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Simulations of underwater plumes of dissolved oil in the Gulf of Mexico

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[1] A simple model of the temperature-dependent biological decay of dissolved oil is embedded in an ocean-climate model and used to simulate underwater plumes of dissolved and suspended oil originating from a point source in the northern Gulf of Mexico, with an upper-bound supply rate estimated from the contemporary analysis of the *Deepwater Horizon* blowout. The behavior of plumes at different depths is found to be determined by the combination of sheared current strength and the vertical profile of decay rate. For all plume scenarios, toxic levels of dissolved oil remain confined to the northern Gulf of Mexico, and abate within weeks after the spill stops. An estimate of oxygen consumption due to microbial oxidation of hydrocarbons suggests that a deep plume of hydrocarbons could lead to localized regions of prolonged hypoxia near the source, but only when oxidation of methane is included. **Citation:** Adcroft, A., R. Hallberg, J. P. Dunne, B. L. Samuels, J. A. Galt, C. H. Barker, and D. Payton (2010), Simulations of underwater plumes of dissolved oil in the Gulf of Mexico, *Geophys. Res. Lett.*, *37*, L18605, doi:10.1029/2010GL044689.

1. Introduction

[2] Since the explosion of the *Deepwater Horizon* (hereafter DWH) drilling platform on 20 April 2010, there has understandably been much media and academic attention on the surface expression of the resultant oil leak (which continues at the time of writing). This spill is the largest in U.S. history and the ensuing environmental impact may be unprecedented. In addition to the very visible surface slick, there has been concern raised about the appearance of underwater, horizontally extended, plumes of dissolved oil. In particular, there is evidence that a fairly contiguous deep plume formed approximately 200–500 m above the ~1500 m deep wellhead [*Joint Analysis Group* (*JAG*), 2010].

[3] There are extensive resources and experience in forecasting the propagation of a surface oil slick and projecting the consequences [*National Research Council* (*NRC*), 2003]. There is comparatively less experience in forecasting the evolution of spilled oil from deep leaks. A deep oil leak, ejected under pressure, may form an entraining, vertical plume of oil, gas, hydrates and ambient water (see Figure S1 of the auxiliary material).[1] The plume is buoyant so long as there are large volumes of oil and gas in the mix, but may reach a terminal layer in which the upward motion is substantially reduced. This transition may be triggered, for example, by the dissolution of methane at high pressures, thereby removing one source of buoyancy from the plume. Beyond the transition layer, the larger droplets rise at their individual terminal velocities and ultimately make it to the surface, providing the material to form the surface slick. The more soluble compounds within the oil may dissolve, particularly from small droplets that are prevalent in the vertical plume, where the vigorous turbulence gives rise to small droplet sizes. Subsea injection of dispersants will also create tiny droplets and encourage dissolution of oil [*NRC*, 2005]. There is large uncertainty in the proportion of material that remains within the water column, at what depths, and in what form. Small enough droplets ($<\sim 100\ \mu$m diameter) and the dissolved components are retained in the water column, and can for the most part be considered dynamically passive and neutrally buoyant, at least on time-scales of days to weeks. Tentative observations suggest that a measurable amount is retained at depth and has formed horizontally extended plumes [*JAG*, 2010].

[4] One concern is that the deep source of methane and other hydrocarbons released into the water column through the DWH oil spill may lead to emergent hypoxia in the Gulf of Mexico, comparable to, or larger than, the scale of the “Dead Zone” observed in the coastal waters (see the auxiliary material for background). Microbial oxidation of the hydrocarbons is hypothesized to cause significant consumption of dissolved oxygen in the water column. Another concern raised about the deep plumes is that they are harder to physically intercept than a surface slick (which can be substantially contained by booms, skimmed, burned, etc.), raising the concern that the “deep oil” may re-surface at some location remote from the spill site.

