On the possible long-term fate of oil released in the Deepwater Horizon incident, estimated using ensembles of dye release simulations

2010 Environ. Res. Lett. 5 035301

(http://iopscience.iop.org/1748-9326/5/3/035301)

Environ. Res. Lett. 5 (2010) 035301 (7pp) doi:10.1088/1748-9326/5/3/035301

On the possible long-term fate of oil released in the Deepwater Horizon incident, estimated using ensembles of dye release simulations

Mathew Maltrud[1], **Synte Peacock**[2] **and Martin Visbeck**[3]

[1] Los Alamos National Laboratory, Los Alamos New Mexico, NM 87545, USA
[2] National Center for Atmospheric Research, Boulder, CO 80305, USA
[3] IFM-GEOMAR, Kiel, Germany

E-mail: maltrud@lanl.gov

Received 15 July 2010
Accepted for publication 6 August 2010
Published 16 August 2010
Online at stacks.iop.org/ERL/5/035301

Abstract

We have conducted an ensemble of 20 simulations using a high resolution global ocean model in which dye was continuously injected at the site of the Deepwater Horizon drilling rig for two months. We then extended these simulations for another four months to track the dispersal of the dye in the model. We have also performed five simulations in which dye was continuously injected at the site of the spill for four months and then run them out to one year from the initial spill date. The experiments can elucidate the approximate timescales and space scales of dispersal of polluted waters and also give a quantitative estimate of the dilution rate. Given the uncertainty in rates of chemical or biological degradation for oil or an oil–dispersant mixture, we do not include a decay term for the dye. Thus, these results should be considered an absolute upper bound on the possible spatial extent of the dispersal of oil or oil–dispersant mixture.

The model results indicate that it is likely that oil-polluted waters from the Deepwater Horizon incident will, at some time over the six months following the initial spill date, be transported at relatively low concentrations over a significant part of the North-West Atlantic Ocean. However, this does not imply that oil will reach the eastern shores of North America, or that it will even be detectable. We present probabilities for the transport timescales and estimates of ensemble mean arrival times, and we briefly discuss the likely dispersion timescales and pathways of dye released in the subsurface ocean.

Keywords: ocean modeling, tracer transport, oil spill modeling

1. Introduction

An oil well blowout occurred at the Deepwater Horizon Mississippi Canyon 252 wellhead on 20 April 2010, in the Gulf of Mexico at 28° 44′N, 88° 22′W at a depth of 1522 m. The total amount of oil released has been continuously revised upward since the initial spill date: in late April it was reported that oil was leaking at 1000 barrels per day; by early August the Flow Rate Technical Group estimated a release rate of between 53 000 and 62 000 barrels per day, with an estimated total of 4.9 million barrels of oil having been released from the BP Deepwater Horizon well [1]. Because of the ever-shifting baseline while this research was underway, results here are reported as a dilution relative to the source rather than as an absolute concentration.

One particular issue of concern is whether the oil will enter the swift Gulf of Mexico Loop Current and ultimately be transported into the Atlantic Ocean. The Loop Current, which is a part of the large-scale Western Boundary Current System of the Atlantic, is characterized by a clockwise surface circulation after it enters the Gulf through the Yucatan Channel and exits in the Florida Current via the Florida Straits [2]. The configuration of the current is highly variable in both space and time, sometimes extending as far as about 28°N and 93°W, at other times only reaching about 24°N and 87°W. Due to dynamical flow instabilities, the current sheds Loop Current Eddies at irregular intervals, generally between two and 17 months [3]. These eddies typically travel west, dissipating weeks to months later in the western Gulf, but sometimes reattaching to the Loop Current a number of times before remaining fully detached.

Short-term operational ocean circulation forecasts (days into the future), including estimates of oil trajectories, have constantly been carried out by a number of groups [4]. On a longer timescale (weeks to months), deterministic pathways of the oil-polluted surface waters in the upper ocean are not possible due to the unpredictable evolution of the ocean's mesoscale. In particular, the advection by small-scale eddies in the northern Gulf of Mexico, the mixing by local winds, and the behavior of the Loop Current, are all factors that influence the oceanic behavior over these longer timescales.

