



REVISITING THE DEEPWATER HORIZON SPILL: EFFECTS OF OIL DROPLET SPECTRA FORMULATIONS AND RIVER FRONTS

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The ***Deepwater Horizon* oil spill** (also referred to as the **Macondo blowout**) was an industrial disaster that began on 20 April 2010, in the Gulf of Mexico on the BP-operated Macondo prospect, considered to be the largest marine oil spill in the history of the petroleum industry.

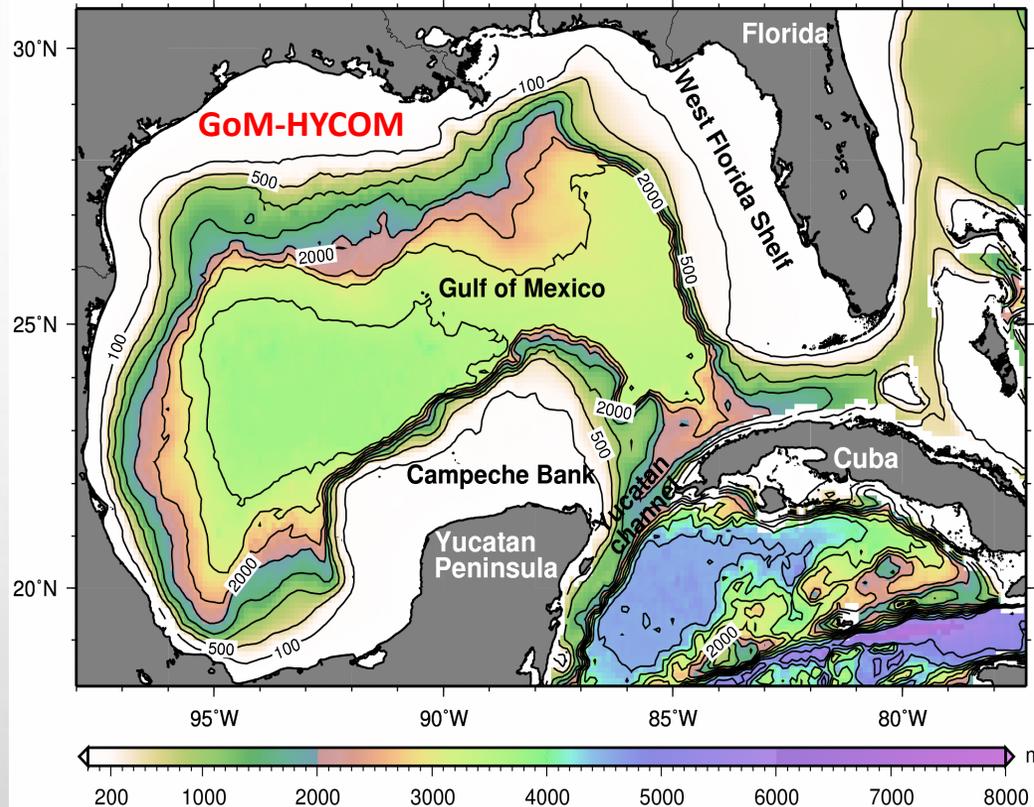
The U.S. Government estimated the total discharge at 4.9 million barrels (780,000 m³). After several failed efforts to contain the flow, the well was declared sealed on 19 September 2010.

FOCUS OF THIS STUDY

- The study is motivated by recent advances in the understanding of the role that river induced fronts and circulation patterns dominated by river plume dynamics may play in the transport of hydrocarbons.
- We focus here on the DWH spill of April-July 2010. A first set of simulations for the period of are carried out to illustrate the effect of oil droplet size distribution. A second set looks at the effect of river fronts.

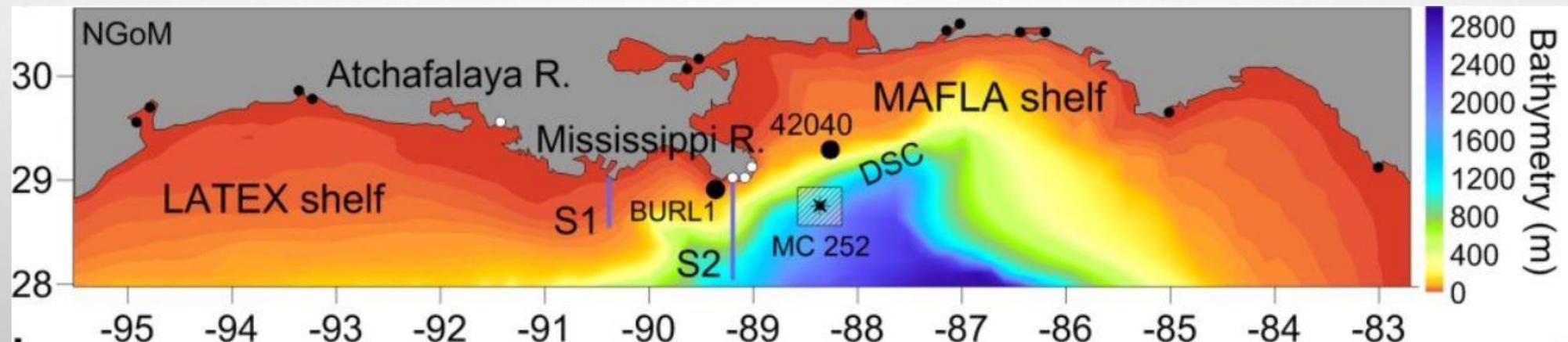


High resolution hydrodynamic model
Gulf of Mexico Hybrid Coordinate Ocean Model (1/50 deg. ~ 1.8 km)
Univ. of Miami/RSMAS <http://coastalmodeling.rsmas.miami.edu>



- ❑ Coastal to offshore interactions well represented (*Le Hénaff and Kourafalou, OceDyn., 2016*)
- ❑ Detailed river plume dynamics; (*Schiller & Kourafalou, OceMod. 2010*)
- ❑ Daily river inputs / all major rivers
- ❑ Atmospheric Forcing: COAMPS, NAVGEM, ECMWF

Close-up of region: NGOM-HYCOM Model domain and bathymetry (m) map indicating the main features, such as continental shelves, deep basins, the desoto canyon (DSC); all river sources are marked with small black circles, except for atchafalaya and mississippi river (MR) input locations that are marked by small white circles (the MR input is distributed in three locations, from west to east: southwest pass, south pass, and pass A loutre); the large black circles designate the positions of the NOAA buoy stations 42040 (29.21°n, 88.21°W) and BURL1 (28.90°n, 89.43°W) *influence of mississippi river induced circulation on the deepwater horizon oil spill transport*
kourafalou and androulidakis, 2013



Estimate of oil spilled into the Gulf through May 20

In millions of barrels of oil.



Ixtoc I
3.3

Gov't est.
1.8

Exxon Valdez
0.3

VIEW 100-DAY
COMPOSITE



Map Key

- Estimated extent of oil on surface
- Surveyed extent
- Fishing ban
- Loop current
- Marshes
- Urban areas
- Reports from locations where oil has made landfall

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THE FATE OF OIL IN THE OCEAN

*The fate and transport of a surface oil slick over time is controlled by varying components of **winds** and **currents**, the **turbulent** movement of oil within the upper ocean, and oil **weathering** processes such as evaporation, emulsification and vertical dispersion into the water column.*

***Waves** enhance **vertical mixing** of surface oil, with the actual depth of downward mixing and its possible return to the surface dependent on wave height, turbulence, and wind, along with the **oil droplet size**, mass, and resultant buoyancy.*

OpenDrift is an open-source Python-based framework for Lagrangian particle modeling

OpenDrift allows for the ingestion of forcing fields (scalar and vectorial) from various sources, including Eulerian ocean, atmosphere and wave models, but also observations or estimates of the same variables.

CURRENT MODELS:

- HYCOM GULF OF MEXICO 10KM RESOLUTION
- ROMS NORCOAST 800M RESOLUTION NORWEGIAN COASTAL MODEL
- TOPAZ MODEL COVERING NORTH ATLANTIC
- MERCATOR GLOBAL OCEAN MODEL
- PARAMETERS ARE: U, V, S, T IN SPECIFIED MODEL LEVELS

ATMOSPHERE MODELS:

- ECMWF GLOBAL MODEL ~10 KM RESOLUTION
- AROME, A 2.5 KM RESOLUTION REGIONAL MODEL
- PARAMETERS: U10, V10

WAVE MODELS:

