1). Also, around the location (−88.6, 30.4) (i.e., on the shorelines of Mississippi), Figure 3a agrees closest with observations (Figure 1), while panels b and c of Figure 3 result in a large oil deposition. Because of the decrease in resolution near the shorelines, GNOME simulations in embayments should not be considered accurate and, thus, should not be compared to observations there. There are situations where the model provided no deposition, whereas deposition actually occurred, such as, for example, at Cat Island.[38] However, given that the size of the computational block of the hydrodynamic model is 10 × 10 km, it is likely that some areas at smaller spatial scales may not be accurately portrayed.

Using $k = 0.2$ day^{-1}, we provide in Figure 4 further comparison of the model to data obtained from overflight and satellite observation.[39−41] Figure 4a shows that the model predicted the presence of two plumes on May 7th, 2010: one extending west of MC252 and another in the northern part of

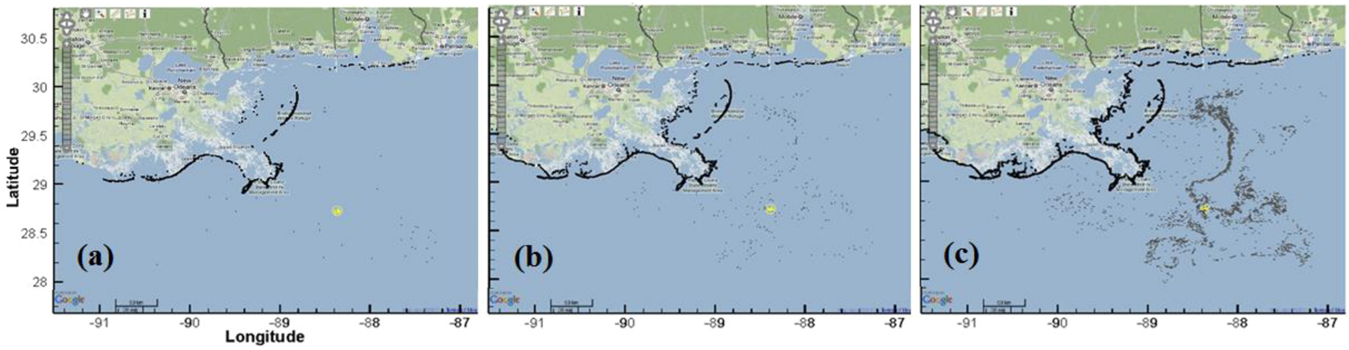

Figure 3. GNOME simulation results of the DWH on August 6th, 2010 assuming a constant rate of oil release to the water surface above the wellhead from April 22nd, 2010 until capping on July 15th 2010. Surface depletion based on eq 1 is (a) $k = 0.2$ day^{-1} (i.e., 20% of the oil depletes off the surface per day), (b) $k = 0.1$ day^{-1} (10% of the oil depletes off the surface per day), and (c) $k = 0.0$ day^{-1} (i.e., no depletion). Black dots denote the oil splots. Note the similarity of the oiled beach results for $k = 0.2$ day^{-1} to those observed in Figure 1.

the GOMEX. The predicted western plume seems to underestimate the observed plume. However, the agreement with observation is better for the northern plume, especially in terms of the zonal (west to east) extent. The model accurately reproduced the western migration of the plume south of Louisiana toward Texas on May 9th, 2010. The model however underestimated the southern migration of the plume south of MC252. The model predicted landfall of the western plume on May 11th (Figure 4c) and also on May 12th (not shown). Landfall on these dates was confirmed by Shoreline Cleanup and Assessment Technique (SCAT) reports communicated to us by the NOAA SCAT Coordinator, Dr. Jacqueline Michel. Note that Michel et al.[3] discusses the oiling of the shorelines at the end of 2010 and subsequent years but does not contain information on the time history of the landfall during the spill (i.e., Summer 2010).