On timescales longer than a few weeks, statistical estimates based on a variety of possible Loop Current behaviors can help address the question of whether oil from the spill is likely to remain confined to the Gulf of Mexico or whether the oil might disperse into a broader region and eventually be transported by ocean currents into the North Atlantic. In order to investigate a suite of scenarios for the possible fate of the oil on a timescale of several months to a year from the time of the spill, our approach has been to use an eddy-resolving (1/10th degree) global ocean model to conduct an ensemble of dye tracer release simulations each experiencing a different realization of ocean currents. Results are presented for the ensemble mean behavior.

2. Experimental setup

The simulations described here were performed using a fully global configuration of the Parallel Ocean Program (POP) [5] developed at Los Alamos National Laboratory, now the ocean component of the National Center for Atmospheric Research (NCAR) Climate Community System Model (CCSM). The setup is identical to that used by Maltrud *et al* [6], and details of the model configuration can be found therein.

Each ensemble member was initialized with differing Loop Current configurations, with restart conditions selected from the 120-year climatologically forced control run described in [6]. Based on the configuration of the Loop Current, using sea surface height (SSH) as a guide, we were able to select very different SSH evolution scenarios for each ensemble member. The dye tracers were added on 21 April and run for two (or four) months with a constant injection rate at the site of the Deepwater Horizon spill, after which time the source was turned off in the model and the simulations continued for several more months. Dye tracers (along with Lagrangian particles) are routinely used in ocean circulation models to help quantify dispersion (e.g., [7]), making them very appropriate for this investigation.

Because the future atmospheric state is not known, a decision needed to be made as to how to force the model. The choice was made to restrict the timescales introduced by the surface forcing by specifying the future atmospheric state on the repeat annual cycle (normal-year) coordinated ocean reference experiment (CORE) forcing dataset [8], with the six-hourly forcing averaged to monthly values. Wind stress was calculated offline using a sea surface temperature (SST) climatology [9] and bulk formulas [10]; evaporation and sensible heat flux were calculated online using the same bulk formulas and the model-predicted SST. Precipitation was also taken from the CORE forcing dataset.

It should be noted that this model does not use any kind of data assimilation, which is in contrast to the models that are being used to perform operational short-term ocean predictions. Another important difference between this model and those used for the short-term predictions is that the tracer is released as a 'dye' rather than using a finite number of particle trajectories to simulate the dispersal. The release rate was set to 1/day for the assumed duration of the spill (21 April–21 June for the 20-member ensemble; 21 April–21 August for the five-member ensemble). In each ensemble member, four distinct dye tracers were carried, each with a constant source vertically distributed over distinct depth intervals: 0–20, 20–210, 210–820, and 820–1500 m. Although much attention has been paid to the oil at the ocean surface, it is important to note that large amounts of chemical dispersants have been added to the mix over the duration of the spill, resulting in droplets of oil suspended within the water column below the surface that can be tracked with the deeper dyes.

The choice was made to simulate a passive dye tracer rather than oil in order to avoid the large uncertainties that would be inherent in attempting to model actual oil concentrations (which are of the order of tens of parts per million [11]). By definition, a passive dye transport equation has no sink terms, thus we make no attempt to incorporate biological, chemical or physical decay of oil. To accurately simulate oil, it is necessary to parameterize physical processes such as evaporation, emulsification, and dissolution; chemical processes such as photo-oxidation; and biological processes such as microbial oxidation [12]. To further complicate matters, there have been major efforts underway to remove parts of the oil from the surface by skimming and direct extraction from the containment cap. The inclusion of such processes will be an important next step in any attempt to model the possible fate of the oil. A first step in this direction has been made with a model of very rapid microbial consumption of oil that (not surprisingly) significantly reduces the spread of polluted waters, especially near the surface [13].

3. Results

3.1. 20-member ensemble with two-month dye source

An ensemble of 20 simulations was performed in which dye was continuously injected at the site of the spill between 21 April and 21 June. After 21 June, the existing dye continued to be advected and mixed in the ocean through October in the