- WAM ECMWF GLOBAL ~10KM
- WAM 4KM RESOLUTION COVERS NORDIC SEA AND NORTH SEA
- PARAMETERS: HS, TZ, STOKES DRIFT U AND V

BATHYMETRY: RESOLUTION IS ALWAYS THE SAME AS THE CHOSEN OCEAN MODEL CURRENT RESOLUTION

MODEL CAN BE INITIALIZED FROM POINT SOURCE, OR OBSERVED POLYGON FROM SATELLITE OR PLANE

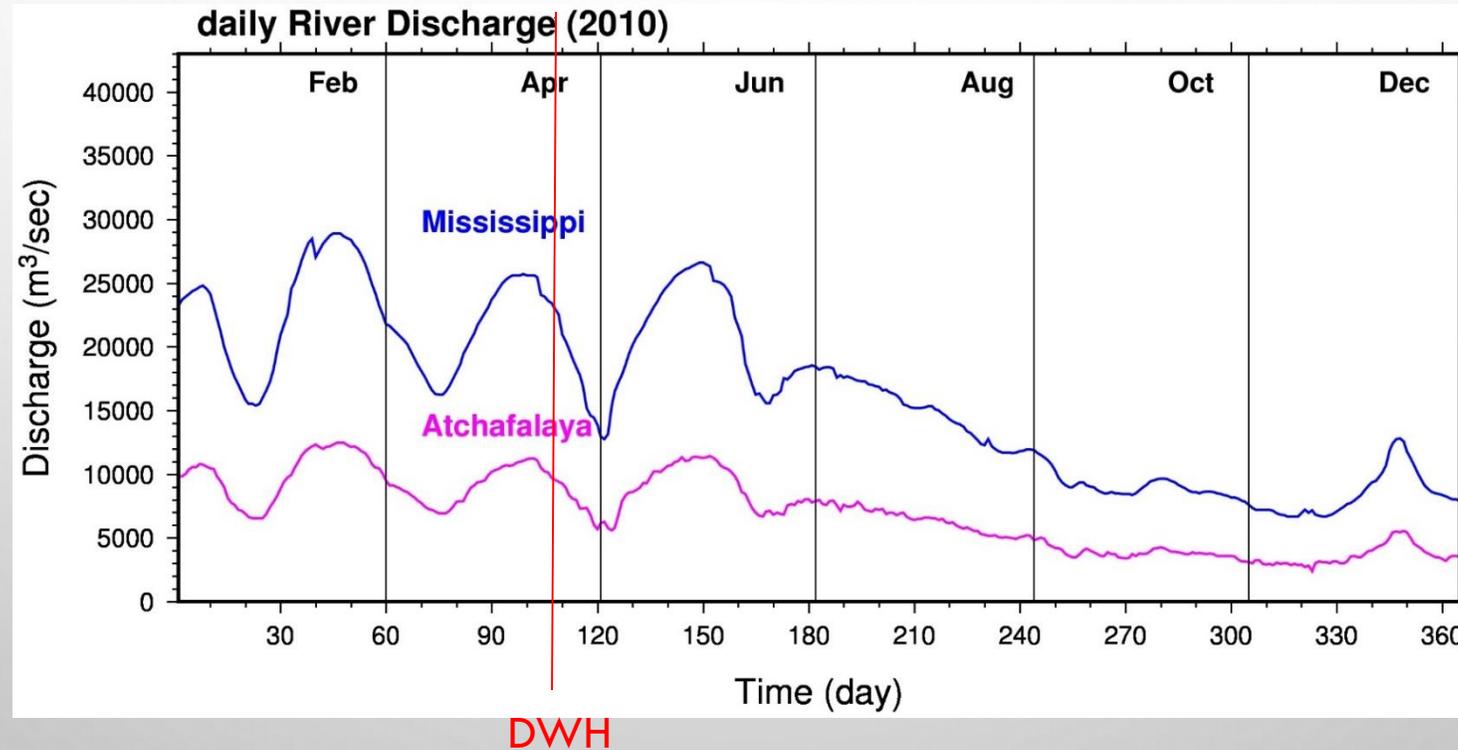
ALL INPUT CAN EASILY BE EXCHANGED WITH OTHER SOURCES, AND ALSO OTHER FORMATS.

RIVERS

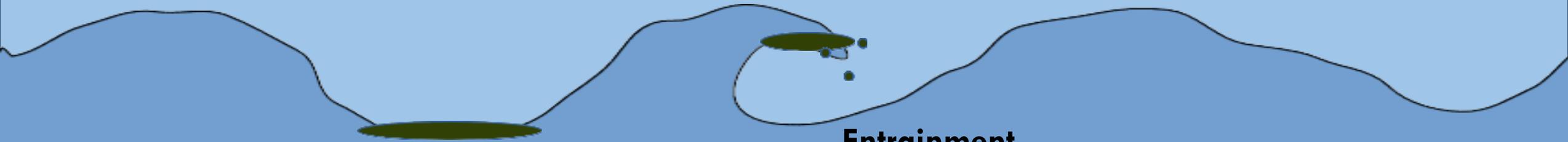
- The river plume dynamics are parameterized in the ocean model. Daily freshwater discharges are prescribed for 17 major rivers along the NGOM coastal zone.
- The development and evolution of **river induced fronts** in the northern Gulf of Mexico (GoM) is largely controlled by the Mississippi river plume and, therefore: the amount of river discharge, wind stress and interaction with offshore flows, in the presence of complex topography.
- The strong outflow discharge rates of freshwater via various passes around the delta form an extensive plume of brackish waters with several successive density fronts between the high salinity open sea and the delta (multiple fronts), as usually observed around large outflow rivers
- These frontal formations and the overall river plume evolution are controlled by changes in winds and discharge rates, especially during spring and early summer when the discharge rates usually increase. The topography and continental shelf morphology over the NGOM also attribute unique characteristics to the MR river plume patterns
- The buoyancy-driven MR plume waters have three distinct pathways that are common for large-scale rivers where the Coriolis effect is important: an anticyclonic bulge around the MR delta, a “downstream” coastal current in the direction of Kelvin wave propagation toward the LATEX shelf and an “upstream” current toward the MAFLA shelf
- During the 2010 DwH spill, periods of upstream MR plume currents kept oil away from the MAFLA coast, while periods of downstream MR plume currents entrained oil toward the LATEX coast.

Discharge from major rivers in the Northern Gulf of Mexico during spring 2010.

Daily Mississippi (blue line) and Atchafalaya river (pink line) discharges for 2010. We see four major periods of MR discharge variability: first period (22 April to 3 May, Q decreasing); second period (4 May to 1 June, Q increasing); third period (2 June to 20 June, Q decreasing); and fourth period (20 June to 15 July, Q increasing). In this paper we study the period of May – June 2010 – the third period.



Vertical motion of oil



Oil weathering: NOAA

OilLibrary:

- evaporation
- emulsification

-> strong increase in viscosity



Vertical mixing

due to turbulence

Random walk scheme: Visser (1997)

Entrainment

due to breaking waves

Entrainment rate: Li et al. (2017)



Droplet spectrum:

Johansen et al. (2015)

Buoyancy

- large droplets rise faster than small droplets

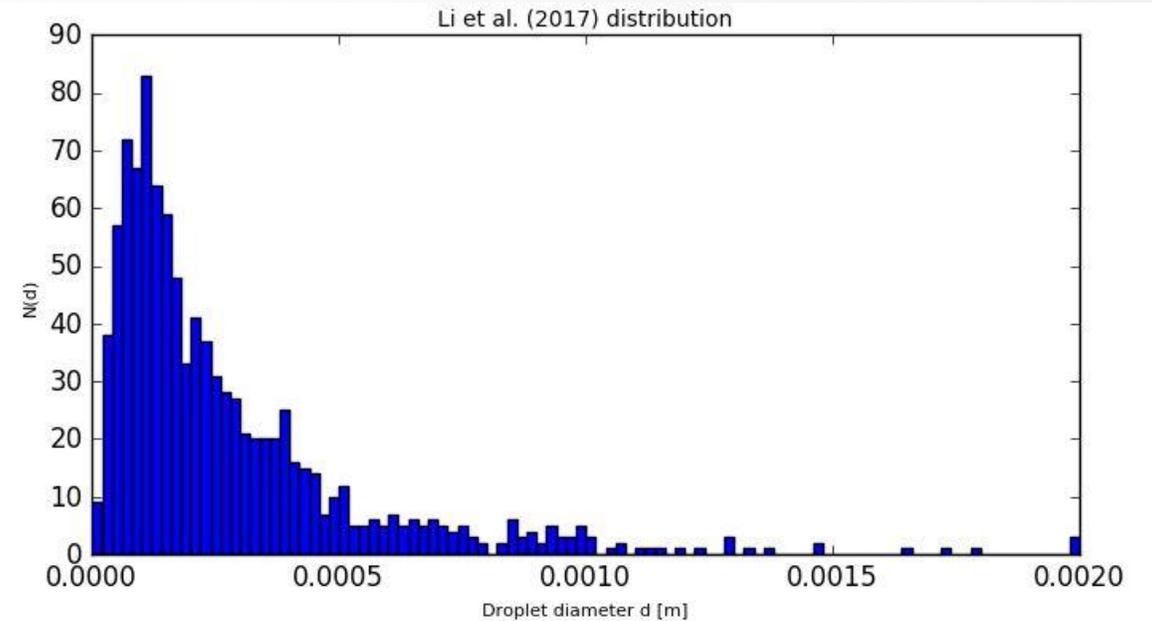
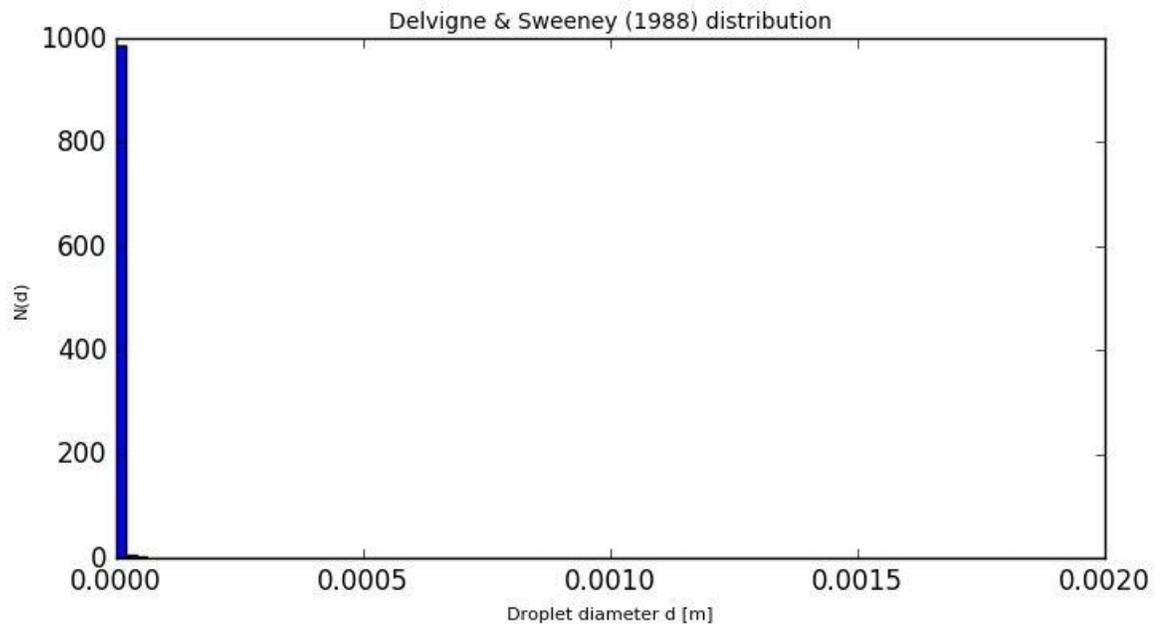
- OpenDrift includes parameterizations of the most important oil **weathering processes** in short-term (first days)
- OpenDrift uses the NOAA ADIOS library for calculations of evaporation and emulsification. The database contains characteristics of more than 1000 oil types
- Evaporation and emulsification impacts the oil drift, especially through the increase of viscosity, which has a significant impact on the wave entrainment rate and oil droplet size spectrum
- Entrained/submerged oil droplets are subject to vertical turbulence. **Vertical mixing** is one of the key components of the oil drift.
- **Oil droplet** buoyancy is important, and depends on the droplet radius. Large oil droplets are more buoyant, and will reemerge quickly at the surface to rejoin the original slick, or form new slicks. Smaller droplets may remain dispersed in the water column.
- Entrained oil will move with the ambient currents, while oil on the surface is subject to forcing from wind, waves, and surface currents.