[5] This study presents results from a numerical study that considers only the dissolved and neutrally buoyant material retained within the water column. This is an assessment of dispersal and decay mechanisms, and not a forecast and does not address the evolution of surface slicks or floating oil which are the target of tactical response modeling and clean-up activity. We examine the potential for a far-field impact of the deep material, particularly with regard to whether the deep material might exit the Gulf of Mexico. We also examine the varying lifetimes of the plumes depending on the depth of insertion and assess the impact on dissolved oxygen in the vicinity of the plumes. We find that, when the

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ocean circulation and microbial oxidation rates are taken into account, the interior ocean hypoxia or toxic concentrations of dissolved oil arising from the Deepwater Horizon blowout are likely to be locally significant but regionally confined to the northern Gulf of Mexico.

2. Methodology

[6] The essence of our approach is to add passive tracers, subject to simple decay laws, to a climatologically-forced ocean-only model. The ocean model is a 49-layer isopycnal model configured for global simulation with a 1/8° Mercator resolution, forced by climatology superimposed with artificial high-frequency "weather" [*Griffies et al.*, 2009].

[7] Each plume is modeled by a pair of passive tracers injected into the grid cell horizontally spanning the DWH site (28.737°N, 88.387°W). The passive tracers do not alter the density (which is appropriate at low enough concentrations). There is no differential rising of the oil tracer after it is introduced. The passive tracers are transported by the resolved and parameterized flow and are subject to the same parameterized vertical and lateral mixing as would apply to salinity. The explicit vertical mixing is the only mechanism that can allow vertical migration of tracers across isopycnals.

[8] The first of the pair of tracers is conserved (non-decaying) while the second undergoes a simple decay to approximate the biological consumption of hydrocarbons. The decay time-scale, R^{-1}, is temperature-dependent with

$$R^{-1} = 12\,days \times 3^{-(T-20^{\circ}C)/10^{\circ}C}, \tag{1}$$

which is broadly consistent with the studies reviewed by *Atlas* [1981]; (1) gives R^{-1} = 62 days at 5°C and 7 days at 25°C. The timescales represented by (1) reflect both the time required for the dissolved oil to be colonized by microbes, as well as the rates with which some of the more refractory compounds within the oil are metabolized. More recent studies support the idea that decay should have a significant temperature dependence and give decay rates that are of a comparable magnitude [e.g., *Venosa and Holder*, 2007]. These decay rates are broadly consistent with the natural seepage rate into the Gulf of Mexico (2900 barrels per day, hereafter bpd) and observed background concentration, of order 10 parts per trillion [*NRC*, 2003]. In practice, the variations of temperature along a layer are small enough that the decay rate can be considered constant for each plume. The purpose of using a pair of tracers (decaying and non-decaying) is that it allows us to easily compute the consumption by a simple difference, as well as illustrate the role of decay in determining the lateral extent of plumes.

[9] An analysis of a possible upper bound on the potential supply of oil to the whole interior, as well as to individual plumes at depth and in the mixed layer, is provided in the auxiliary material. We argue that an interior supply of order 10,000 bpd is consistent with all cited estimates although the error estimate varies from 5,100 bpd to 15,800 bpd. Each numerical experiment uses the same 10,000 bpd as the supply of oil to each simulated oil plume, with the intent of over-estimating the extent of any one plume but also allowing comparison between the plumes at different depths. The supply of oil to the plumes starts on 20 April 2010 and is held constant in time until it is stopped on 31 August 2010 and is a point source in space, even for the mixed layer plume, in the grid cell immediately above the location of the DWH leak. We consider one particular realization in which the Loop Current Eddy is in a broadly similar stage of separating from the contiguous Loop Current as appeared to be the case in June 2010. The simulations go for a full year.

[10] When estimating the consumption of oxygen within the water column due to the blowout, the oxidation of methane must be accounted for. In terms of carbon supply to the water column, methane is likely to be the biggest contributor since essentially all of it dissolves before reaching the surface. It is estimated that the flow of methane from the well is 40% that of the oil by mass. We thus use 2,400 tons/day of methane (the mass equivalent of 18,000 bpd of oil; see the auxiliary material). We assume the same consumption rate for methane as for oil.