Further comparison of the model to the data is reported for June 10th, 2010 in Figure 4d, where the model accurately reproduced the observed plume south of MC252 along with the thinning toward the west. However, the model did not reproduce well the plume north of MC252.

June 25th (Figure 4e) is an important date because it is the day before Hurricane Alex (National Weather Service, NOAA, http://www.srh.noaa.gov/crp/?n=hurricanealex) arrived to the GOMEX. The model was able to reproduce both the western plume and the "arch" to the east that emanated from the oil plume northwest of the well. As the Hurricane moved toward Texas, it advected oil northward toward the shorelines of Alabama and Mississippi and westward toward Atchafalaya Bay and the State of Texas. The model closely reproduced these observations as noted on June 28th, 2010 (Figure 4f) and June 30th, 2010 (Figure 4g). Further discussion on the model prediction is provided in the Discussion.

Figure 5 depicts the percentage of oil released (left axis) and the oil that reached the shorelines (right axis) as a function of time for the case where $k = 0.2$ day^{-1}. Approximately 10% of the oil released reached the shorelines and beached there. Figure 5 also shows a high rate of beaching around May 10th, which was due to the deposition of oil on the Chandeleur Barrier Islands and the marshes of Louisiana (panels a, b, and c of Figure 4) and, subsequently, on the shorelines of Alabama and Texas (in this order). The plateau in Figure 5 reflects that little beaching occurred until June 26th−30th, the dates of Hurricane Alex (panels e, f, and g of Figure 4).

Figure 5 also reports the oil deposition on the shorelines for $k = 0.1$ day^{-1}. One could note that the trend was the same as for $k = 0.2$ day^{-1}, but the amount of oil deposition was almost triple that resulting from $k = 0.2$ day^{-1} (i.e., 30% of the oil released to the surface above MC252 reached the shorelines). One also notes that the plateau phase for $k = 0.1$ day^{-1} is not as flat, reflecting oil beaching during these periods. For the case of $k = 0.0$ day^{-1} (i.e., no depletion), more than 96% of the oil reached the shorelines by August 6th, 2010, which is not realistic based on observations of other spills.

Sensitivity Analyses. Figure 5 also reports the oil deposition mass for $k = 0.2$ day^{-1} when using only the model National Ocean Service Gulf of Mexico (NGOM) rather than the daily selection of models adopted by NOAA ERD (see Tables S1 and S2 of the Supporting Information). The difference is relatively small in terms of the time history and total mass. The largest difference occurred in July, probably because of the usage of Texas A&M University (TAMU) by NOAA ERD on July 7th, 2010. However, the results of NGOM show a similar spatial distribution of oil (see Figure S1 of the Supporting Information) to that obtained in Figures 3a and 1, indicating the capability of the NGOM model to predict the overall oil deposition along the shorelines. As Figure S1 of the Supporting Information shows, the model NGOM predicted more oil deposition behind the Chandeleur Islands in Louisiana. However, it is worth noting that the purpose of the NOAA ERD was to direct response efforts, and it is probable that some hydrodynamic models provided more accurate information than others at a particular location. For example, the West Florida Shelf model (see Table S1 of the Supporting Information) is most likely more accurate than NGOM in the west Florida region. In summary, regardless of the depletion rate or the hydrodynamic model, Figure 5 indicates that the bulk of the oil on the water surface reached the shorelines in two batches: May 10th and June 30th.