DROPLET SIZE DISTRIBUTIONS

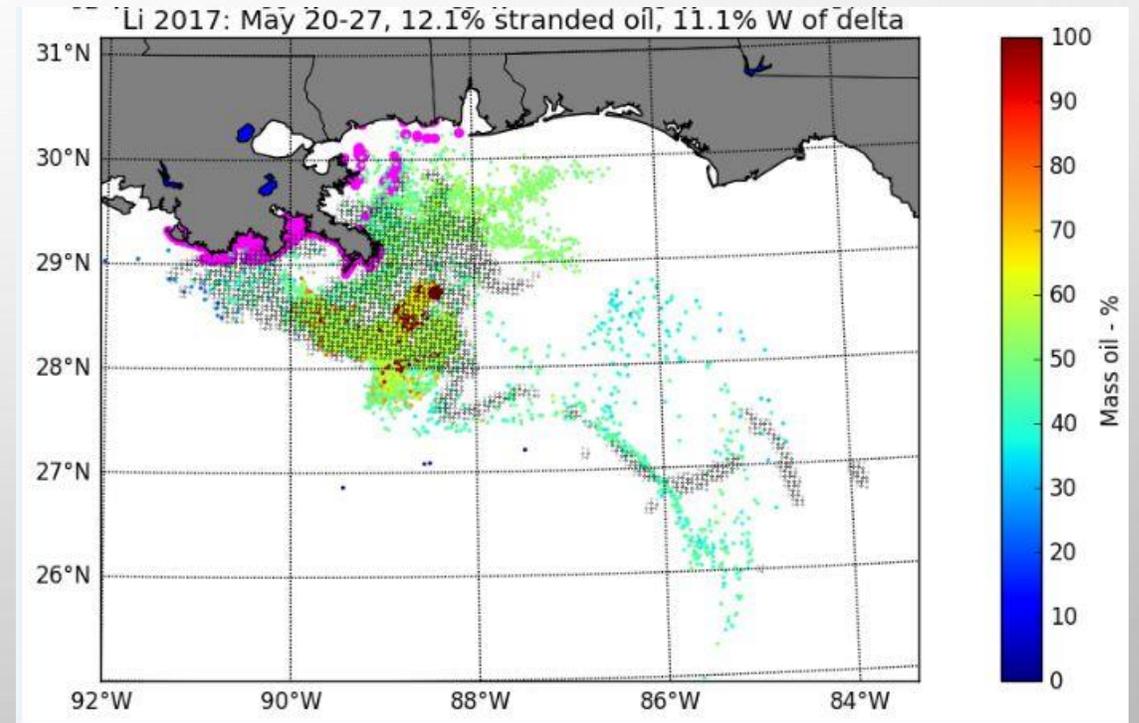
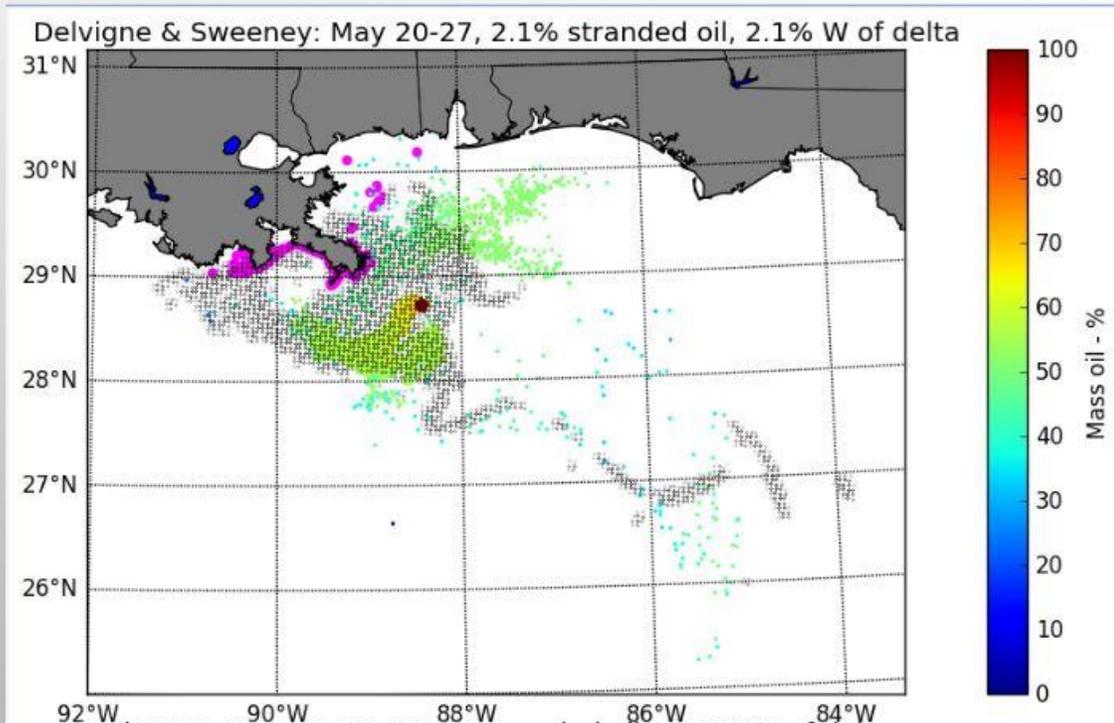
- The classical power law distribution of **Delvigne and Sweeney (1988)** (DS) is often used as the basis for modelling of natural dispersion in most oil drift and fate models today. This distribution has no dependency on oil type, weathering state, or thickness.
- With the **Li (2017)** (Li) parametrization the droplet size distribution depends on the diameters of submerged oil particles.
- The droplet size distribution is sensitive to oil type – more viscous oils will have a droplet spectrum shifted towards larger droplets, compared to less viscous oils.
- Sea state is also a factor - an increase in wave height of the breaking waves will shift the spectrum towards smaller droplets.

Oil droplet size distribution after one hour using the Light Louisiana Sweet, the BP oil type that was spilled in DWH, during 12 ms^{-1} wind.

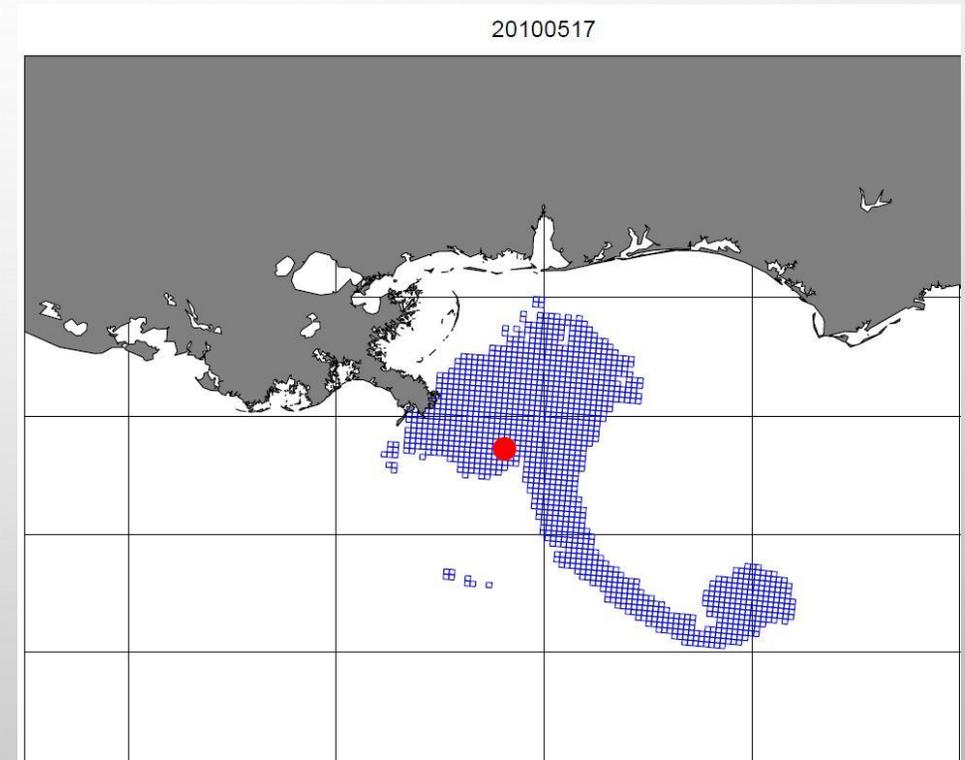
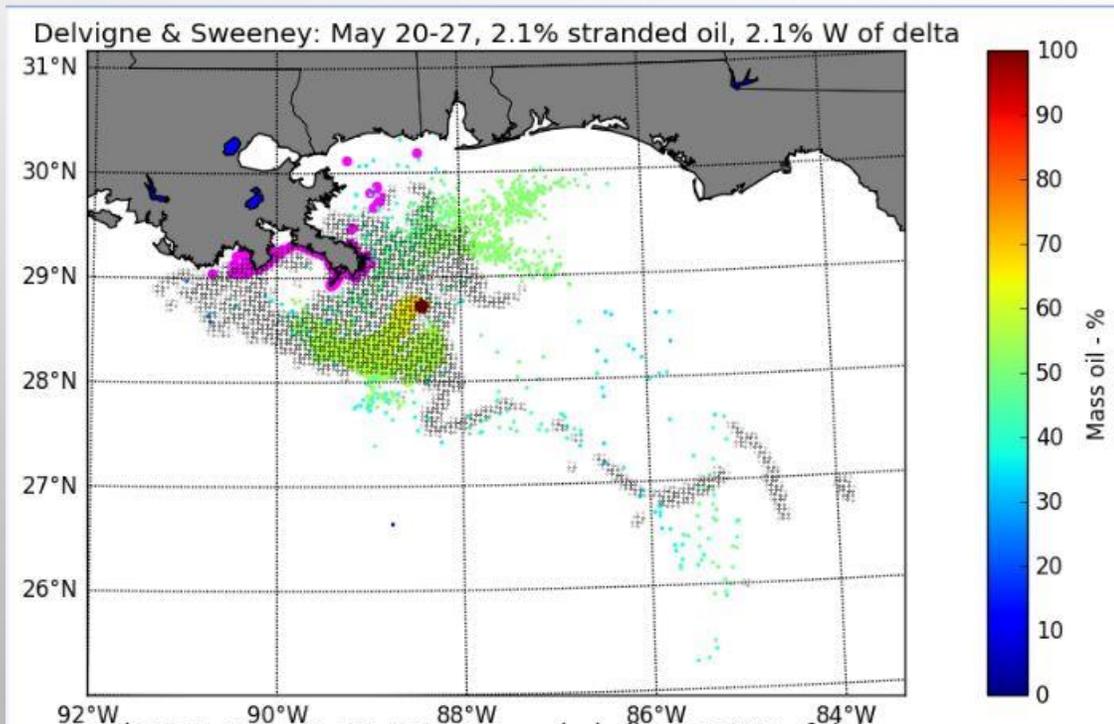
Classical Delvigne & Sweeney (1988), DS, formulation on the left and Li et al. (2017) on the right.