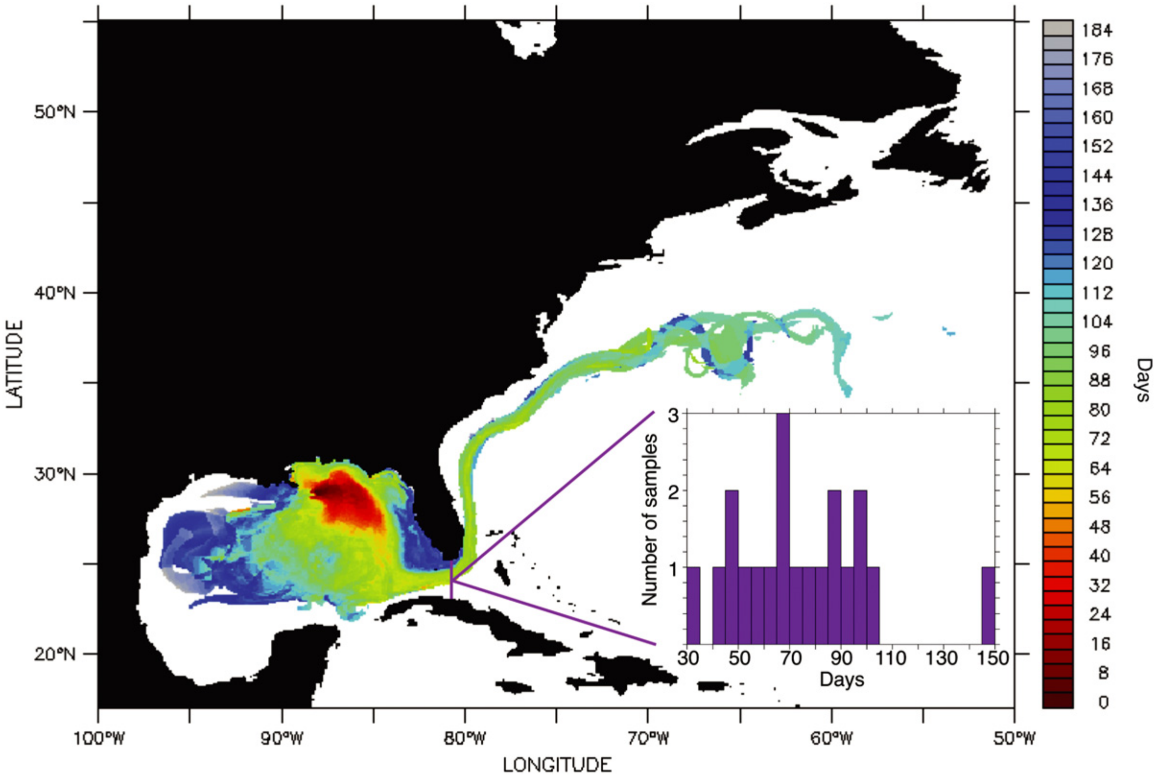

Figure 1. Ensemble mean arrival times (in days) of dye based on a 0.01 dilution factor in the 20-member ensemble. The inset histogram shows the number of days taken for each of the 20 ensemble members to be transported from the spill site to the Florida Straits (81W) with a dilution factor of 0.01. Based on the actual evolution of the Loop Current over June/July 2010, the extreme member (150 day transit time) is probably the best approximation to actual conditions in summer 2010.

model. Each ensemble member 'sees' a different underlying oceanic eddy field but identical atmospheric forcing. The differences in dye dispersal between the ensemble members, therefore, gives a measure of how the response of an impulse injection of dye will differ when subjected to different oceanic eddy fields. It should be noted that any major anomalies in atmospheric forcing (from anomalous local winds to a hurricane, for example) would change the details of the dye's response.

The results in this section focus on the dye injected into the uppermost two model levels (upper 20 m of the ocean model). At the model grid point closest to the spill, an amount of dye necessary to create a concentration of one is injected each day into these layers. Because there is rapid local advection and mixing of the dye away from the site of the spill, the actual model dye concentrations averaged over a day at the spill site are significantly less than 1 (typically around 0.2); this number then progressively decreases as the dye is further diluted. We will be reporting the results in terms of a 'dilution factor,' which is the ratio of the total amount of dye in the water column to the amount injected at the source.

The reason for reporting results in terms of dilution factor instead of concentration units are twofold: first, the uncertainty in the rate of oil injection will directly map to uncertainties in concentration far from the source; and second, there is uncertainty as to the meaning and ecological interpretation of a concentration of oil per cubic volume of seawater. For example, if the oil is a surface slick tens of microns thick, it may have severe implications for bird life and coastal impacts, but still be in very low concentrations. At the same time, the estimated dilution factors can guide scenarios for oil removal due to chemical reaction and biological consumption. In all of the results that follow, we will use a dilution factor of 0.01 as a threshold value for the presence of a significant amount of dye. This value has no physical meaning (i.e., it is not related to oil detectability or toxicity levels) but was chosen somewhat arbitrarily. A dilution factor of 0.01 represents a 100-fold dilution relative to the dye injected at the spill site.