Le Hénaff et al.[18] observed that wind drift plays an important role in the oil movement, and thus, we investigate herein the impact of the windage factor. We select for this purpose two extreme values of the windage factor: i.e., 0 and 6%. Figure 6 shows the predicted oil distribution on August 6th, 2010. The 0% windage factor resulted in a much smaller oil deposition on the shorelines than observed (Figure 1), which reflects the fact that the water currents were southward and westward, as discussed in details by Le Hénaff et al.[18] and Paris et al.,[16] and that the northern migration of oil was due in large part to wind

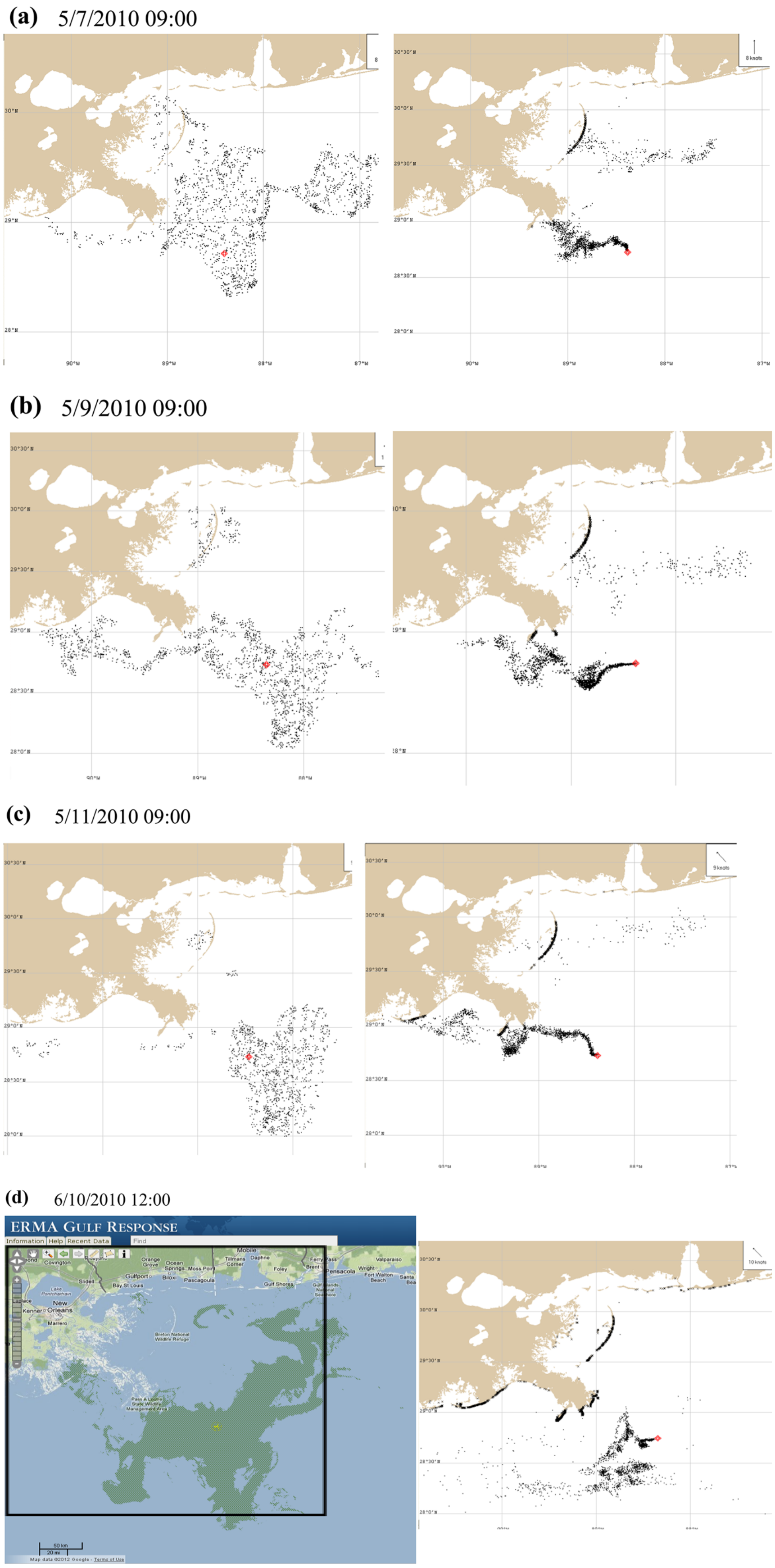

Figure 4. continued

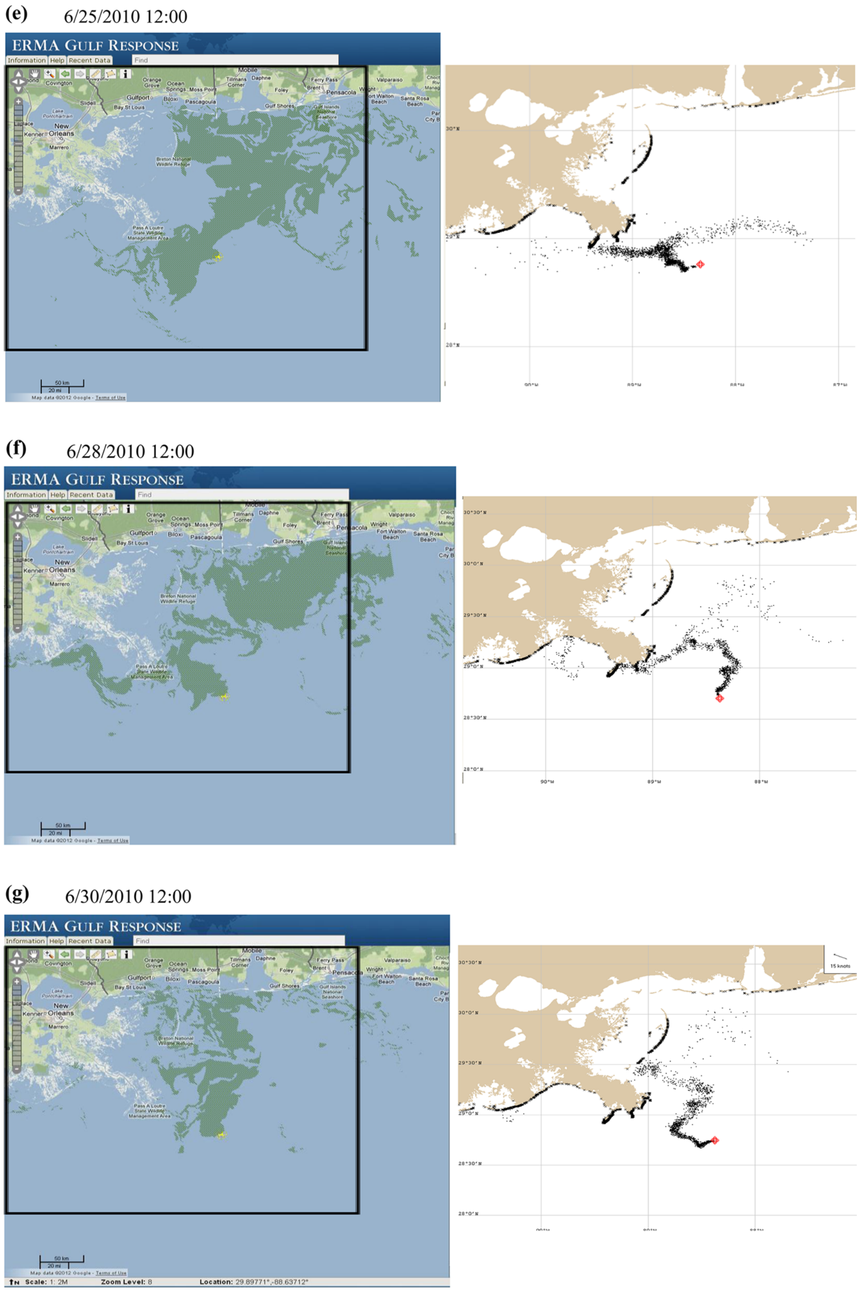

Figure 4. Comparison between (left panel) observations and (right panel) simulations at 7 dates throughout the DWH spill.

drift. The 6% windage case resulted in a higher number of oil splots deposited along the shorelines, especially along the shoreline of Mississippi, Alabama, and Florida, which does not agree with the observation (Figure 1). This suggests that the range of 1−4% of windage factor (selected by NOAA ERD) is the optimal range.