3. Results

[11] We present all of our results as comparisons between scenarios within the context of the model, since our purpose here is to illustrate the role of dispersal and decay mechanisms. We consider five plume scenarios by injecting 10,000 bpd of oil 1) into the mixed layer, 2) into the isopycnal layers that are approximately 300 m deep, 3) 700 m deep, 4) and 1100 m deep, and 5) uniformly with depth. We will refer to these plumes as "mixed layer", "thermocline", "mid-depth", "deep" and "uniform", respectively. For the four vertically localized plumes, the temperature-dependent decay time-scales from (1) are approximately 9, 28, 53 and 60 days, respectively.

[12] Oil is toxic or mutagenic at concentrations varying from 10's of parts per billion (ppb) to 10's of parts per million (10 ppm) depending on the organism in question [*NRC*, 2005]. We contour the column peak concentration in factors of 10 starting at 1 ppb in Figure 1 for the model date 1 September 2010. The deep plume (Figure 1d) has the highest peak inventory and the smallest areal extent because the currents are weakest and the decay is slowest. The currents become stronger moving up the water column and so the extension of the plume at each depth becomes greater. However, the mixed layer plume (Figure 1a), for which the currents are the strongest, has less extension than the thermocline plume (Figure 1b) because the decay time-scale is so much shorter (9 days for the mixed layer versus 23 days for the thermocline).

[13] The mixed layer plume (Figure 1a) is more concentrated than the deeper plumes (Figures 1b–1d) because it is thinner (of order 10–25 m). The uniform plume (Figure 1e) is much less concentrated than the isolated plumes, simply because it is spread throughout the entire water column (a dilution of order 100 m:1500 m with respect to other plumes). The vertical extent of the isolated plumes is mostly correlated with the layer thickness (of order 70–110 m) and the parameterized vertical mixing does not significantly diffuse the plumes in the vertical on the month time scale (not shown). The finite vertical resolution of the numerical model provides a minimum thickness for the plumes (i.e., the thickness of the isopycnal layer). Our decision to use a point source, rather than specify a vertical structure for the input, is based on a lack of detailed understanding of the termination process of the turbulent plume phase of an oil leak. The most defensible vertical plume scale is that of the mixed layer, whose scale is primarily determined by physical processes that are represented credibly in the model.