- OpenDrift simulations for 20-27 May 2010, using the DS oil droplet size distribution (left) and the Li et al. (2017) distribution (right).
- Around 20-25 May 2010 there was a significant outflow of the Mississippi and part of the surface oil patch was caught in the anticyclonic Loop Current resulting in a formation popularly referred to as the tiger tail.
- The Li formulation resulted in a much higher percentage of stranded oil.



- OpenDrift simulations for 20-27 May 2010, using the DS oil droplet size distribution (left) and the Li et al. (2017) distribution (right).
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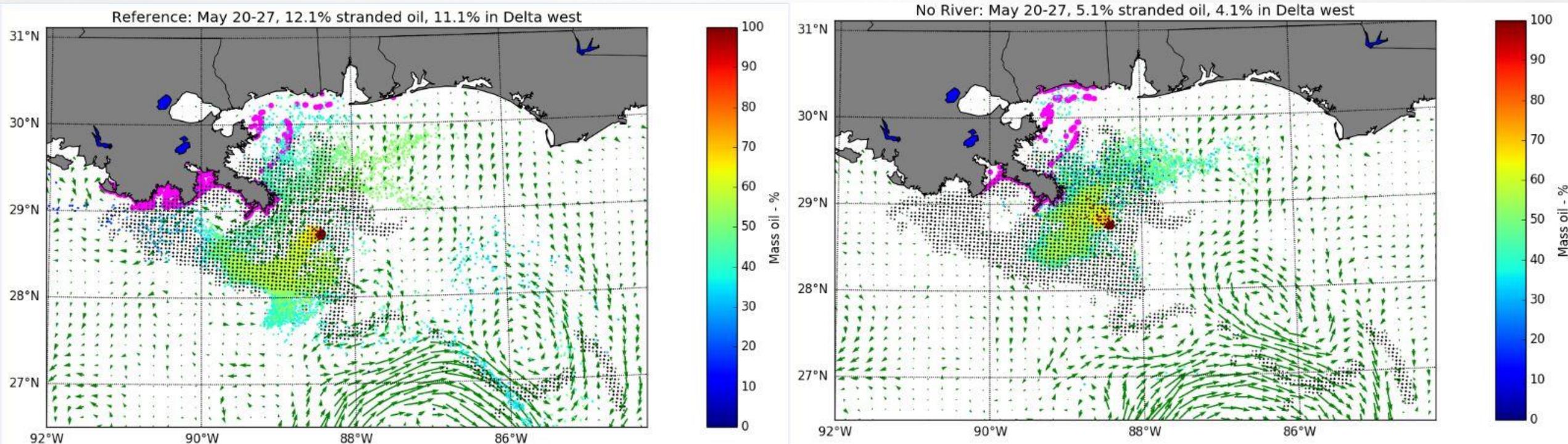
Comparing droplet size distributions

- Application of the Li formulation results in a much higher fraction of oil at the surface (about 40%) compared to DS where less than 20% is at the surface after 7 days.
- The reason for the difference is that the Li formulation provides a higher fraction of larger oil droplets which will rise faster to the surface. When a higher fraction of oil is at the surface, it will be more subject to wind and wave transport.
- The Li simulation results in about 6 times as many particles stranded after five days, particularly west of the Mississippi delta.
- At a first glance, the results in the upper and lower panels of look quite similar, but the higher fraction of oil at the surface provides more efficient transport by the wind towards the shore and larger likelihood of stranding.

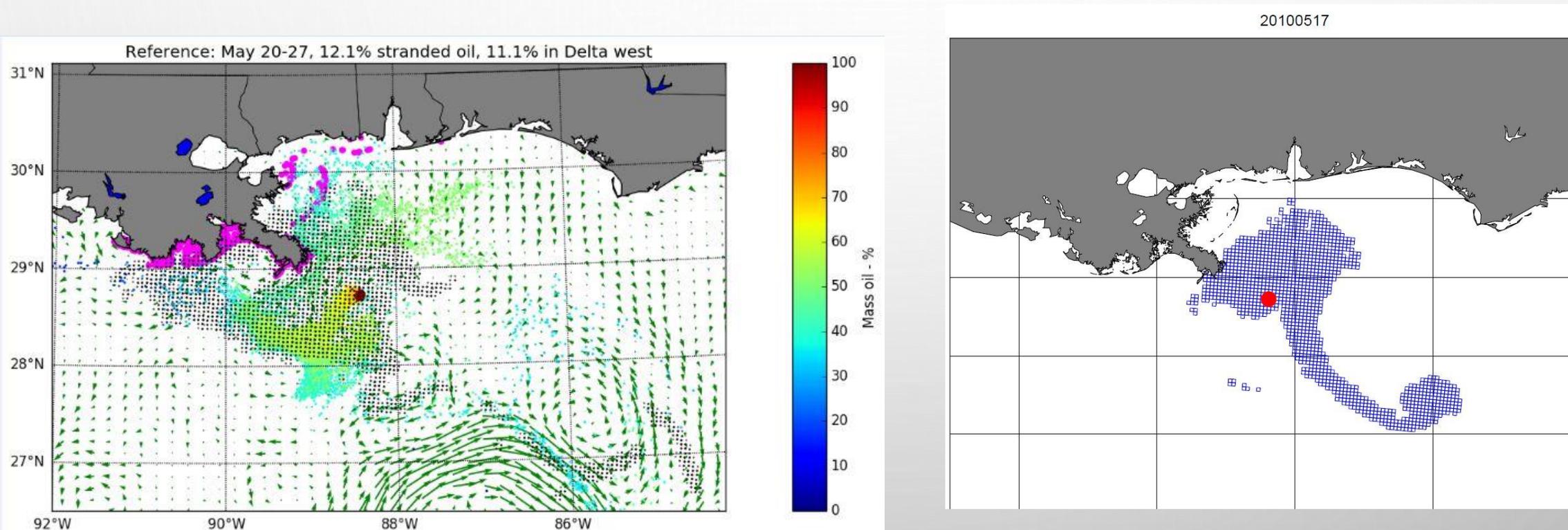
High vs lower river discharge

- Next, we try to separate the effect of realistic river discharge on the simulations.
- We carried out two simulations for the same period with high river discharge (20-27 May) and also for a period with lower discharge, 2-10 July, using the Li formulation and the same forcing data (reference experiments).
- We also applied a set of ocean forcing data with no river discharge and precipitation (no river experiments).
- Wind and wave forcing were kept the same.
- We saw how the inclusion of river discharge in the ocean forcing can have opposite (and sometimes counter-intuitive) effects on oil transport

End condition of the simulation 20-27 May 2010, showing active (at surface) and stranded oil particles. Forcing data as above. Reference simulation at top, and no river simulation below. Stranded oil is shown in magenta. The color scale indicate how much mass is left in each particle. Black dots is the surface oil patch observed by NOAA, and the green arrows are the HYCOM forcing surface currents at the last time step of the simulation.