Figure 7 provides the temporal accumulation of the beached splots under different windage conditions. The results show that the currents brought the oil to the shorelines on circa May 10th and June 30th but that a large windage factor would have increased the deposition. Figure 7 is also important because it produces the value of 30% for the oil deposition by August 6th, 2010, which agrees with the simulation with k = 0.1 day^{-1} (Figure 5). This suggests that 30% is clearly a high upper limit for the percentage of oil (released to the surface above MC252) reaching the shorelines, because it was obtained under extreme modeling conditions. To put things in percepetive, the percentage of the Exxon Valdez oil[7,8] that reached the Prince William Sound (Alaska) shorelines was 50%,[42] and it occurred in a cold climate where the oil source (the tanker) was relatively close to the shorelines. An additional comparison between the two spills is reported by Atlas and Hazen.[43]

Table 1 reports the deposition of oil on each of the five GOMEX U.S. States for k = 0.2 and 0.0 day^{-1} (no depletion). For k = 0.2 day^{-1}, the table shows that more than 98% of the oil deposition occurred in Louisiana. The distant second was Alabama (1.14%). The deposition at Mississippi was an order of magnitude smaller than that at Alabama, which is due to the sheltering effects on Mississippi shorelines because of the barrier islands of Louisiana (e.g., Chandeleur Islands). However, the model grid is relatively coarse (10 × 10 km), and a loss of precision would occur at the small scale. For

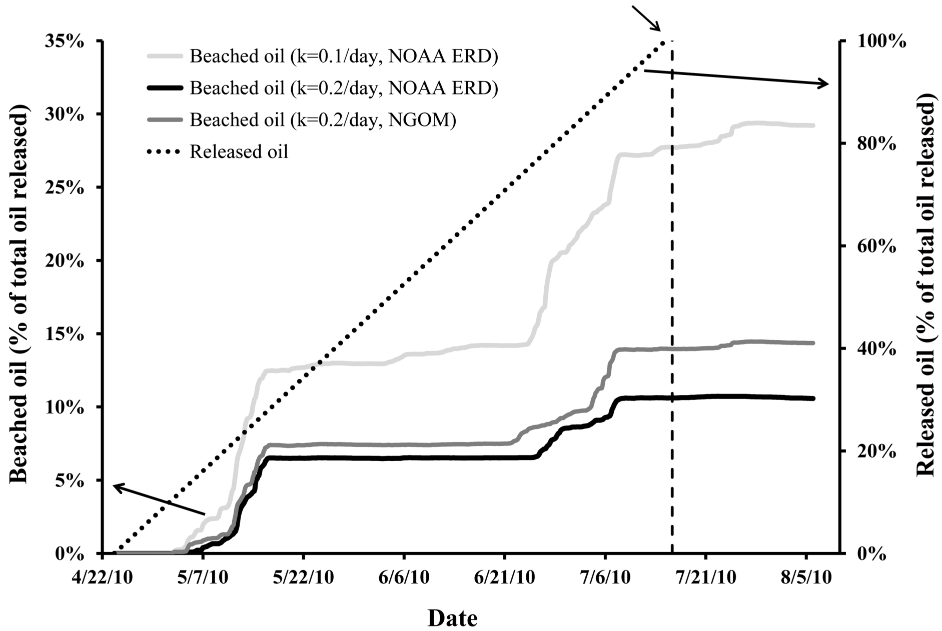

Figure 5. Oil beached, as fraction of total oil released to the surface, as function of time based on the hydrodynamic models selected by NOAA ERD daily (see Tables S1 and S2) for k = 0.2 day^{-1} and k = 0.1 day^{-1} (eq 1). Also shown is the plot for the beached oil using only the model NGOM with k = 0.2 day^{-1}. The release of oil to the surface, assumed constant with time until July 15, 2010, is reported on the right axis.