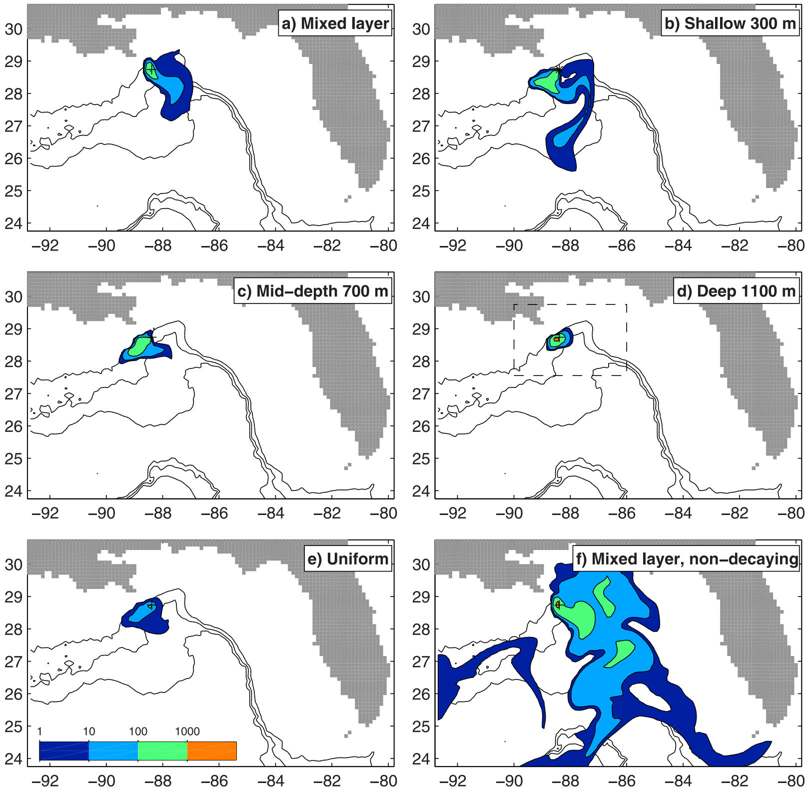

Figure 1. Peak concentration of dissolved oil (in color) within the water column, in parts per billion (ppb), on 1 September 2010 for plumes originating from a point source of 10,000 bpd at different depths. Bathymetry is contoured with a 1000 m interval. The peak concentrations for each panel are (a) 1010, (b) 250, (c) 380, (d) 1950, (e) 190 and (f) 1660 ppb, respectively. The mixed layer has the highest concentrations primarily because the mixed layer plume is thinner (of order 5–30 m) than the deeper plumes (of order 200–300 m thick) or the uniform plume, which is spread throughout the water column. The dashed box in Figure 1d indicates the sub-domain plotted in Figure 2.

The distribution of the column inventory of dissolved oil (shown in the auxiliary material) is broadly similar to the peak concentrations (shown in Figure 1), but is largely independent of the exact choice of vertical plume scales. This similarity suggests that the main findings of this study are not especially sensitive to the choice of the vertical scales of the interior plumes.

[14] The role of decay is made apparent by comparing Figure 1a with Figure 1f, which shows a mixed layer plume of non-decaying oil. The large areal extension of the non-decaying plume is indicative of the strong surface currents. We note that potentially significant levels of the non-decaying tracer (1 ppb) do reach into the Florida straits and Gulf Stream by mid-summer (consistent with passive tracer simulations carried out by *Maltrud et al.* [2010]), while the decaying tracer (Figure 1a) remains regionally confined to the northern Gulf of Mexico.

[15] The oxygen (O_2) consumption is calculated using the oxidation of octane ($2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O$) and for the deep plume only we also include the oxidation of methane ($CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$). Figure 2 shows the percentage draw-down of dissolved O_2 relative to the climatological values. The areal extent of any significant O_2 consumption is smaller than the extent of toxic concentrations for all plumes. Ignoring the role of methane, the three shallowest plumes have peak draw-downs of order 30–35% which is not sufficient to lead to hypoxia (here defined as dissolved O_2 concentrations of less than 2 mg/kg), even in the vicinity of the climatological O_2 minimum. The uniform plume has the lowest draw-down (which peaks in the O_2 minimum, not shown) and the deep plume has a draw-down peaking at 80% which is not quite sufficient to reach hypoxia. However, when methane is included in the calculation of O_2 consumption within the deep plume, the draw-down far exceeds 100% with an approximately 1,330 km^2 region of hypoxia. Our model's ability to exceed 100% draw-down is due to the lack of an interactive biogeochemistry model which would otherwise shut down the consumption of oil and methane when the O_2 is depleted, but also allows the results to be scaled for weaker sources. Figure 3 shows the time series for the peak draw-down and area of hypoxia for the deep plume with methane. The peak draw-down of dissolved O_2 begins to ease shortly after termination of the oil leak (as does concentration, not shown) due to continued dilution. However, the area of hypoxia continues to grow due to lateral mixing, so long as the localized draw-down exceeds the hypoxia threshold, reaching a maximum three months after the leak stops.