In all 20 ensemble members, dye with a dilution factor of 0.01 or higher joins the Loop Current and exits into the Atlantic Ocean on a timescale of between 30 and 150 days after 21 April. Figure 1 shows the ensemble mean arrival time of the dye at each horizontal grid point location. Focusing on the exit location, it can be seen that the ensemble mean time taken for dye to arrive at the Florida Straits (81°W) is around 70 days. This does not imply that an actual dye released at the spill site would take 70 days to arrive there; the spread across the ensemble is large (see histogram in figure 1). Note that the average time taken for dye to arrive on the West Coast of central and southern Florida is significantly longer than the time taken for dye to enter the Atlantic Ocean since the oceanic circulation tends to be relatively weak and isolated from the major currents in the eastern shelf region of the Gulf. Note also that on this timeframe, none of the ensemble members comes very close to the Texas or Mexico coastlines, nor are there any

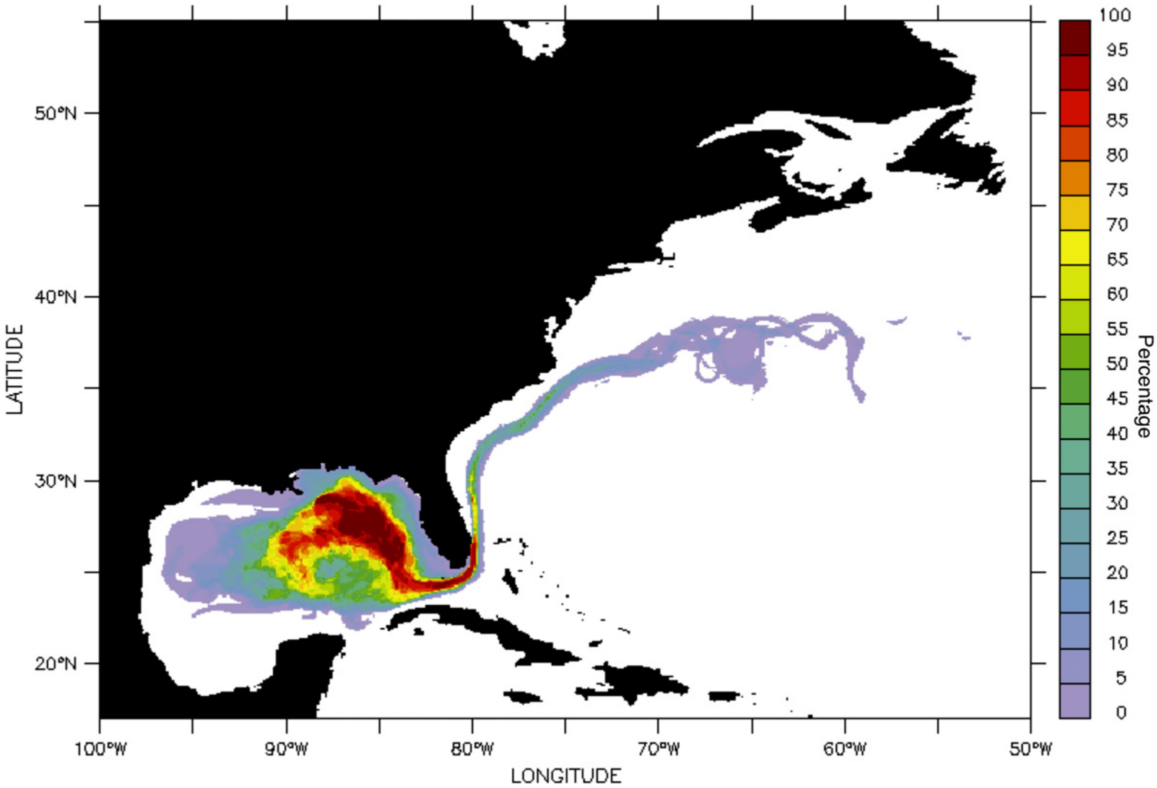

Figure 2. Percentage of ensemble members where dye (based on a 0.01 dilution factor) has reached a given location 190 days after the start of a two-month dye release.

cases in which dye reaches the coastlines of North or South Carolina.

The presence of dye in figure 1 does not necessarily imply that there is a high probability that dye will reach a given place. Information about the likelihood that dye will be transported to a given location is illustrated in figure 2, which shows the percentage of ensemble members that have reached each grid point 190 days after the initial spill.