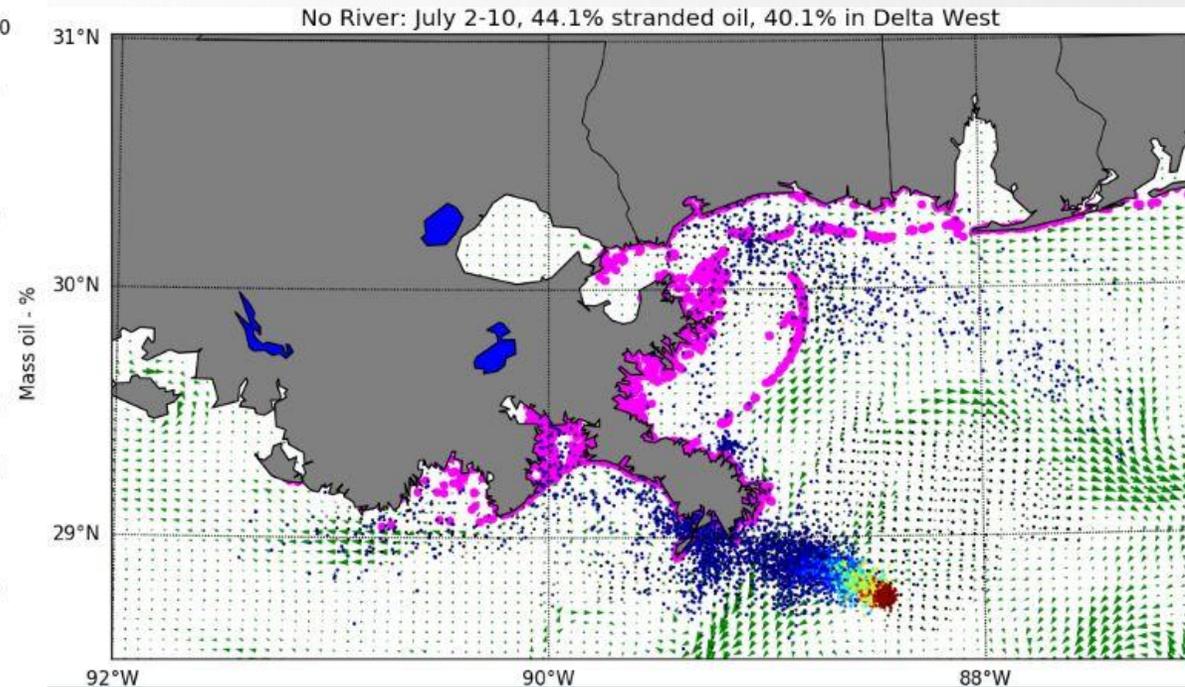
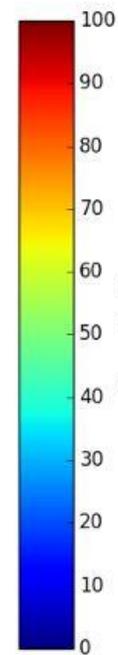
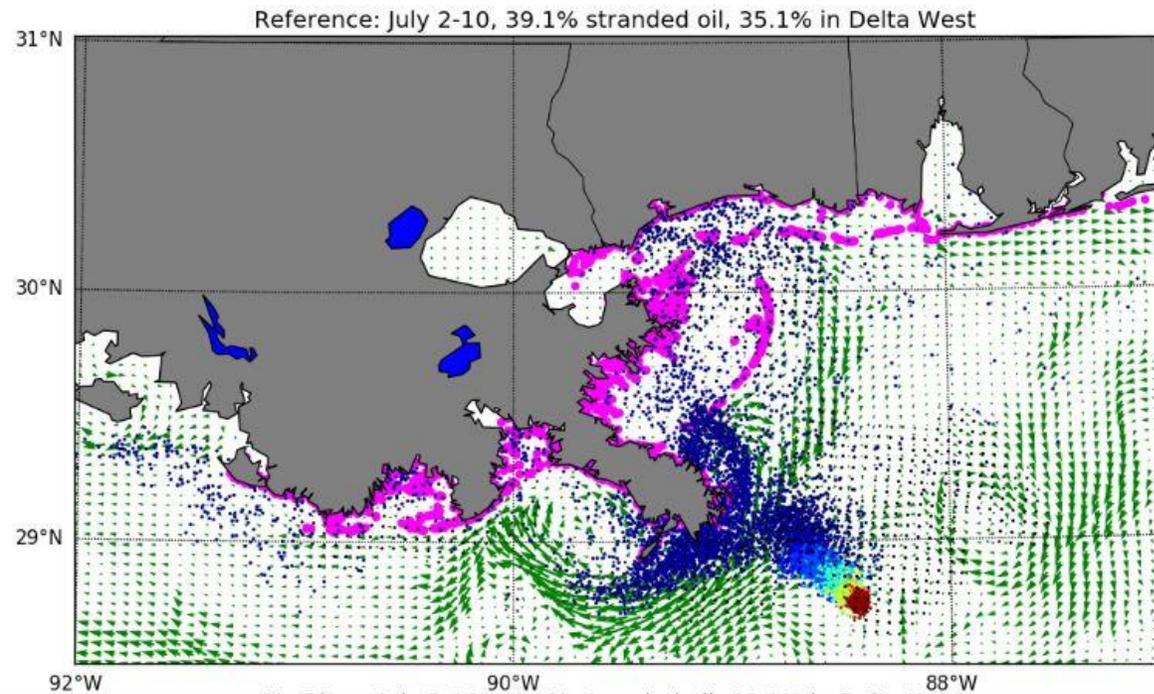
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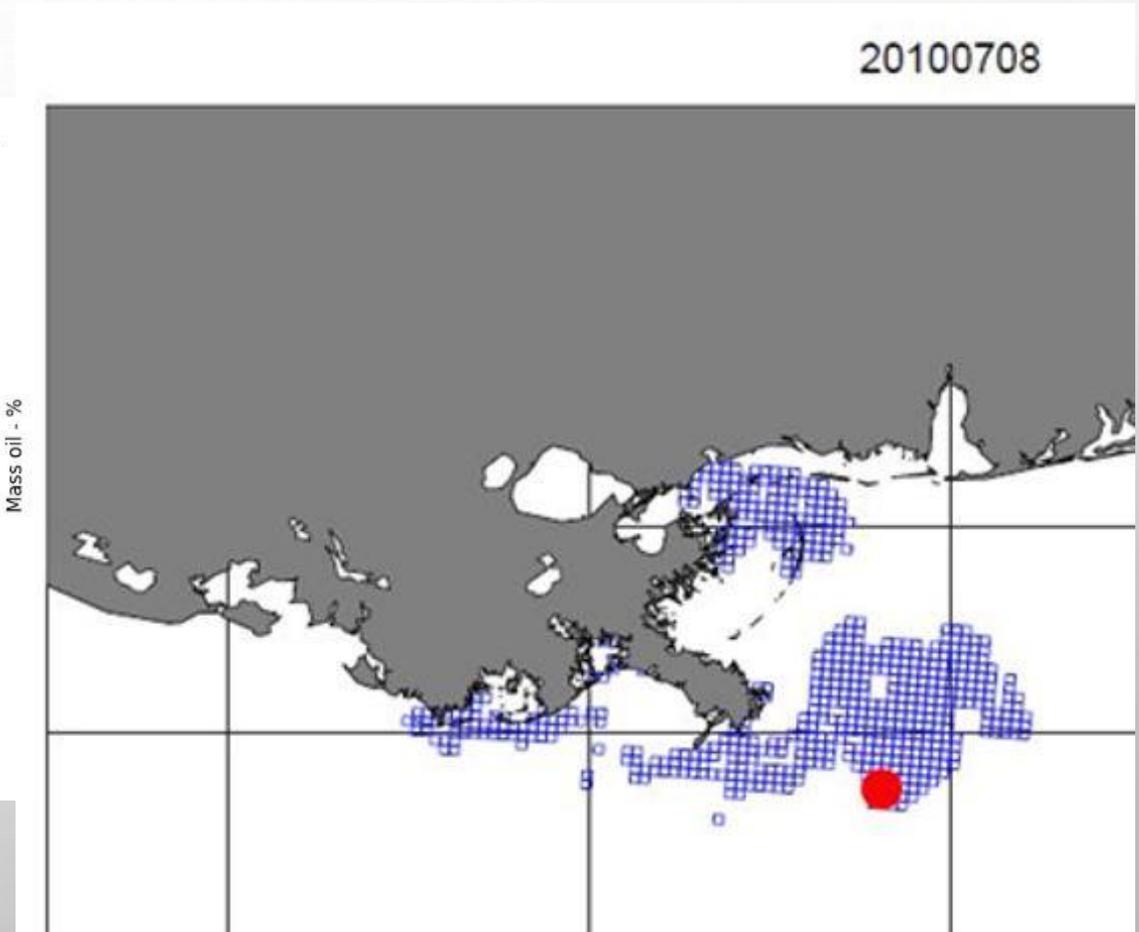
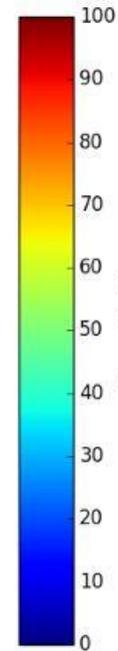
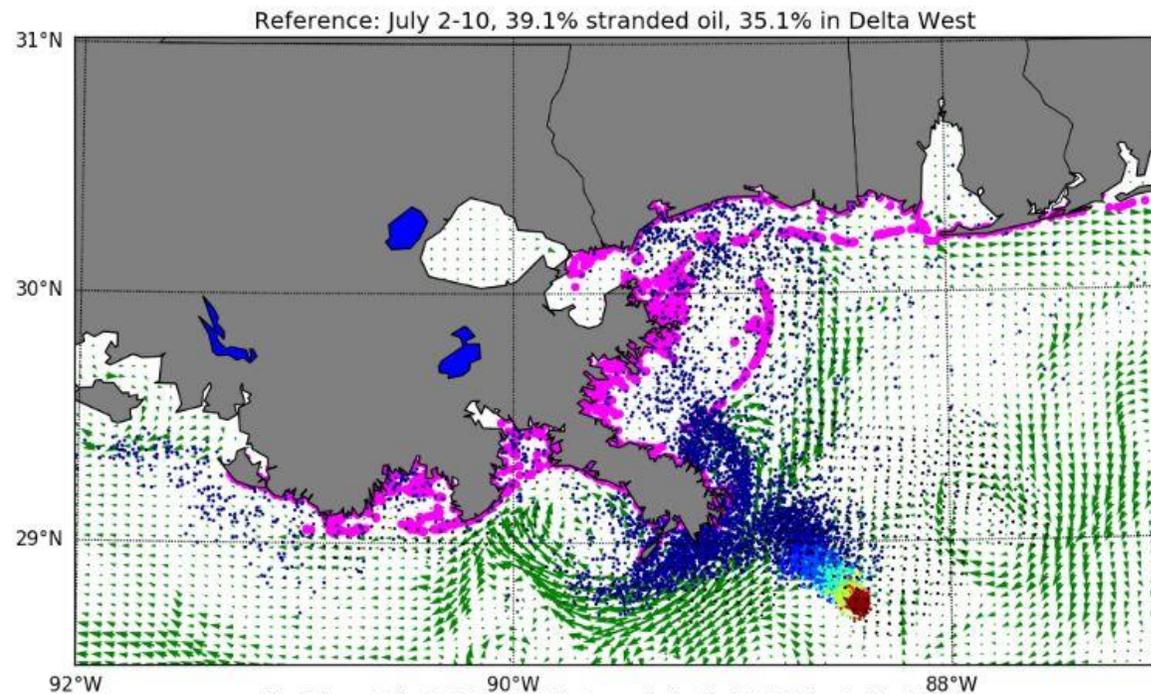
Mississippi river influence in May simulation

- The MR discharge peak around 20 May led to the formation of downstream and upstream plume areas that acted as a conduit for guiding oil toward the LATEX shelf and away from the MAFLA shelf, respectively. (Kourafalou and Androulidakis, 2013)
- The removal of the MR input in the no river experiment allowed the spreading of the oil toward the western MAFLA shelf due to the absence of the upstream currents; the stranded oil along the MAFLA coasts is more apparent in the no river case in comparison to the reference experiment.
- In contrast, the stranded oil is less along the western coasts (90W-91W) in the no river experiment due to the absence of the downstream MR plume pathway, which played a significant role on the westward spreading of oil during the DWH period.
- The "tiger tail" pathway is weaker in the no river simulation; the strength of this MR offshore jet could have been an important factor in forming the "tiger tail" oil distribution pattern as also confirmed from satellite data and confirmed with drifter data

End condition of the simulation 2-10 July 2010, showing active (at surface) and stranded oil particles. Forcing data as above. Reference simulation at top, and no river simulation below. Stranded oil is shown in magenta. The color scale indicate how much mass is left in each particle. Black dots is the surface oil patch observed by NOAA, and the green arrows are the HYCOM surface currents at the last time step of the simulation.



End condition of the simulation 2-10 July 2010, showing active (at surface) and stranded oil particles. Forcing data as above. Reference simulation at top, and no river simulation below. Stranded oil is shown in magenta. The color scale indicate how much mass is left in each particle. Black dots is the surface oil patch observed by NOAA, and the green arrows are the HYCOM surface currents at the last time step of the simulation.