4. Discussion

[16] An idealized model of dissolved oil and suspended oil droplets was embedded into a climate-scale ocean general circulation model and used to assess the possibility

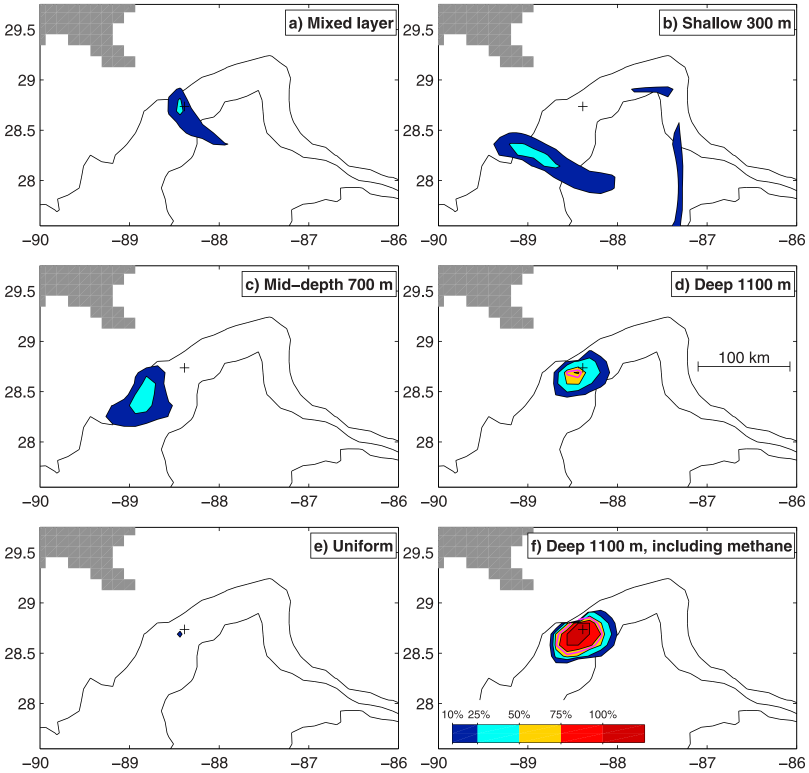

Figure 2. As for Figures 1a–1e but showing the dissolved oxygen deficit (in color) as a percentage draw-down from climatological dissolved oxygen at each depth, in the sub-domain indicated in Figure 1d. The red contour indicates the hypoxic region (panels d and f). The significant areal extent of oxygen deficit is smaller that the areal extent of potentially toxic water (Figure 1). The three shallowest plumes (Figures 2a–2c) have peak values in the range of 30–35%. The deep plume (Figure 2d) has a peak draw-down of 80% while the uniform source leads to a peak draw-down of 12% near the climatological oxygen minimum. For plumes (Figures 2a–2e), methane oxidation is not included and none of these plumes reach hypoxic levels. Figure 2f shows the deep plume including a 2,400 ton/day source of methane (compare to Figure 2d with no methane) with peak values in excess of 200% implying significant potential for hypoxia.

of far field impact of the deep underwater oil plume(s) observed in the Gulf of Mexico following the explosion and sinking of the *Deepwater Horizon* oil rig on 20–22 April 2010. The model assumes a temperature dependent decay of oil, representing the microbial oxidation of oil. The simulated underwater oil plumes do not extend beyond the northern Gulf of Mexico, despite the strong ocean currents associated with the loop current. Significant concentrations of oil in the Florida Straits and Gulf Stream only arise when decay is not taken into account. In the decaying-oil simulations, the restricted extent of the mixed layer plume is primarily due to the rapid decay while the deep plume (sourced at a few hundred meters above the bottom) is even more restricted due to the much weaker currents at depth.

[17] Oxygen (O_2) depletion is dominated by the decay of dissolved methane, which in this model is all incorporated into the deepest simulated plume, and has the potential to lead to regions of hypoxia in the same regions where the oil concentrations are toxic. The hypoxic regions are restricted to regions within a few hundred km of the oil/methane source, and depths of ~1000–1300 m. The mixed layer and mid-column plumes do not reach hypoxic levels, primarily because no methane reaches these layers. Concomitant with the depletion of O_2 during the conversion of hydrocarbons into CO_2 is an ocean acidification impact. As the anticipated CO_2 production is limited by the availability of O_2, acidification impacts (e.g., undersaturation of aragonite and calcite) may be analogous to natural low-O_2 areas of the deep Pacific.