The dark red color in figure 2 indicates locations for which all ensemble members have experienced a dye dilution factor in excess of the threshold value of 0.01. On the other end of the scale, the grayish regions indicate that very few of the ensemble members show dye having arrived there in the 190 days after the spill began. The model results indicate that it is very unlikely that there would be any dye transported by ocean currents near the shorelines of Texas, Mexico, Cuba, or the Bahamas 190 days post-spill. It is also unlikely that a concentration of dye with a dilution factor greater than 0.01 would be expected on the coast on most of the eastern seaboard of the United States on this timeframe. Conversely, there is a high chance that dye will be present in the Florida Current and in the Gulf Stream at 190 days post-spill. By 190 days post-spill, dye from most of the ensemble members has not yet made it (again, at a 0.01 threshold) into the interior of the Atlantic Ocean; the longer timescales required for dye to be mixed over large regions of the Atlantic Ocean are discussed in section 3.2.

A measure of the total export of dye from the Gulf of Mexico into the Atlantic Ocean is provided by the relative volume of dye east of 81°W (figure 3), which shows a remarkable spread across the 20-member ensemble. The simulation with the lowest export leaves more than 75% of the dye in the Gulf of Mexico six months after the initial release. On the other extreme, one ensemble member has

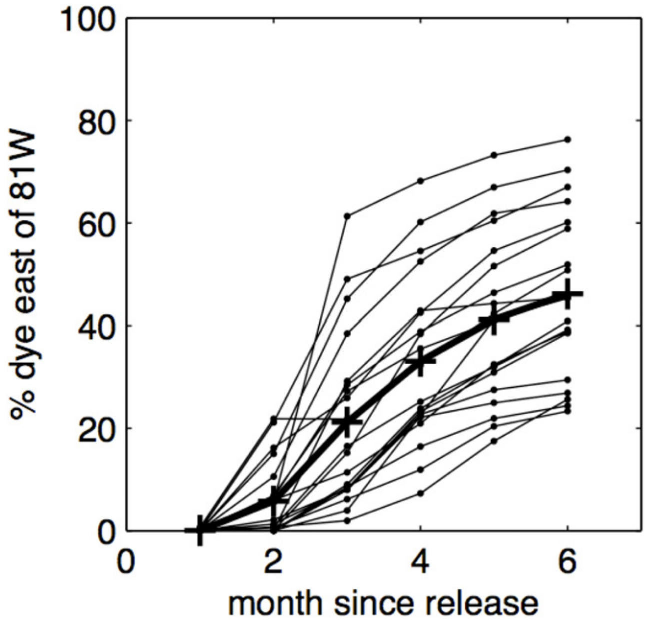

Figure 3. Percentage of total dye that exits the Gulf of Mexico at 81°W for all 20 ensemble members (thin lines). The thick line with '+' symbols denotes the ensemble mean.