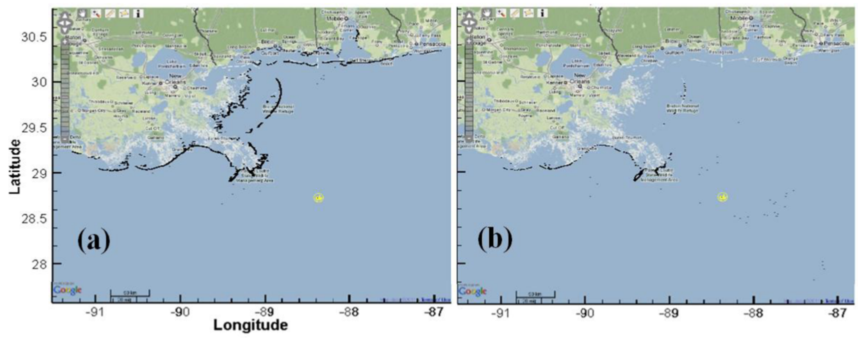

Figure 6. GNOME simulation results on August 5th, 2010 for the DWH for a windage factor of (a) 6% and (b) 0%. Surface oil depletion was assumed to follow an exponential decay with k = 0.2 day^{-1} (eq 1).

example, Cat Island in Mississippi (Figure 1) received a large amount of oil considering its size.[38] However, the simulation results (Figure 3) do not show deposition on that island for k = 0.2 day^{-1} (Figure 3a) but for k = 0.1 day^{-1} (Figure 3b) and k = 0.0 day^{-1} (Figure 3c). Because Louisiana was the closest to MC252, it was thought that the depletion of oil as it traveled to other States resulted in this large percentage of oil deposition on Louisiana's shorelines. For this purpose, we report in Table 1 the percentage deposition per State for k = 0.0 day^{-1} (i.e., no depletion). Indeed, less oil deposited at Louisiana in this case. However, this amount remains approximately 2 orders of magnitude larger than all of the other states combined.

■ DISCUSSION

Lehr et al.[36] provided estimates for the volumes of the DWH oil in various sectors of the GOMEX. They reported their estimates as expected, best, and worst, with an understanding that "worst" implies more oil on the water surface and the shorelines (to be removed by the response operations). For their expected estimates, they reported that the percentages of volumes were direct recovery (17%), naturally dispersed (13%), chemically dispersed (16%), evaporated or dissolved (23%), burned (5%), skimmed (3%), and other oil (23%). The other oil increased to 30% for worst and dropped to 11% for best. It is therefore reasonable to assume that the total volume of oil released in our simulation is the other oil, which was 1 100 000 barrels (≈200 000 tons) for the expected, 520 000 barrels (≈94 000 tons) for best, and 1 500 000 barrels (≈270 000 tons) for worst. For an 11% total deposition (Figure 7), the amount of deposited oil varies between best (≈10 000 tons), expected (≈22 000 tons), and worst (≈30 000 tons). For comparison, the total volume of the Exxon Valdez oil spill was ≈40 000 tons, and approximately 20 000 tons of it beached.[42]

Most of the simulated splots remained within a small percentage (10−30%) of the oiled area[44] (see also Plate 1 of refs 45 and 46), which is not suprising considering the adage "90% of the oil is within 10% of the area", reflecting the fact that oil occupies various thickness down to micrometers,[47] and the limited number of splots that we used precluded us from predicting very thin oil away from the bulk of the plume. This also explains the visual discrepancy between our modeling results and observations for the northern plume (Figure 4),