Mississippi river influence in July simulation

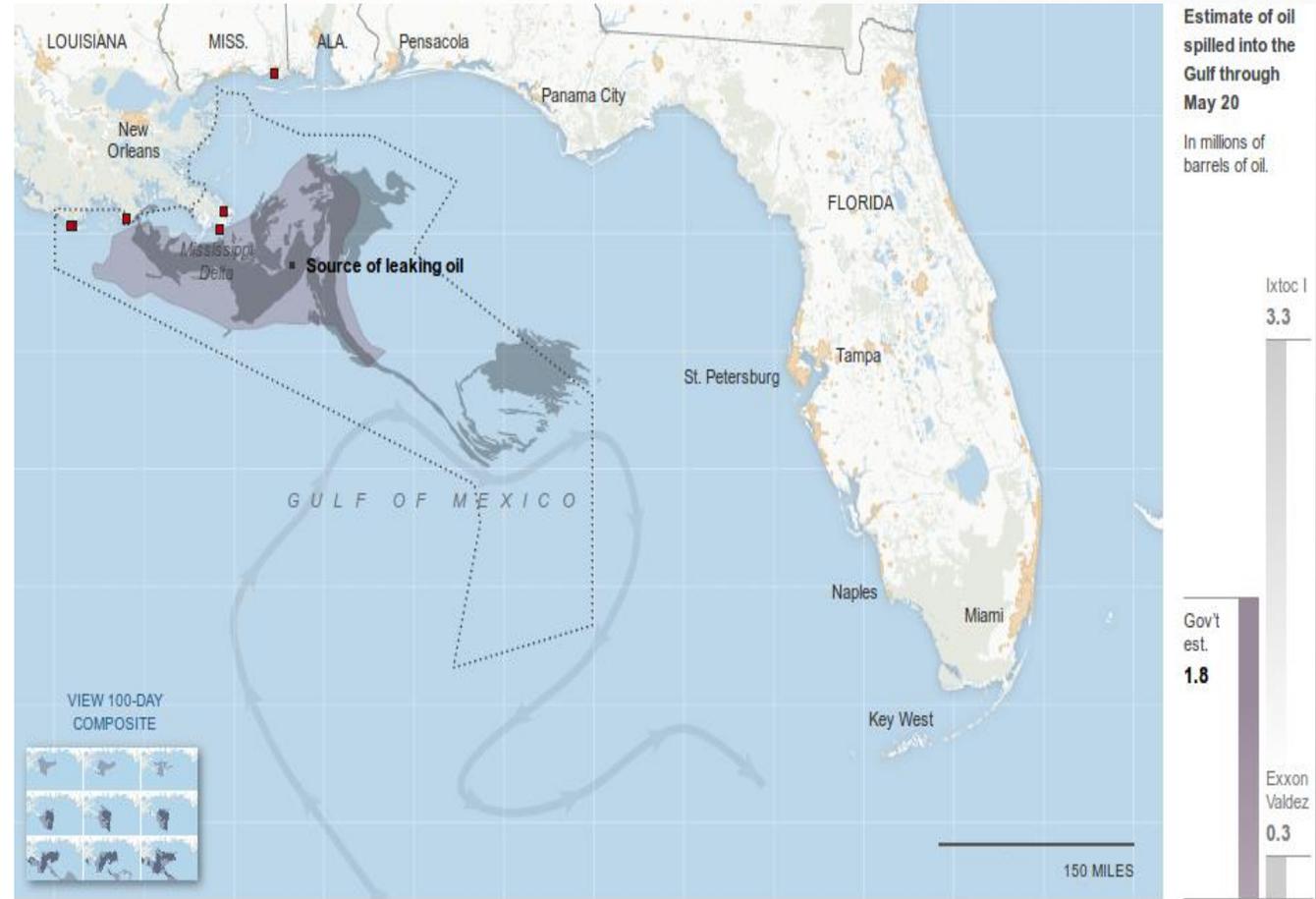
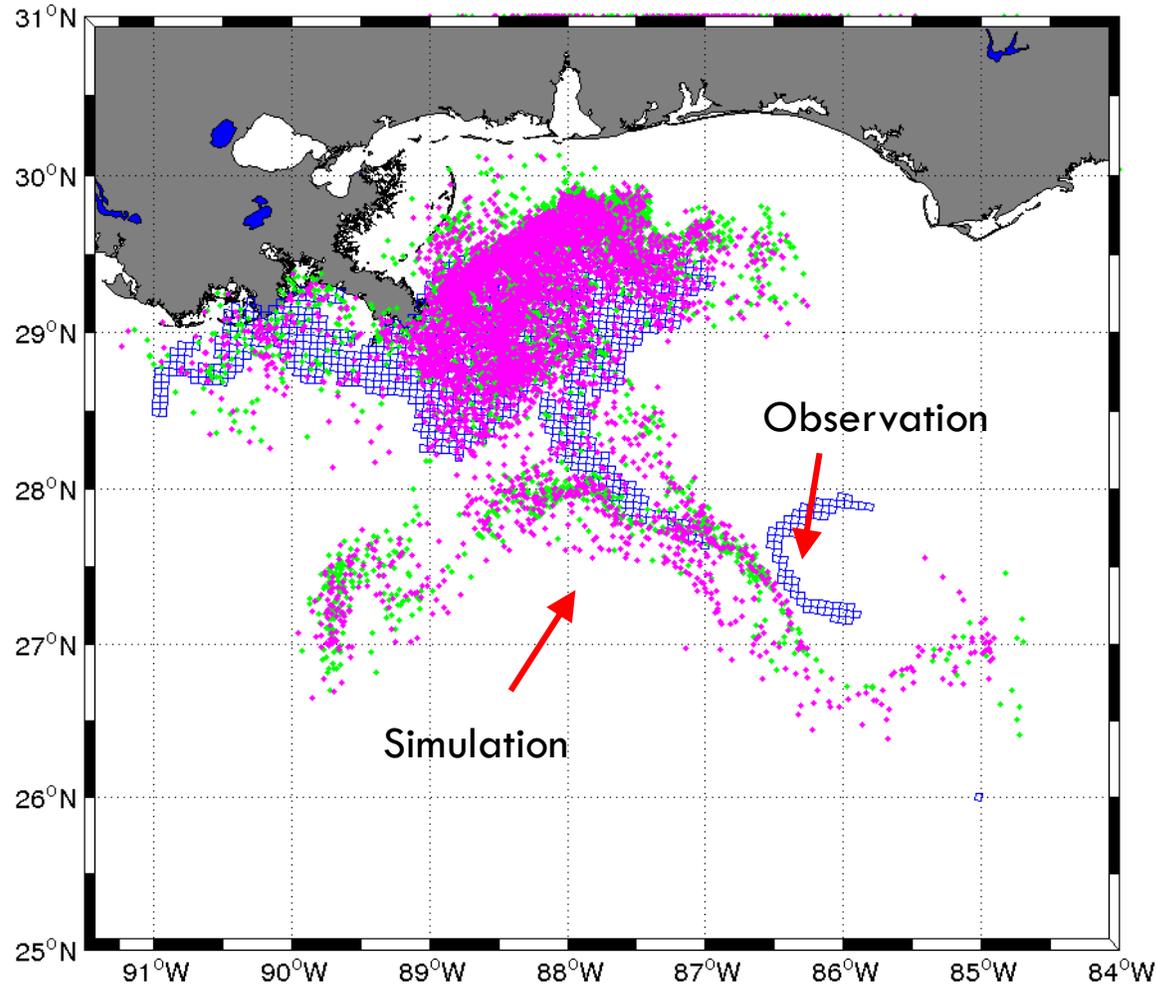
- The second simulation period (2-10 July) was right after a second high discharge period, promoting again a buoyancy-driven downstream current.
- This tendency is supported by downwelling-favorable winds, resulting in a clear westward transport of both low-salinity and oil-containing waters, along a narrow band close to the LATEX coast and surrounding the Mississippi delta; extensive coastal areas of stranded oil are apparent along the western coasts in the reference experiment.
- The removal of MR input (no river experiment) led to weaker downstream currents both close to the delta (89.5W) and along the western coasts (west of 90W) and thus less stranded oil over the same region.
- The anticyclonic bulge, common in strong discharges and source of the downstream current, is completely absent in the no river experiment. However, more stranded oil was computed closer to the delta, inside Louisiana bight in the no river case;
- it seems that the absence of the anticyclonic bulge that was able to lead surface oiled waters directly west of the Louisiana bight allowed the accumulation of oil very close to the delta.
- In contrast, no differences between the two experiments are detected over the MAFLA region due to the weaker upstream currents during early-july (Kourafalou and Androulidakis, 2013)

DISCUSSION AND CONCLUSIONS

- We have carried out several simulations of the DWH oil spill with high resolution forcing data and a Lagrangian oil spill model. Simulations were initialized from satellite observations of the Spilled Oil Patch (SOP) and a continuous point source with a realistic spill rate was placed at the sea floor
- We showed how important it is to have a realistic oil chemistry module and oil droplet size distribution, since this will influence the vertical mixing of the oil.
- Our results indicate that the use of a realistic oil droplet distribution will have significant effect on both vertical and horizontal distribution of the oil and the amount of oil stranded was increased 6-fold in the example shown here.
- Both formulations of the oil droplet size distribution result in the characteristic tiger tail shape of the SOP for the period 20-27 May 2010, but the more realistic Li formulation shows a more distinct tail in the loop current, and much more stranding in the delta west of the Mississippi river mouth in line with the observed SOP.

- One may think the removing river discharge would always bring the oil nearer to the shore, but interactions are complex. In the simulations presented here, salinity fronts in the ocean model are eliminated by removing precipitation and any assimilation of CTD profiles in addition to the daily river discharge. The no river simulations showed more stranding oil, particular close to the delta (Louisiana bight) but more stranding oil further downstream, along the LATEX shelf.
- The removal of the MR input reduced the downstream currents that were responsible for the westward transport of oiled waters along the LATEX shelf. The MR plume and the accompanying river fronts were responsible to either entrap oil close to the coasts (e.g. LATEX shelf) or keep oiled waters offshore (e.g. MAFLA shelf) due to the formation of upstream currents.
- These results are in line with the NOAA satellite observations. It is also obvious that, in the simulation with daily river discharge, the oil particles are further away from the coast and pushed into the Loop Current south of 28N and E of 88.5W. In the case with lower discharge (July 2-10), there is smaller difference in the amount of stranded oil and slightly more in the no river case. The river contribution has influence on the circulation pattern all over the northern gulf, and near shore currents are reversed and stronger, bringing the oil near the shore.
- The result showing that with no river we have less stranded oil west of the delta. This result agrees with Kourafalou and Androulidakis (2013) who showed that the downstream current can carry oil along the coast toward the west during May.
- A second interesting result is that the no river experiment has less active oil south of the delta (offshore 88.5W-28N) - the river plume keeps the oil away from the delta.

MAY 2010 SIMULATION



Estimate of oil spilled into the Gulf through May 20
In millions of barrels of oil.