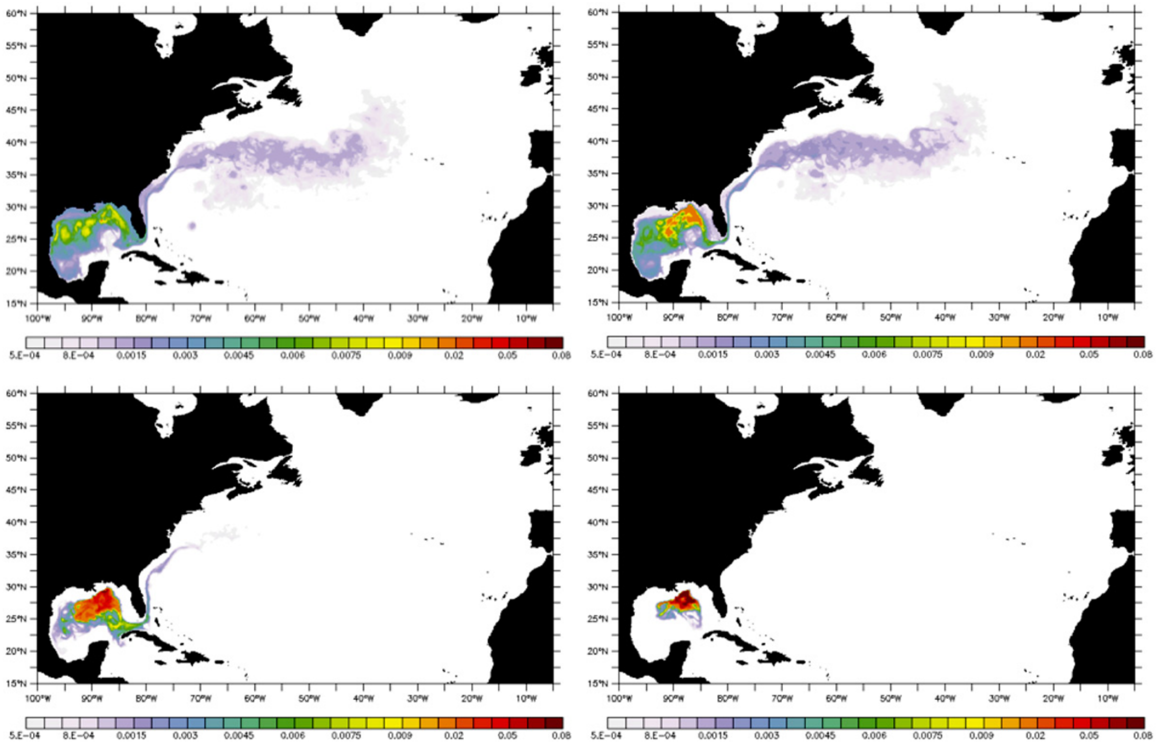

Figure 4. Mean dilution factors based on a five-member ensemble one year after the initial spill: (a) dye release at 0–20 m depth; (b) dye release at 20–210 m depth; (c) dye release at 210–800 m depth; (d) dye release at 800–1500 m depth. Color represents dilution factor on a logarithmic scale.

already exported more than 75% of the dye into the open North Atlantic Ocean after only four months.

3.2. Five-member ensemble with four-month dye source

When we began our simulations (mid-May 2010), oil had been entering the Gulf for about a month, so we needed to speculate how long the spill would continue. With little information available, we chose to shut off the dye source after two months. However, as various attempts to stop the leak were not fully successful, we decided to perform additional runs (a five-member ensemble) with a four-month duration continuous dye source under the assumption that the oil spill would be capped sometime in late August 2010 after the completion of the relief wells. These four-month continuous source simulations are intended to provide a 'worst-case scenario' envelope of possible trajectories and dilution factors for the dye dispersal.

In contrast to the six-month duration of the two-month source simulations, each member of the five-member ensemble was run for a year past the date of the spill, and results from these simulations give an idea of the possible longer-term dispersal of a dye released at the site of the Deepwater Horizon incident. If the flow from the well was significantly reduced prior to late August, or if the majority of the oil was captured on the surface before late August, the dilution factors would be expected to be lower than suggested by the modeling results herein.

The upper left panel of figure 4 shows the ensemble mean dilution factor (for the surface dye from the five-member ensemble with the four-month duration dye source) one year after the date of the initial spill. One year post-spill, it is very likely that dye will have entered the North Atlantic Ocean via the Gulf Stream and have become highly diluted and mixed in the upper water column. Low concentrations of dye are apparent along the entire Gulf of Mexico coast, as well as the eastern seaboard of the United States up to the latitude of Cape Hatteras, North Carolina, though this does not imply that oil will actually reach the shore in these locations. The simulations also show that one year is not long enough for any dye to reach the coast of Europe or Maritime Canada.

3.3. Summary of results for deeper tracers

In addition to the surface dye, the simulations carried three additional dye releases at greater depths to better understand the vertical dependence of the dye transport. Figure 4 shows the ensemble mean dilution factor for these subsurface dyes across the five ensemble members at 12 months after the initial spill date. For the 20–210 m dye injection, both the dilutions and the spatial extent are very similar to the surface dye. There are also strong similarities between the spatial distribution of the 210–800 m dye and those at higher levels in the water column. This dye does not show up in high concentrations on the continental shelf areas, which are sufficiently shallow that this deep dye has difficulty reaching these regions. There is a signature of the 210–800 m depth dye in the Florida Current and Gulf Stream, although the amount of this dye that enters the Atlantic Ocean is significantly smaller than for the dyes injected higher in the water column. The broad similarity in the spatial distribution of the dyes in the upper 800 m of the water column is to be expected, given that Florida Current and Gulf Stream system extends to a depth of about 800 m [14].

