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ARTICLE *in* ENVIRONMENTAL SCIENCE & TECHNOLOGY · MAY 2012

Impact Factor: 5.33 · DOI: 10.1021/es301570w · Source: PubMed

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Surface Evolution of the Deepwater Horizon Oil Spill Patch: Combined Effects of Circulation and Wind-Induced Drift

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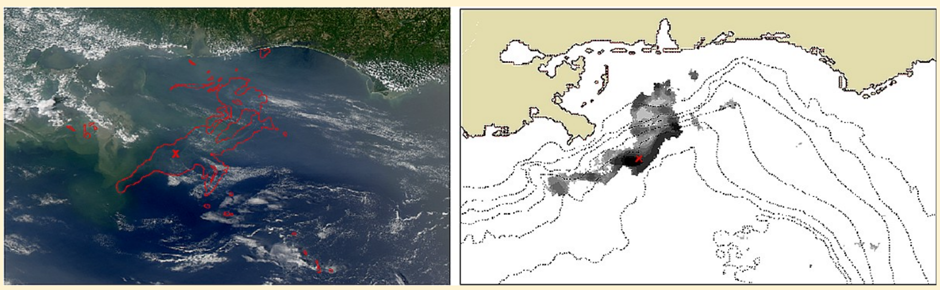
S *Supporting Information*



ABSTRACT: Following the Deepwater Horizon blowout, major concerns were raised about the probability that the Loop Current would entrain oil at the surface of the Gulf of Mexico toward South Florida. However, such a scenario did not materialize. Results from a modeling approach suggest that the prevailing winds, through the drift they induced at the ocean surface, played a major role in pushing the oil toward the coasts along the northern Gulf, and, in synergy with the Loop Current evolution, prevented the oil from reaching the Florida Straits. This implies that both oceanic currents and surface wind-induced drift must be taken into account for the successful forecasting of the trajectories and landfall of oil particles, even in energetic environments such as the Gulf of Mexico. Consequently, the time range of these predictions is limited to the weather forecasting range, in addition to the range set up by ocean forecasting capabilities.

INTRODUCTION

The Deepwater Horizon (DWH) accident is the largest oil spill in the United States history, with about 4.4 millions barrels (0.7 million m^3, almost 600 000 tons) released in the Gulf of Mexico.[1] In the weeks following the blowout of the oil platform, the magnitude of the leak became increasingly apparent, as the surface area covered with oil expanded. The spread of some oil toward the Loop Current, which flows from the Yucatan Channel to the Straits of Florida, raised concerns among the oceanographic community and coastal managers that the entrained oil might reach South Florida, the Florida Keys and downstream Atlantic coastal areas.[2] European and world press were concerned about oil crossing the Atlantic, for example the Spanish newspaper El Pais (http://teknociencia.wordpress.com/2010/05/17/el-petroleo-puede-llegar-a-la-corriente-del-golfo/). Using numerical models, some studies showed the possibility for such a development, with oil being advected to the Atlantic Ocean.[3] However, only small quantities of oil were detected in the Gulf interior in May and June. After the capping of the wellhead, the continuous oil discharge stopped and the observed quantities of oil at the surface were dramatically decreased. No oil has been detected at the surface since August 20, 2010.[4] In particular, no oil related to the DWH source has been reported along the South Florida coastal areas or in the Atlantic Ocean. How come the anticipated disastrous downstream effects did not materialize? What were the particular environmental conditions that controlled the surface transport of detectable oil products? Using a fully three-dimensional oil model, we focus here on the surface evolution of the oil spill patch in the Gulf of Mexico, and especially on the role played by the wind-induced drift, in synergy with the basin-wide currents.

The DWH platform was located between the edge of the Northern Gulf of Mexico shelf and the Gulf interior. This is an

Received: April 19, 2012
Accepted: May 31, 2012
Published: May 31, 2012

area where the ambient circulation is affected by the regional open sea dynamics, dominated by the Loop Current and associated eddy field, and by shelf processes, largely affected by Mississippi-induced buoyancy driven and wind-driven flows.[5] At the time of the DWH accident, in late April, the Loop Current was well extended into the Gulf of Mexico, but it was still south of the platform position (Figure 1). The anticyclonic