[18] We used a point source for the plumes in both the horizontal and vertical directions. Dissolution and mixing of

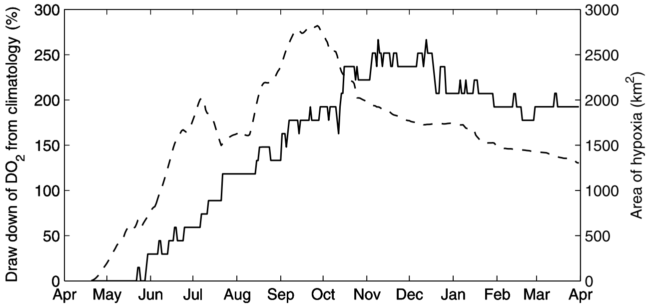

Figure 3. Time series of peak draw-down of dissolved O_2 (dashed) for the deep plume including methane (Figure 2f) and the approximate area of hypoxia (solid). The discrete nature of the area time series is due to the relatively small area compared to the size of a grid cell in the numerical model. The peak O_2 draw-down begins to relax within a few weeks of terminating the oil leak (here 31 August 2010) but the extent of hypoxia continues to rise until the end of the year.

surface oil into the mixed layer is likely to be a laterally broader source than represented here, but we do not think this detail would greatly change the concentrations or inventories. However, the vertical scale of the plumes is initially determined by the vertical resolution of the model (of order 70–110 m at the deep plume depths) and vertical mixing processes act relatively slowly to broaden the Gaussian width of the plume by of order 100 m over ten months. In reality, the vertical scale of the plume is initially set by the processes that lead to the transition of the vertically entraining plume into a layer of more slowly drifting particles and bubbles. A vertical broadening of the simulated source would lead to lower local concentrations (not column inventory) and a lessening of oxygen draw-down.

[19] We must emphasize that the results have no bearing on the evolution of surface slicks originating near the spill site. None of the simulations showed any indication that the deep plumes of dissolved oil could appear at the surface before decaying.

[20] We have shown the simulated plumes on an essentially equal footing, supplying equal amounts of oil to each. In all likelihood, only the deep plume, mixed-layer plume and uniform plume will be realized and if they were to coexist, the sum of the supply rates would match the individual plume supply used here. In such a scenario, the local concentrations would be reduced although the distribution of column inventories would be a normalized combination of the distributions obtained here.

[21] The use of the column supply as a source for each simulated plume and the assumption of a point source in the vertical, both act to overestimate the concentrations of oil and draw-down of oxygen. Thus, we expect the simulated plumes shown here provide an upper bound on the severity of impacts.

[22] The sensitivity to the state of the ocean was not examined here, although a second simulation with a loop current in a slightly different phase of separating showed very similar results (not shown). Y.-L. Chang and L.-Y. Oey (personal communication, 2010) use drifting particles in the context of a higher resolution regional model, using an ensemble of runs and data-assimilated initial conditions. They conclude that very few drifters at the surface and in the mid-column (~800 m) pass through the Florida Straits. We find their distribution of drifters to be in broad agreement with scales of the simulated oil plumes shown here.

[23] We have assumed that all of the simulated oil is labile. We expect that this is a reasonable assumption for the dissolved component of the plume, but may be inappropriate for some fraction of the suspended material (bubbles and particles). A linear combination of the non-decaying and decaying tracer plumes (e.g., Figures 1a and 1f) would suffice to represent such a composition, were the proportions known. However, the refractory component would have to constitute a significant fraction to change the results shown, since the contour intervals are logarithmic.

[24] Based on the simulations presented here, even with all caveats taken into account, we find that potentially toxic concentrations of dissolved oil are localized to within about 100–200 km of the vicinity of the leak. Significant dissolved oxygen consumption is found when methane is considered for the deepest plume, with a total area of potential hypoxia limited to about a tenth the area of the “dead zone” on the shelf, but with an estimated volume of similar magnitude. The resulting regions of oxygen depletion are expected to be confined to the vicinity of the leak, but last longer than the toxic regions, with a peak oxygen draw-down delayed a few months from when the source is stopped.

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