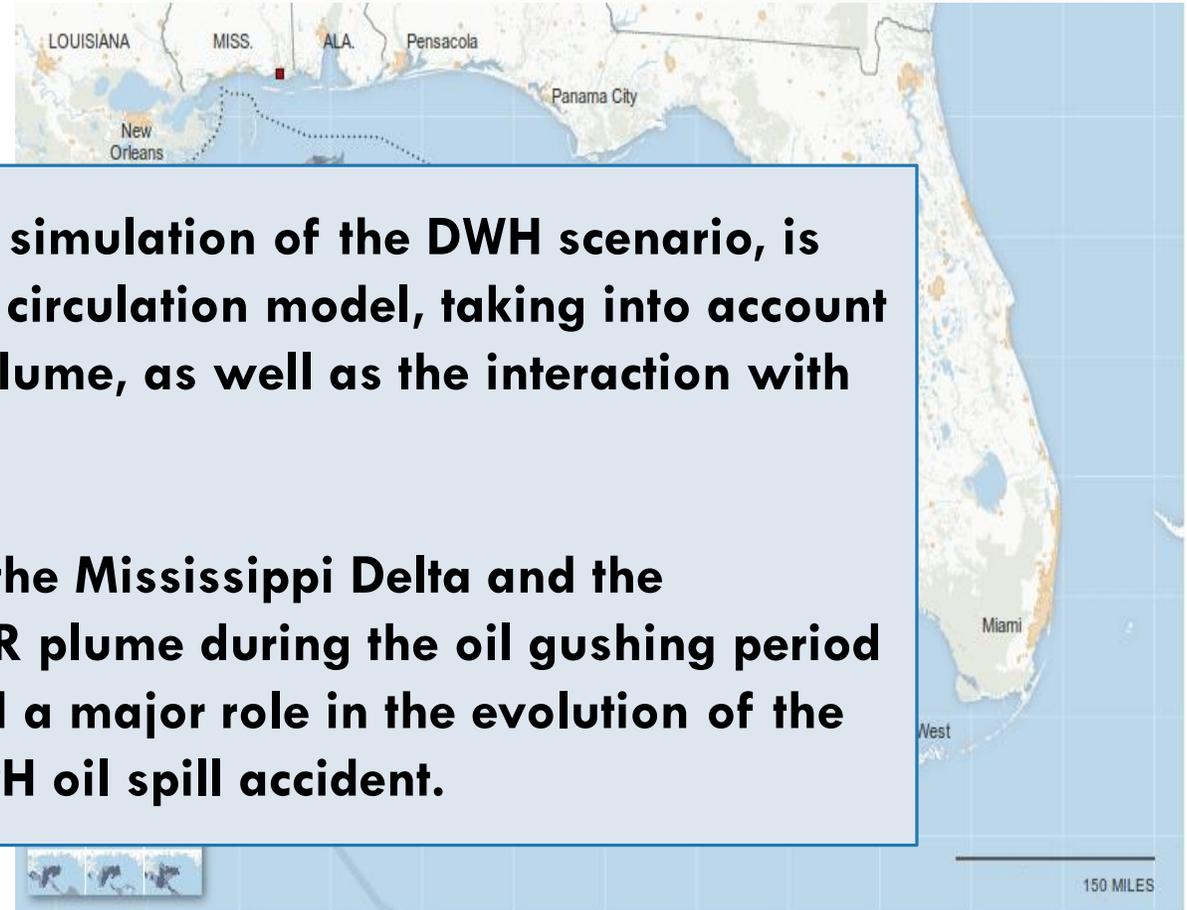
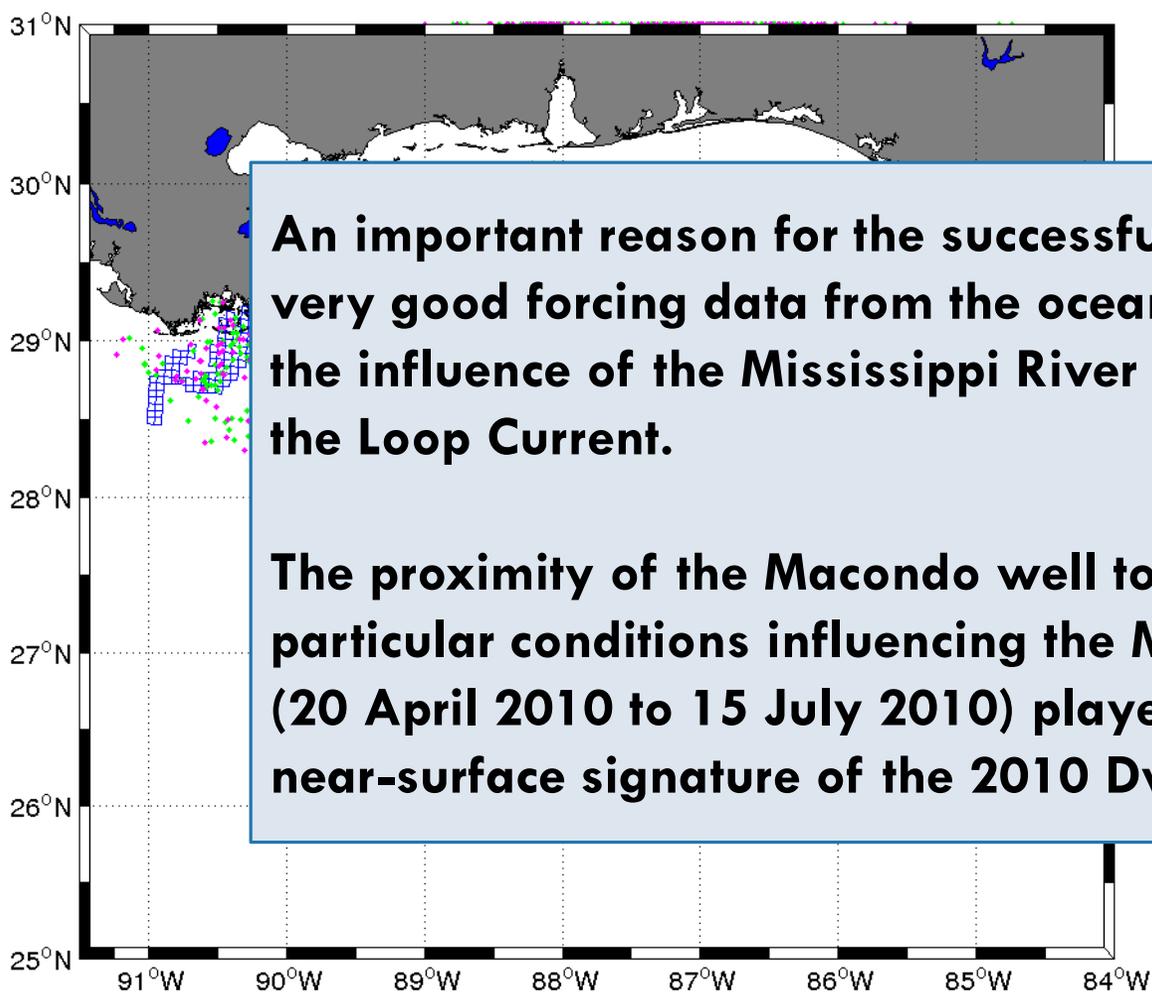


- Map Key**
- Estimated extent of oil on surface
 - Surveyed extent
 - Fishing ban
 - Loop current
 - Marshes
 - Urban areas
 - Reports from locations where oil has made landfall
 - For updates, follow us on Twitter @nytoilspillmap.

IMPORTANCE OF THE COASTAL OCEAN MODEL

An important reason for the successful simulation of the DWH scenario, is very good forcing data from the ocean circulation model, taking into account the influence of the Mississippi River plume, as well as the interaction with the Loop Current.

The proximity of the Macondo well to the Mississippi Delta and the particular conditions influencing the MR plume during the oil gushing period (20 April 2010 to 15 July 2010) played a major role in the evolution of the near-surface signature of the 2010 DwH oil spill accident.



Map Key

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RIVERINE FRONTS AND OCEAN VERTICAL STRUCTURE

- The location of riverine fronts, the proximity of oil slicks and the prevailing winds are important inter-dependent factors triggering initial pathways that determine the fate of hydrocarbons potentially released near the Mississippi delta, toward the NGOM coastlines or over the broader Gulf of Mexico. (Androulidakis et al, 2018)
- Hydrocarbons released close to the MR delta have the potential to reach several coastal northern GoM locations. It is noted that the magnitude of such potential effects largely depends on the quantity of the oil and the dimensions of a certain spill, which are vital factors on the final destination and impacts of the related hydrocarbons.
- **The existence of strong pycnoclines due to river plumes, besides the effects on the horizontal transport of the oil, can play a significant role on the rise of oil toward the surface and the fate of hydrocarbons in the case of bottom leaks (as was the case of the 2010 Deepwater Horizon accident).**
- The ocean vertical structure is a very important topic and requires further investigation.
- New field studies, satellite analyses and modeling using fronts created from a specific oil seep in the GoM are in progress. This includes: **measuring and modeling oil thickness.**

THANK YOU!