The ensemble mean dilution for the dye released between 800 and 1500 m depth shows a very different behavior compared to the shallower dyes. Because of sluggish currents at these depths relative to higher in the water column, the dye spreads extremely slowly and is still largely confined to an area within a few hundred miles of the spill site one year later. Because this deep dye undergoes relatively little mixing and advection, the dilution factors are much higher one year after the spill than for the shallower dyes, showing values as high as 0.1 (a ten-fold dilution relative to the source) after one year.

4. Discussion and conclusions

The goal of this study was to provide a range of scenarios tracking where a dye released at the Deepwater Horizon spill site might be likely to go and to provide estimates of the possible range of timescales over which dye would be likely to exit the Gulf and join the basin scale surface circulation in the Western North Atlantic Ocean. While it is not possible to deterministically forecast the fate of the oil on a timescale of weeks to months, it is possible to run a large number of ocean model simulations, each of which is characterized by a very different Loop Current evolution, and obtain an statistical (ensemble averaged) understanding of where a passive dye released at the site of the spill is likely to go and on what timescales.

It should be re-emphasized that the model described here is not a forecast model (such as a weather prediction model). The model ocean state knows nothing of the state of the true ocean in April 2010; that is, no data from satellites, buoys, floats, cruises, etc, are used to guide the integration of the model. This is why an ensemble of simulations is required to bracket the range of likely outcomes under climatological atmospheric forcing. It is also important to note that the actual evolution of the Loop Current (as observed by satellite altimetry) exhibited the shedding of an eddy, which our simulations indicate will skew the exit of oil from the Gulf toward longer times.

The dye tracer employed here is essentially a 'food coloring' which is best regarded as the sum of oil plus an oil–water–dispersant mixture, yet has no physical resemblance to true oil. This dye is not buoyant (it has the same density as the surrounding water), it does not coagulate or form slicks, is not exposed to surface containment efforts, and is not subject to physical, biological, or chemical breakdown. If there is a small benefit to the modeling community resulting from this disaster, it is that more advanced models of the behavior of oil in seawater will probably be developed.

One important question is that of how sensitive the arrival time of dye at a given location, and its spatial extent, is to the duration of the source at the spill site. We have compared model results of dye dispersal resulting from a two-month source with that of a four-month source. The total amount of dye that makes its way into the Atlantic Ocean after six months is 50% greater when the source is four months in duration than for a two-month duration source. A single simulation was also carried out assuming an 85 day source (based on the observation that the leak was stopped on 15 July 2010). The dye behavior was consistent with that observed in previous runs: the spatial distribution of dye in all runs was very similar at one year post-spill, regardless of whether the assumed duration of the source was two or four months, but concentrations of dye were everywhere smaller for the shorter duration of source.

Another key question is how different the distribution of a passive dye might be from that of actual oil. Given that the neglected processes in the model would tend to reduce the concentration of oil, the spatial extent of dye predicted by the model simulations should be considered an upper bound relative to actual oil. Based on the results of these simulations, it can be concluded that if a dye with no removal terms was released at the site of the spill, there is a very high likelihood that it would be transported to the Atlantic Ocean on a timescale of months. The key difference between dye and oil is that a significant portion of the oil has been removed from the water column by direct recovery from the wellhead, burning, or skimming operations. Evaporation has also removed a significant amount of the oil from the surface, and microbial activity has likely consumed an unknown amount of the oil. Chemical dispersants have broken the oil in the tiny droplets which enable it to become mixed in the upper ocean water column, and therefore no longer visible as a surface slick. Official estimates at the time this paper went to press are that 26% 'residual' oil remains and that 24% is 'naturally or chemically dispersed' [1]. Assuming a total input of 4.9 million barrels, this leaves approximately 2.45 million barrels (or around 103 million gallons) of oil in Gulf waters in early August 2010. Because the Gulf's Loop Current detached and formed an eddy in the central Gulf in early June, which persisted through June and July 2010, there was no clear pathway for oil to exit the Gulf over this time period. When the Loop Eddy propagates to the west and the Loop Current re-establishes itself, it will begin to transport waters from the northern Gulf southward, and ultimately into the Atlantic Ocean. Because very little oil remains in the form of a surface slick in early August 2010, it will be oil that is either dissolved or dispersed in the water column (the oil–water–dispersant mixture) that is transported out of the Gulf. Unless this subsurface oil can be completely degraded on a timescale of months, then it is very likely that there will be dissolved or dispersed oil transported out of the Gulf and into the Atlantic Ocean.