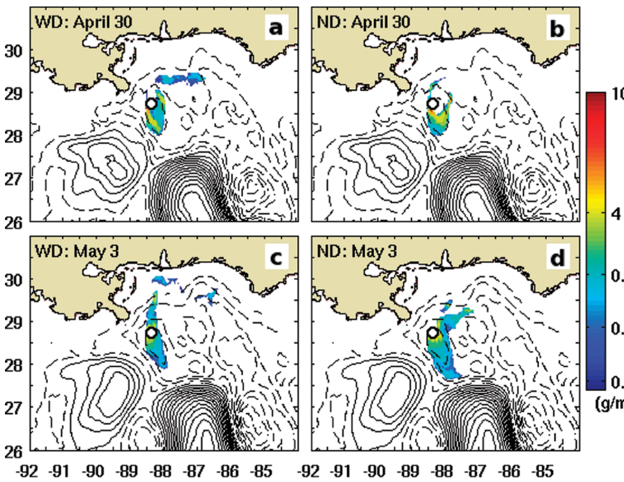


Figure 1. Modeled surface oil concentration (g/m^2) on April 30, (a) for the reference (WD) simulation and (b) the simulation ignoring the wind-induced drift (ND simulation), and on May 3rd for (c) the WD simulation and (d) the ND simulation. Levels of concentration on the color bar correspond to the definition of colorless and silver sheen (0.05−0.2 g/m^2), rainbow sheen (0.2−0.8 g/m^2), dull brown sheen (0.8−4 g/m^2), dark brown sheen (4−100 g/m^2), and black oil (>100 g/m^2).[32] Black lines represent the sea surface height (SSH) contours from the hydrodynamic model. Contours are every 4 cm. Solid lines are for high SSH, dashed lines are for low SSH. Through geostrophy, concentric solid lines are associated with anticyclones, and dashed lines are associated with cyclones. The Loop Current is visible by the semicircle of concentric solid lines between 86°W and 88°W.

Loop Current front was surrounded by frontal cyclones,[6] but also by a residual anticyclone. In the following weeks, the Loop Current evolved due to the growth of a cyclone on its eastern side,[7] which led to the detachment of a large anticyclonic Loop Current Eddy, named Eddy Franklin, around mid-June. Eddy Franklin partially reattached to the Loop Current for months, before totally separating in late September.[8] This sequence of events is visible in altimetry and *in situ* observations, available for example on the NOAA Web site (www.aoml.noaa.gov/phod/dhos/altimetry.php). The ring separation resulted in a southward position of the Loop Current and effectively eliminated connectivity between the Northern Gulf and the Florida Straits. Although we do not focus on near-shore processes, we seek to elucidate how the combination of the above oceanic conditions with the wind-induced drift determined the fate of the oil at the surface of the Gulf of Mexico.

MATERIALS AND METHODS

The oil spill model was developed and calibrated for the study of the specific chemical and physical conditions of the DWH blowout. It couples a hydrodynamic model of the three-dimension ocean circulation to a deep-water blowout, multi-fraction oil model, which was implemented in the Connectivity Modeling System (CMS)[9,10] individual-based model framework. These components are described below. The novelty of this approach is to examine the surface evolution of the oil spill patch resulting from a deep blowout, as compared to surface releases as in other studies of the DWH incident.[11]

Hydrodynamic Model Component. We employed the HYbrid Coordinate Ocean Model (HYCOM),[12−14] set up over the Gulf of Mexico (GoM) with 1/25-degree horizontal resolution and 20 vertical layers, to determine the displacement of the oil by ocean horizontal currents and the prevailing hydrographical conditions. This GoM-HYCOM simulation is run in near-real time at the Naval Research Lab at Stennis (NRL-SSC), forced by the 0.5-degree Navy Operational Global Atmospheric Prediction System[15] (NOGAPS) winds and surface fluxes and by large-scale model fields at the Caribbean and Atlantic boundaries.[16] This simulation uses the Navy Coupled Ocean Data Assimilation (NCODA) system[17] to assimilate sea surface height and sea surface temperature, as well as available observations from in situ profiles. It has been successfully used for several studies of the DWH oil spill.[11,18,19] The archives used for the oil spill simulations are the current velocity, but also temperature and salinity fields, which are critical to the fluid particle evolution.