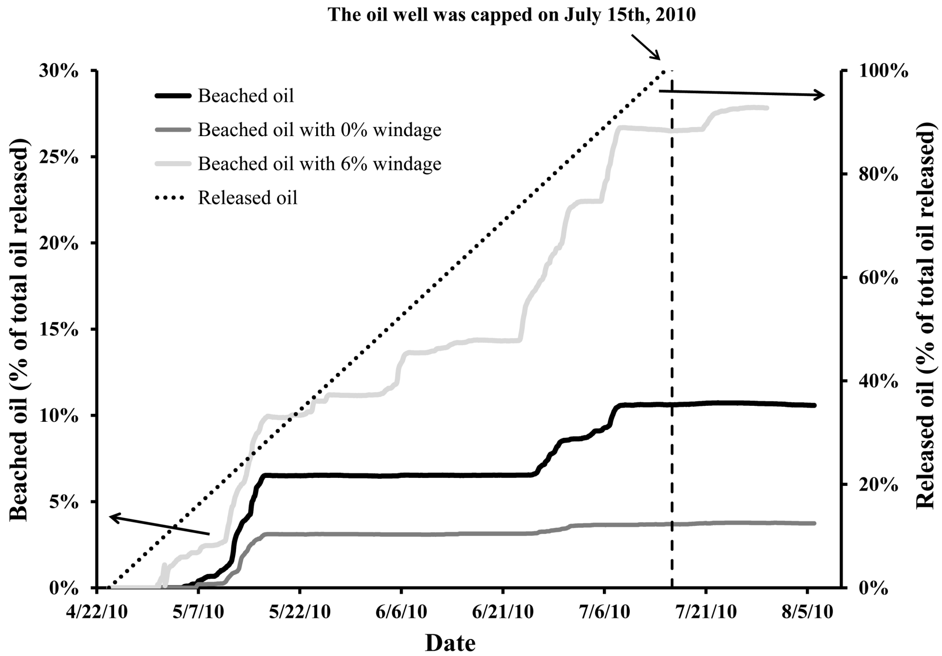

Figure 7. Percentages of total and beached oil using different windage percent for depletion following $k = 0.2$ day^{-1}. The percentages of oil on the left axis are with respect to the total (100%) released to the surface above the wellhead until capping on July 15, 2010.

Table 1. Percent Deposition of Oil Per State Based on the Total Amount Deposited

State	$k = 0.2$ day^{-1} (Figure 3)	$k = 0.0$ day^{-1}, no depletion, (Figure 5)
Louisiana	98.6	96.4
Alabama	1.14	1.5
Mississippi	0.09	1
Florida	0.07	0.05
Texas	0	1.0

because only a small amount of oil deposited on the eastern states. In addition, Langmuir cells, when they occur, have a major effect on the spatial distribution of oil and its residence below the surface, as noted in the Braer Incident when oil disappeared for 2 days because of a storm to remerge later and reach the shorelines,[48,49] and the GNOME model does not model explicitly the effects of Langmuir cells (and we are not aware of any oil spill model that does).

It was suggested that the large extent of the oil slick might be due to the DWH oil droplets released at depth eventually surfaced at locations that are far (e.g., 50 km) from the MC252 well. However, we are not aware of any model that predicted such a behavior (see, for example, the study by Paris et al.[16]). However, we believe that because surface oil spills spread to very thin thickness and that deep spills that emerge above the well are expected to be even thinner,[50] the observed spatial distribution of oil is not due to oil upwelling after tens of kilometers from the source.

Large-scale imaging platforms, such as moderate-resolution imaging spectroradiometer (MODIS), synthetic aperture radar (SAR), and side looking airborne radar (SLAR), provided synoptic views of the slick, but they are unable to provide oil thickness, which was obtained using a multispectral approach[45,51] at select locations because the approach cannot cover areas larger than 500 km^2 per flight mission. In addition, the multispectral approach was usually focused on potential spots of thick oil to alert response vessels for interception.[40] Therefore, a complete mapping of the oil thickness is not available. These challenges make visual observations of spilled oil a well-accepted technique.[46] However, the wide range for each color reflects the large uncertainty in evaluating the volume of oil, as noted in the last column of Table 2, especially for thicknesses less than 50 μm.