Thus, despite all the above caveats associated with the model simulations, it is possible to conclude with a high degree of confidence that dissolved oil, or oil–water–dispersant mixture, is likely to enter the Atlantic Ocean within roughly six months from the initial spill date. The amount of oil may be significantly reduced, however, if physical, chemical, and biological processes act strongly on timescales of weeks. In addition, if the oil leaving the Gulf is in the form of tiny droplets in the water column, it will not be detectable as a surface slick, so comprehensive subsurface measurements may be required. Since the model dye remains offshore in the Gulf Stream, it appears to be unlikely that large amounts of oil will reach the shores of eastern North America unless it is driven there by strong winds or small-scale currents. It is even more unlikely that any of the oil or oil–water–dispersant mixture released in the Deepwater Horizon incident will reach Europe in detectable amounts; rather it will most likely become highly diluted in a region centered around the Gulf Stream within the North Atlantic Ocean. It is likely that long-term ecological and coastal impacts will be small within the Atlantic Ocean due to a considerable amount of dilution, but these impacts remain unquantifiable at this time.

Acknowledgments

The simulations described here were performed at the New Mexico Computer Applications Center and at the National Center for Computational Sciences.

References

[1] *National Incident Command (NIC) Report: BP Deepwater Horizon Oil Budget: What Happened to the Oil?* www.deepwaterhorizonresponse.com/posted/2931/Oil_Budget_description_8_3_FINAL.844091.pdf

[2] Schmitz W and Richardson P 1991 On the sources of the Florida current *Deep-Sea Res.* **38** (Suppl. 1) S379–409

[3] Gulf of Mexico Altimeter Viewer, Real-Time Altimetry Project, Colorado Center for Astrodynamic Research http://argo.colorado.edu/~realtime/gsfc_gom-real-time_ssh/

[4] The West Florida Shelf ROMS hindcast/forecast system from University of South Florida, the Gulf of Mexico HYCOM nowcast/forecast system from Naval Research Laboratory, the SABGOM nowcast/forecast system from North Carolina State University, the Global HYCOM + NCODA Analysis from the HYCOM Consortium, and the RTOFS (Atlantic) hindcast/forecast system from NOAA Environmental Modeling Center (http://ocg6.marine.usf.edu/~liu/oil_spill_ensemble_forecast.html)

[5] Dukowicz J K and Smith R D 1994 Implicit free-surface method for the Bryan-Cox-Semtner ocean model *J. Geophys. Res.* **99** 7991–8014

[6] Maltrud M, Bryan F and Peacock S 2010 Boundary impulse response functions in a century-long eddying global ocean simulation *Environ. Fluid Mech.* **10** 275–95

[7] Lee M M, Nurser A J G, Coward A C and DeCuevas B A 2009 Effective eddy diffusivities inferred from a point tracer in an eddy-resolving ocean model *J. Phys. Oceanogr.* **39** 894–914

[8] Large W and Yeager S 2004 Diurnal to decadal global forcing for ocean and sea–ice models: the datasets and flux climatologies *NCAR Technical Note TN-460+STR* National Center for Atmospheric Research

[9] Hurrell J, Hack J, Shea D, Caron J and Rosiniski J 2008 A new sea surface temperature and sea ice boundary data set for the community atmosphere model *J. Climate* **21** 5145–53

[10] Large W and Pond S 1982 Sensible and latent heat flux measurements over the oceans *J. Phys. Oceanogr.* **12** 464–82

[11] JAG, *Report of the Joint Analysis Group 2010* www.noaa.gov/sciencemissions/PDFs/JAG_Report_1_BrooksMcCall_Final_June20.pdf

[12] Oil in the Sea III: Inputs, Fates, and Effects. Ocean Studies Board; Marine Board; Transportation Research Board 2003

[13] Adcroft A, Hallberg R, Dunne J P, Samuels B L, Galt J A, Barker C H and Payton D 2010 Simulations of underwater plumes of dissolved oil in the Gulf of Mexico *Geophys. Rev. Lett.* at press (doi:10.1029/2010GL044689)

[14] Sturges W, Chassignet E and Ezer T 2004 *Strong Mid-Depth Currents and a Deep Cyclonic Gyre in the Gulf of Mexico: Final Report* US Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Regions, New Orleans, LA. OCS Study MMS 2004-040, 89 pp