Oil Model Component. The oil spill is represented in the CMS by individual particles mimicking oil displacement and fate based on oil droplets parameters. The modeled oil is described by eight oil groups, each defined by a range of possible densities. Percentage ratio of the hydrocarbon groups and oil specific density were derived based on the literature for a light crude oil,[20] which is of comparable type to the oil from the Macondo well.[21] The description of the eight groups is detailed in the Supporting Information. Individual particle size is selected at random from a uniform distribution between 1 and 500 μm. This range is consistent with the observed distribution of oil droplet at the site.[22] Once released at depth, oil particles are displaced by the ambient ocean currents, and by their own buoyancy. The vertical terminal velocity is gained by an oil particle due to buoyancy;[23] it depends on the oil droplet density and size. At depth, oil particles are biodegraded, depending on ambient temperature.[24] After the oil particles evolution has been simulated at depth,[25] the larger ones eventually rise to the surface of the GoM. Here we focus on the fate of these oil particles once they reach the surface. Oil particles at the surface are subject to biodegradation, as at depth,[24] but also to evaporation. The evaporation of oil depends on the hydrocarbon groups:[20] the lighter groups have a half-life of 10 h, the heavier groups have a half-life of 250 h (more details in the Supporting Information). The oil model, of intermediate complexity for the surface oil representation, does not include emulsification, density changes, nor specific surface vertical dispersion, in particular forced by waves breaking, which leads to resuspension of oil droplets. Oil particles that reach a minimum depth of 3 m thickness of the ocean model are considered having made landfall along the coast.

Wind-Induced Surface Drift. Once they reach the surface, oil particles have already been affected by the ocean currents they encountered during their rise; thus, they may not emerge directly above the wellhead. At the surface, oil particles are further advected by ocean surface currents. In addition, the displacement of oil at the surface is also influenced by the wind, leading to the formation of waves, to wave breaking, and to Langmuir circulation, which all influence the displacement of the oil. We implemented a model using the same atmospheric model as the one used to force the ocean simulation, NOGAPS,