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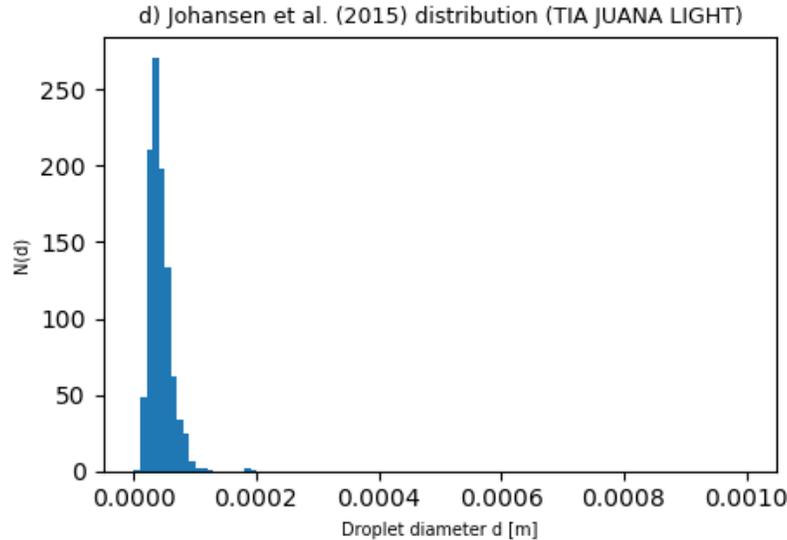
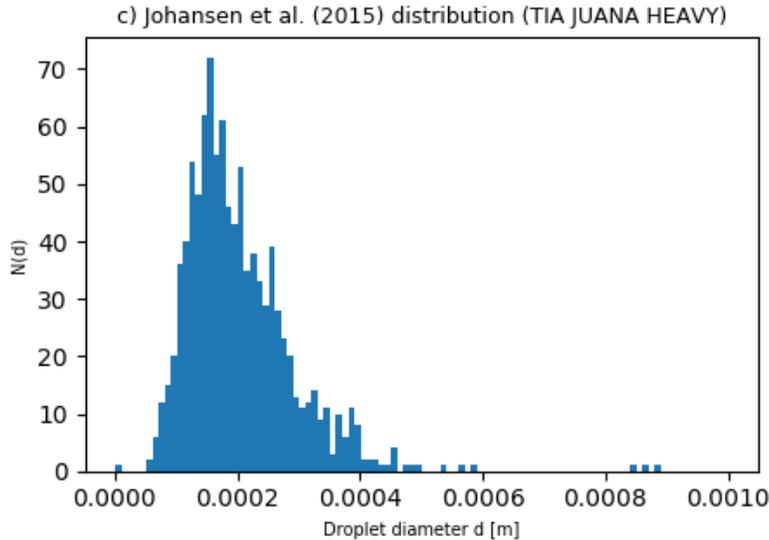
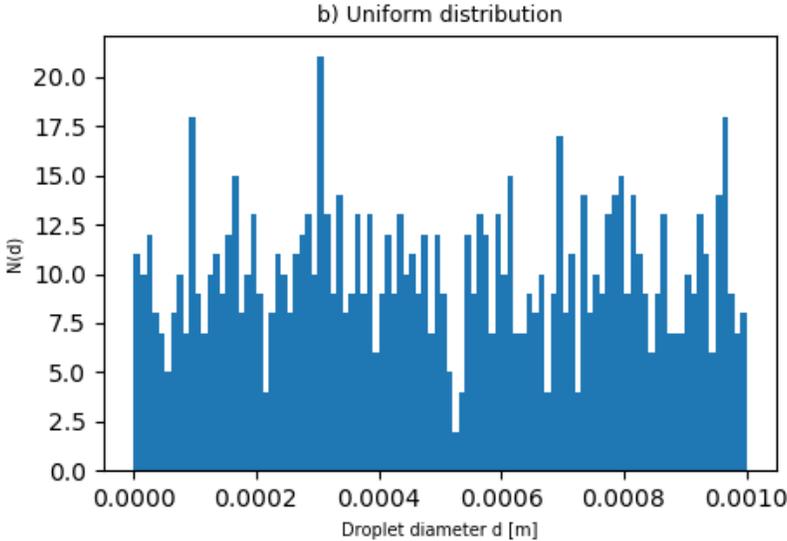
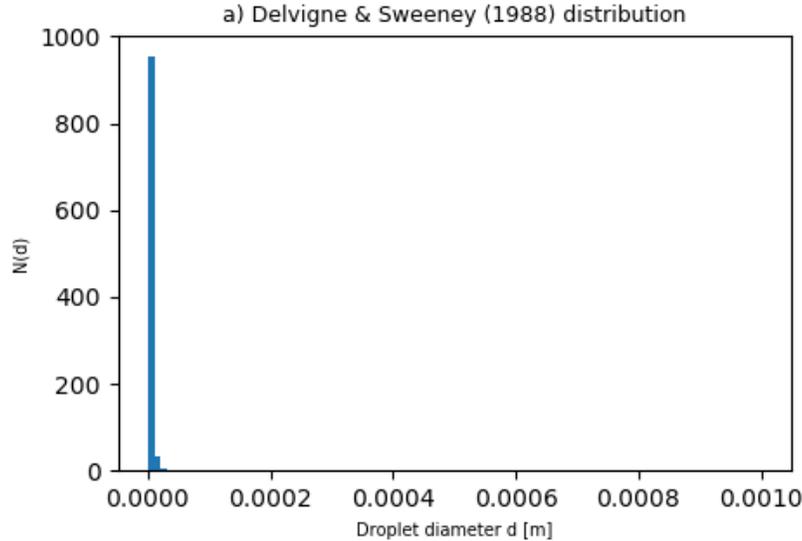
Entrainment of oil

- The entrainment of oil droplets depends on both the wind and wave (breaking) conditions, but also on the oil properties, such as viscosity, density and oil-water inter facial tension.
- The buoyancy of droplets is calculated according to empirical relationships and the stokes law, dependent on ocean stratification (calculated from temperature and salinity profile, normally read from an ocean model), oil and water viscosities and densities.
- The buoyancy is strongly dependent on the oil droplet size (diameter). Two parameterizations are compared:
 - One is a generic power law, with droplets between a minimum and maximum diameter, and a configurable exponent where -2.3 corresponds to the classical work of Delvigne and Sweeney (1988) (DS).
 - The second option for droplet size spectrum is a "modern" approach introduced by Li, who have formulated a new entrainment rate algorithm to accompany their droplet size distribution algorithm. The entrainment rate is derived from dimensional analysis, and is expressed by the Weber number, Ohnesorge number, and fraction of sea surface covered with breaking waves. More oil is entrained with increasing wave height and wind speed.
- In addition to the wave induced entrainment, the oil elements are also subject to vertical turbulence throughout the water column, as parameterized with a binned-random-walk numerical scheme.
- In addition to the vertical and horizontal drift, weathering of the oil also has to be considered.
- The OpenOil module instead interfaces with the already existing oil library software developed by NOAA.

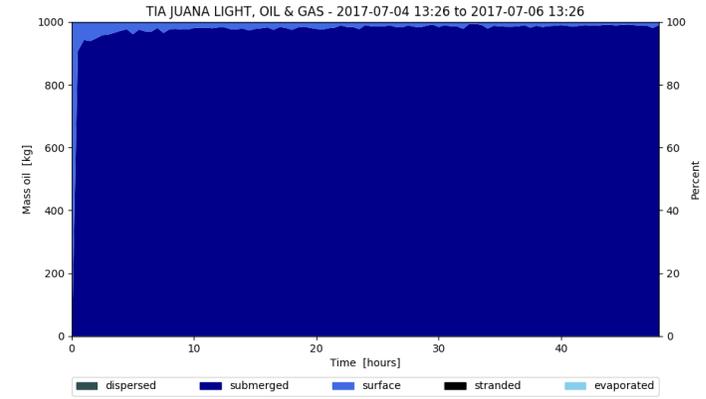
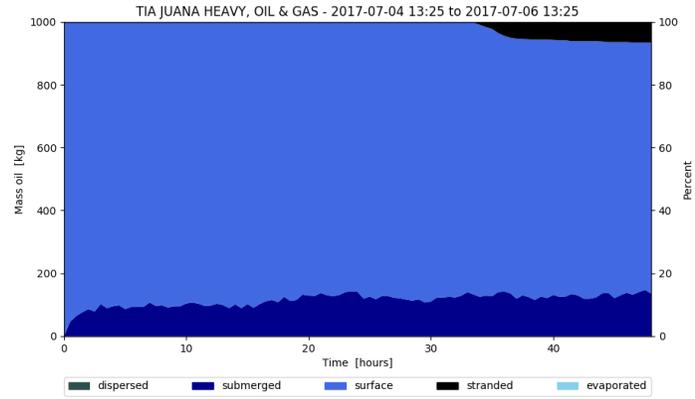


- «Horizontal Oil Transport Depends On Vertical Transport»
- With regard to horizontal drift, three processes are considered:
 - Any element, whether submerged or at the surface, drifts along with the ocean current.
 - Elements are subject to Stokes drift corresponding to their actual depth. [Surface Stokes drift is obtained from a wave model].
 - Oil elements at the ocean surface are moved with an additional factor of 2% (configurable) of the wind. Together with the Stokes drift (typically 1.5% of the wind at the surface), this sums up to the commonly found empirical value of 3.5% of the wind.
- The three drift components may lead to a very strong gradient of drift magnitude and direction in the upper few meters of the ocean. Thus it is of critical importance to have a good description of the vertical oil transport processes
- Vertical Transport Depends On **Oil Type And Weathering** (Emulsification, Viscosity)
 - Entrainment Rate
 - Depends on Viscosity, Wave Height, Wave Breaking Fraction, Oil-water Interfacial Tension
 - Droplet Spectrum
 - Important Because Larger Droplets Rise Faster
 - Depends on Viscosity, Wave Height, **Thickness**, Oil-water Interfacial Tension

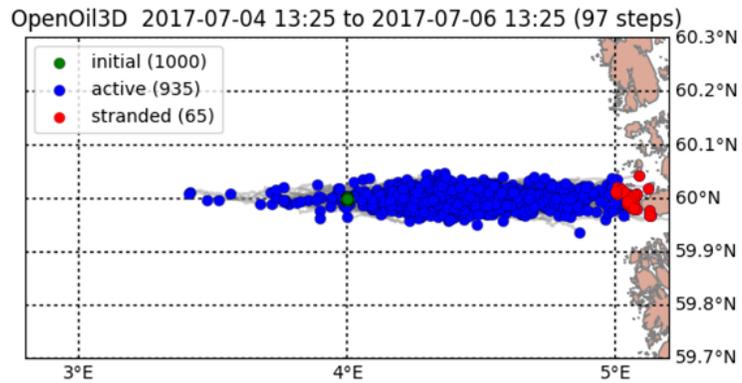
Different oil droplet spectra formulations



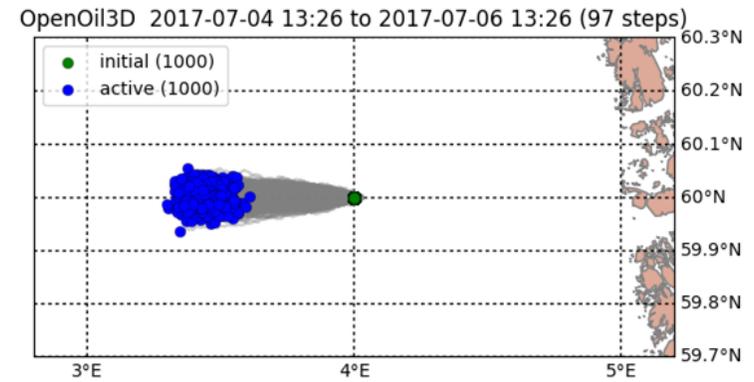
Heavy and light oil - idealized simulations



→ Wind



← Current



Comparison of Mass balance of oil during 7 days for the two formulations. The axis on the left shows the number of particles in the simulation, and the right axis shows percentage of oil submerged, at surface, stranded and evaporated. The DS parametrization is shown on the left, Li parametrization on the right.