Table 2. Estimation of Oil Thickness and Volume Based on Its Color, as Per the Bonn Agreement

code	description/appearance	layer thickness interval (μm)	L/km^2
1	sheen (silver/gray)	0.04–0.30	4–300
2	rainbow	0.30–5.0	300–5000
3	metallic	5.0–50	5000–50000
4	discontinuous true oil color	50–200	50000–200000
5	continuous true oil color	>200	>200000

One of the commonly asked questions in the aftermath of the DWH was what would have been the total amount of oil deposited on the shorelines had the well been capped earlier? To evaluate the impact of earlier capping, we conducted simulations where we assumed capping after 1, 2, 3, and 4 weeks. The results of beached oil as a function of the total released oil (i.e., when capped on July 15th, 2010) are reported in Figure 8, which shows that capping the well after 1 week of the blowout would have resulted in shoreline deposition of only 10% of the oil that was deposited when the well was capped after 89 days. Capping after 2 weeks would have resulted in the deposition of 30% of oil on the shorelines. However, capping after 3 weeks would have been the same as capping after 4 weeks (and 7 weeks; not reported herein) and would have resulted in the deposition of 60% of the total oil deposited when the well was capped after 89 days. With the benefit of hindsight, our results suggest that capping within 1 or 2 weeks

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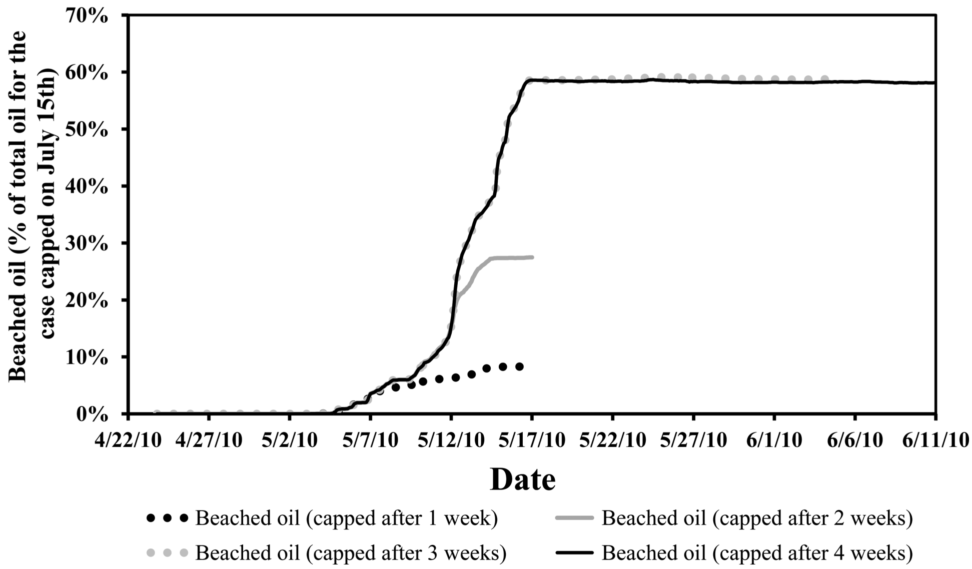

Figure 8. Percentages of beached oil in different capping scenarios of the wellhead for a depletion rate of 20% of the oil off the surface (k = 0.2 day^{-1}). The percentages of oil are with respect to the total deposited oil by August 6, 2010 (Figure 5, darkest plot).

would have greatly decreased the proportion of oil deposition on the shorelines.

■ ASSOCIATED CONTENT

Supporting Information

Hydrodynamic models used during the DWH oil spill response (Table S1), hydrodynamic models selected for the simulation (Table S2), and simulation results in GNOME using the NGOM model (Figure S1). This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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