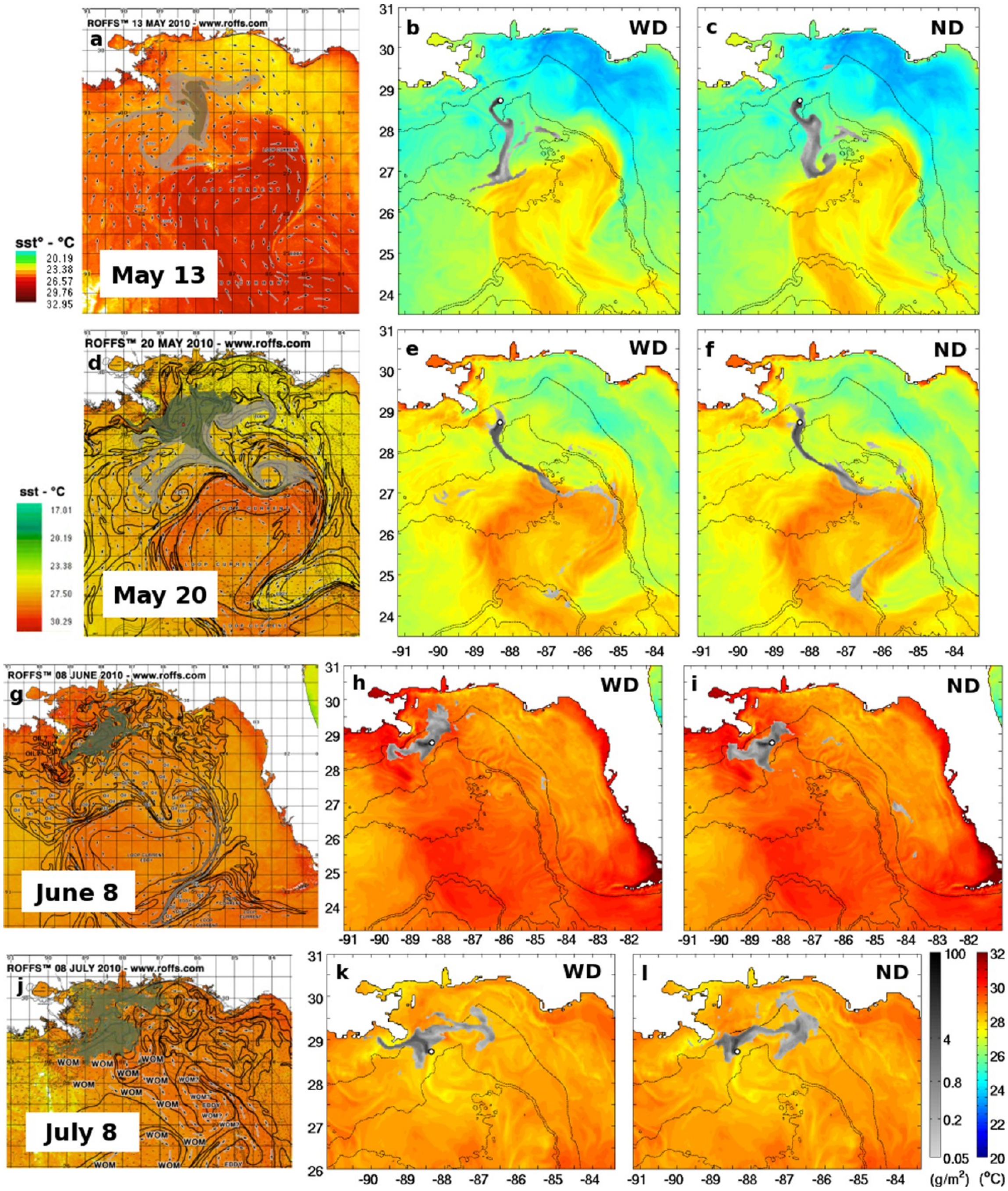


Figure 2. Observed and modeled oil presence and concentration: (a, d, g, j) oil presence as observed on May 13, May 20, June 8, and July 8, data adapted from composites by Roffer's Ocean Fishing Forecasting System (www.roffs.com/deepwaterhorizon.html), (b, e, h, k) oil concentration at the surface (gray scale, g/m^2) in the reference (WD) simulation, and (c, f, i, l) same as in (b, e, h, k), for the simulation ignoring the wind-induced drift (ND simulation). (a, d, g, j) Surface colors indicate sea surface temperature, with yellow to red colors for low to high temperatures. Note that the temperature scale is different between May 13 and the three other dates. Dark and light brown indicate observed and likely presence of surface oil. (b, c, e, f, h, i, k, l) Surface colors indicate sea surface temperature from the GoM-HYCOM simulation. Gray scale indicates oil concentration, based on the various types of oil defined in Figure 1. Black lines are the 200, 2000, and 3000 m isobaths.

to estimate the wind-induced drift component of the oil displacement forced by these processes. It is the sum of the Stokes drift, due to the ocean surface waves, and a complementary component representing the displacement due to wave breaking and Langmuir circulation. The direction for the total wind-induced drift is close to main direction of the wind. More details about this implementation can be found in the Supporting Information.

Numerical Simulations of the DWH Incident. The CMS is used with a hierarchy of embedded Lagrangian Stochastic Particle Models representing subgrid-scale mixing.[26] The horizontal eddy diffusivity was calibrated with observations[27] and corresponds to grid-dependent empirical estimates.[28] The vertical eddy diffusivity is assumed constant over the entire water column and set to a minimum order value of 10^{-5} m^2.s^{-1} observed in the deep ocean.[29] For the current simulations, the horizontal and vertical eddy diffusivities are of order 1 m^2·s^{-1}

and 10^{-5} $m^2 \cdot s^{-1}$, respectively. The Macondo well is located at 1522 m depth on the continental shelf slope.[3] 3000 particles are released every 2 hrs from April 20 to July 15 for a total of more than 3×10^6 particles, at a single source point (28.736°N, 88.365°W) located 300 m above the wellhead, at the estimated separation height between oil and gas.[30] Here we present results from two simulations, one including the effect of the wind-induced drift (WD, for "with drift") and the other ignoring it (ND, for "no drift"). Both simulations start on April 20 and continue until October 5, 2010. The time step for Lagrangian integration is 1800 s. We focus here on the surface transport and fate of oil particles. No change is done on the oil particles geographical distribution during the simulation. This means, in particular, that no observation is used to update the slick extent, which is never modified during the simulation and only follows the oil particles trajectories from their continuous release in the deep Gulf of Mexico to their weathering or landing.

Data used for the evaluation of model results are composites of all sources available, such as observed oil distributions based on satellite images from various instruments, analyzed by the Center for Southeastern Tropical Advanced Remote Sensing (www.cstars.miami.edu), as well as visual observations from flights over the Gulf of Mexico and NOAA in situ data. We have used composites for the extent of the slick provided by the New York Times and by Roffer's Ocean Fishing Forecasting System (www.roffs.com/deepwaterhorizon.html; ROFFS[11,31]).

■ RESULTS AND DISCUSSION

Examination of the early stages of the simulated surface oil spill patch illustrates the effect of the wind-induced drift (Figure 1). The concentration of oil at the surface is estimated by affecting the same mass of oil to each particle at the surface. The total mass of oil considered to have reached the surface represents 50% of the total oil estimated released. This number is still under discussion, as the quantity of oil that stayed at depth is highly dependent on the initial oil droplet size distribution,[25] but it provides realistic numbers for the surface concentration. In the ND simulation, the patch of surface oil tends to be advected southward by the neighboring cyclonic eddy. The southward advection is intensified during the following days, so that the main oil patch gets very close to the Loop Current edge on May 3. In the WD experiment, the initial surface oil patch is mainly advected by the cyclone, as in the ND experiment. However, between April 30 and May 3, the wind-induced drift due to northward winds favors the confinement of the oil main slick, with its core of higher concentration clearly advected northward, opposing the southward spreading of the oil toward the Loop Current. This phenomenon is limited compared to the ND case. The additional effect of the drift on the surface current in the vicinity of the wellhead appears important for determining the initial spread of the oil and eventually its fate.

The model-computed distribution of oil at the sea surface, for both WD and ND simulations, is compared to the ROFFS satellite observation composites for various stages of the oil spill in spring and summer 2010 (Figure 2). On May 13, the main slick in the vicinity of the wellhead extended meridionally, with a wide branch toward the southwest that splits in two smaller branches, eastward and westward, when reaching the edge of the Loop Current (Figure 2a). This main branch and smaller ones are well represented in the WD simulation (Figure 2b), whereas in the ND simulation the oil has a substantially stronger transport to the south and southeast (Figure 2c). Moreover, the ND simulation shows small patches of oil that have been advected close to the Florida Straits, southeast of the Gulf of Mexico, which are not present in the WD simulation. Between May 13 and May 20, the patterns evolved quickly: on May 20, the observed slick kept extending in the surroundings of the wellhead, but on the southern edge a long filament of oil was entrained southeastward, following the Loop Current evolution (Figure 2d). This development is represented in the WD simulation (Figure 2e), in which the slick shows southeastward extension of oil, despite a limited spread in the vicinity of the wellhead. The main oil filament has a realistic extension, although no oil is entrained within the Loop Current frontal eddy, contrary to the observations. Patches of low oil concentration extend southwestward of the wellhead, which is consistent with observations; other patches extend too far southward along the Loop Current compared to the observations. In comparison, the ND simulation shows larger oil patches extending that far south, with higher oil concentration (Figure 2f). The sequence of southward entrainment of oil observed between May 11 and May 22 is closely related to the Loop Current and associated frontal dynamics.[7]

On June 8, the observed main slick in the vicinity of the wellhead extended northeastward toward the Alabama and Florida coasts, with a smaller southwestward branch (Figure 2g). The WD simulation also shows a preferred northeastward extension of the main slick over the continental shelf (shallower than 200 m), with a smaller southwestward branch (Figure 2h). In the ND simulation (Figure 2i), the main oil slick does not extend over the northern Gulf continental shelf, remaining preferably southwestward and exhibiting a southward branch (following a temperature front toward the deep Gulf), which is more pronounced than in the WD simulation. Moreover, in the ND simulation isolated patches of oil are present elsewhere in the Gulf, especially over the West Florida Shelf. Such patches were not observed and are substantially reduced in the WD simulation. On July 8, the observed oil slick was confined to the Northern Gulf, around the Mississippi Delta and toward the Alabama and Mississippi coasts (Figure 2j). The simulated oil slick from the WD simulation shows a northward extension of the oil over the continental shelf toward the Mississippi coastlines, although its extension is limited compared to the observations (Figure 2k). A filament of oil extends eastward along the edge of the continental shelf, whereas observations show oil extending along the Alabama coastlines. The small branch of the oil slick extending around the Mississippi Delta is, however, realistic. This is not the case for the ND simulation, in which the eastward extension of the main slick is more pronounced, with higher oil concentration; no branch is represented around the Mississippi Delta (Figure 2l). Results from both simulations in June 8 and July 8 illustrate how the wind-induced drift acted to have the oil slick cross the continental shelf edge northward toward the Mississippi Delta and the northern Gulf of Mexico coastlines. The effect of the wind-induced drift on the extension and evolution of the surface slick is further illustrated in Figure S1 (Supporting Information).

Our three-dimensional hydrodynamic and oil spill patch simulations suggest that the wind-induced drift played a crucial role in maintaining the surface oil slick toward the northern Gulf coastlines. This effect counteracts the tendency from the surface currents alone, which tended to maintain the surface oil in the deep parts of the Gulf of Mexico under the specific circulation conditions during the DWH incident. The NOGAPS wind and GoM-HYCOM surface currents time series (Figure 3) show that the dominant winds were northward in the first 15 days following the blowout of the platform on April 20, whereas the currents were dominantly eastward. As previously seen (Figure 1), northward winds in the early stage of the spill limited the amount of oil that reached the Loop Current. This local effect had a large-scale influence: when the resulting drift was ignored (ND case, Figure 2), some oil reached the Loop Current on early May and was quickly advected southward, reaching the Florida Straits as soon as mid-May. In June and July, the wind generally remained northward, whereas the main currents were eastward and southward. The wind hence acted as pushing the surface oil along the northern Gulf coastlines, as seen on June 8 and July 8 (Figure 2g–l), at the same time preventing additional oil from spreading toward the interior of the Gulf of Mexico.

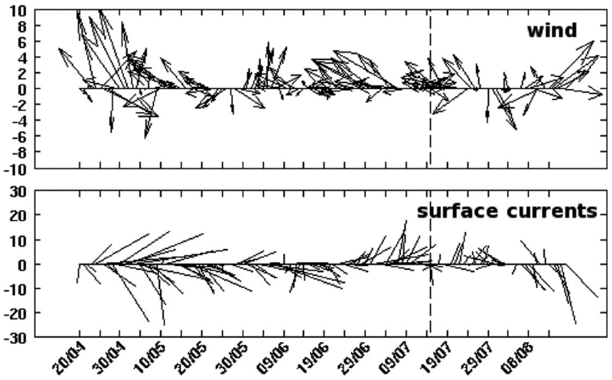


Figure 3. Time series of (top) the mean daily wind vector averaged over the oil spill area (85.5–89.5°W, 27–29.5°N) from the NOGAPS data set, and (bottom) the daily mean surface ocean current vector over the same area from the GoM-HYCOM simulation, between April 20 and August 17, 2010. The dashed line denotes the capping of the wellhead on July 15.

The key role played by the wind-induced drift in the final oil destination, independently from other processes such as biodegradation,[24] is illustrated in Figure 4, showing the total coastline affected by oil landfall in the model for both simulations, compared to the observations of oil landfall. The WD simulation predicts realistic locations for the oil landfall, mainly around the Mississippi Delta, then south of Louisiana and along the Mississippi and Alabama coastlines, but also west of the Florida panhandle (Figure 4a). This is in good agreement with observed oil impact along the northern coast (Figure 4c and d). The WD simulation also exhibits small quantities of oil that reached the south Florida coastlines. These quantities are marginal (0.11% of the total oil that has made landfall). Thus, the wind-induced drift was an important factor in the successful representation of the fate of surface oil particles. In contrast, ignoring the drift effect resulted in substantially erroneous results: (a) although the main locations for oil landfall are also along the coastlines from Louisiana to north Florida, as well as west of the Mississippi Delta (Figure 4b), the ND simulation predicted that the largest quantities of oil affected the coastline at 86°W, along Florida, which is not what was observed (Figure 4d); (b) in the ND simulation, a larger proportion of oil (about 5%) made landfall along the Florida Keys and southeast Florida, areas virtually unaffected during the DWH oil spill event.

Our results suggest that northward winds, through the wind-induced drift, have played an important role in limiting the spread of surface oil inside the Gulf of Mexico and in pushing the surface oil toward the northern Gulf coastlines. The

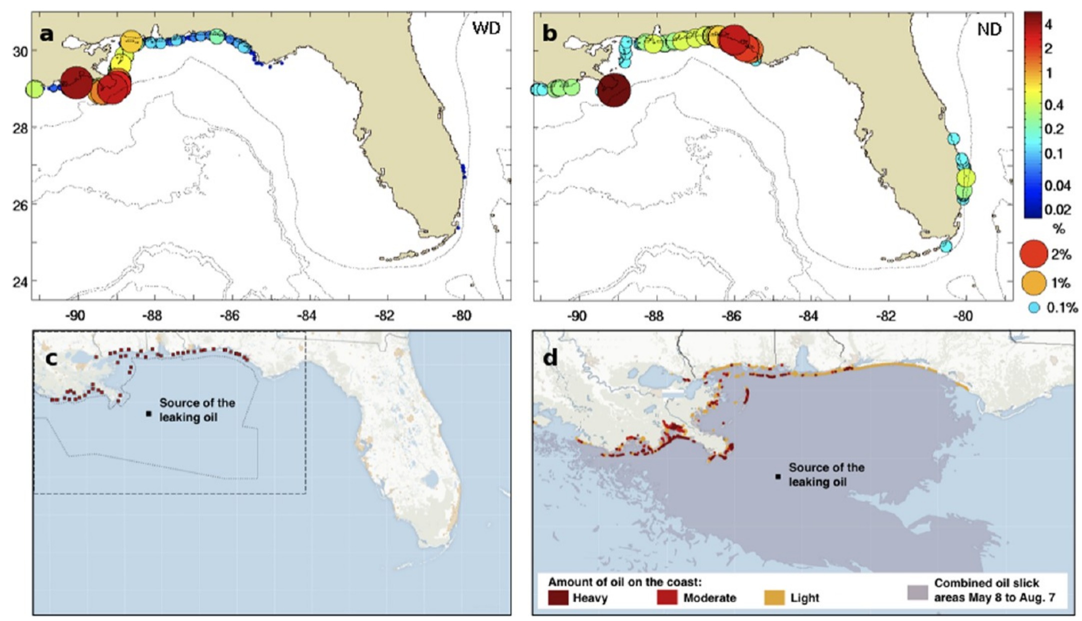


Figure 4. Observed and simulated oil landfall: (a) Total quantities of oil affecting the Gulf coasts (% of total oil particles making landfall along a 1 km segment) in the reference (WD) simulation. (b) Same as (a), but for the simulation ignoring the wind-induced drift (ND simulation). (c) Coastal locations affected by oil landfall (red spots). (d) Zoom over the northern Gulf of Mexico area, defined by the border dashed line on (c), with the level of oil presence on August 7, 2010; the gray zone is the Gulf of Mexico area affected by oil presence during the whole oil spill event. (c) and (d) are adapted from observational composites at the New York Times Web site (www.nytimes.com/interactive/2010/05/01/us/20100501-oil-spill-tracker.html). Thin black lines in (a, b) are the 200, 2000, and 3000 m isobaths.

confinement of the oil spill to the northern Gulf was not initially expected, since the ocean surface currents were supporting advection of the oil toward the interior of the Gulf and the Florida Straits by the Loop Current. We found that the winds played a major role in limiting the offshore and downstream surface oil advection, by counteracting the entrainment of quantities of oil into the interior of the Gulf and the Loop Current. In addition, the small quantities of oil that made their way into the Loop Current were trapped by Eddy Franklin and mainly dissipated while inside the Gulf. Dominant northward winds in June and July also played a crucial role in pushing quantities of oil across the northern Gulf continental shelf edge. We deduce that different conditions for the oil spill could have led to substantially modified spread of the oil, with implications on the extent of the area affected by the spill. Examples include environmental factors, such as different wind direction and alternative Loop Current evolution, but also site specific conditions, such as a different location of the platform or an accident at a different time. Oil spill prediction and forecasting must take into account the wind-induced drift, even in the case of highly dynamical environments, such as the Gulf of Mexico. This reduces the predictability time frame to the limits of synoptic weather forecasting, currently 5−10 days, in addition to limitations imposed by regional ocean forecasting capabilities.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Additional material as noted in the text. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

University of Miami authors were funded by NSF-RAPID grant 1048697 to C.B.P. The contribution of V.K. was also made possible in part by a grant from BP/The Gulf of Mexico Research Initiative. Simulations were carried out at the UM Center for Computational Science. We thank the reviewers for their useful comments and suggestions. Abstract figure uses MODIS image on June 7, 2010 showing oil slicks outlined in red;[33] MODIS Image credit: NASA and University of South Florida.

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