Oil and Chemical Spill Modeling for Risk Assessment (OILMAP/SIMAP, CHEMMAP)

Deborah French McCay, Ph.D.

Director, Research and Model Development
RPS Ocean Science

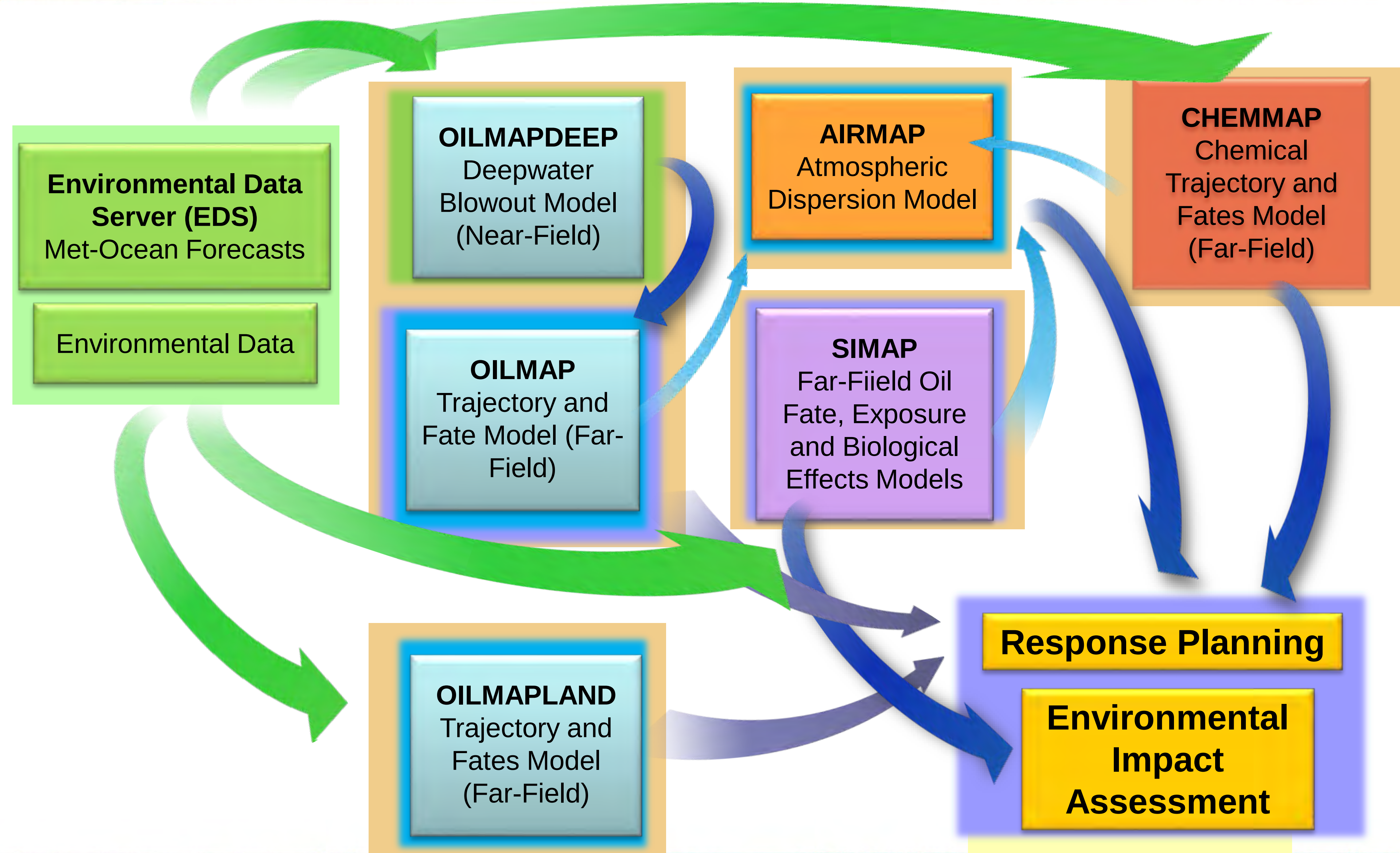
South Kingstown, RI USA
Debbie.FrenchMcCay@rpsgroup.com

RPS ASA – Ocean Science

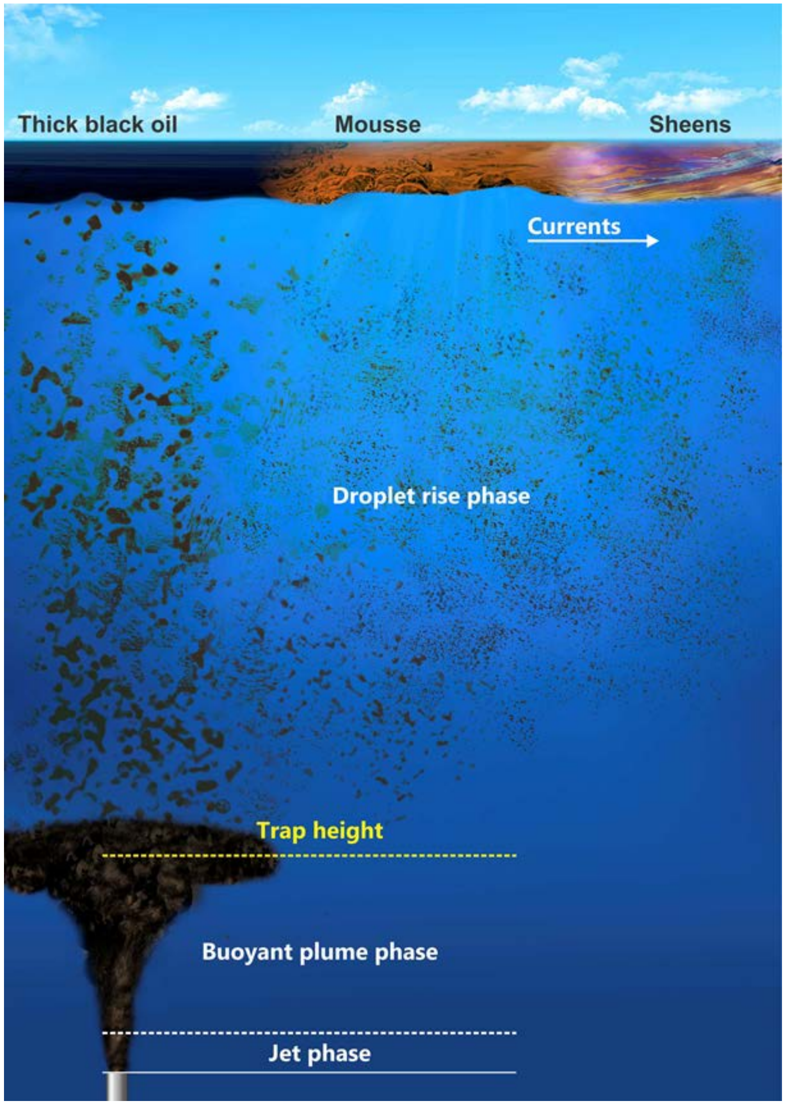
Formerly known as Applied Science Associates,
Environmental scientist and engineers, based in Rhode Island

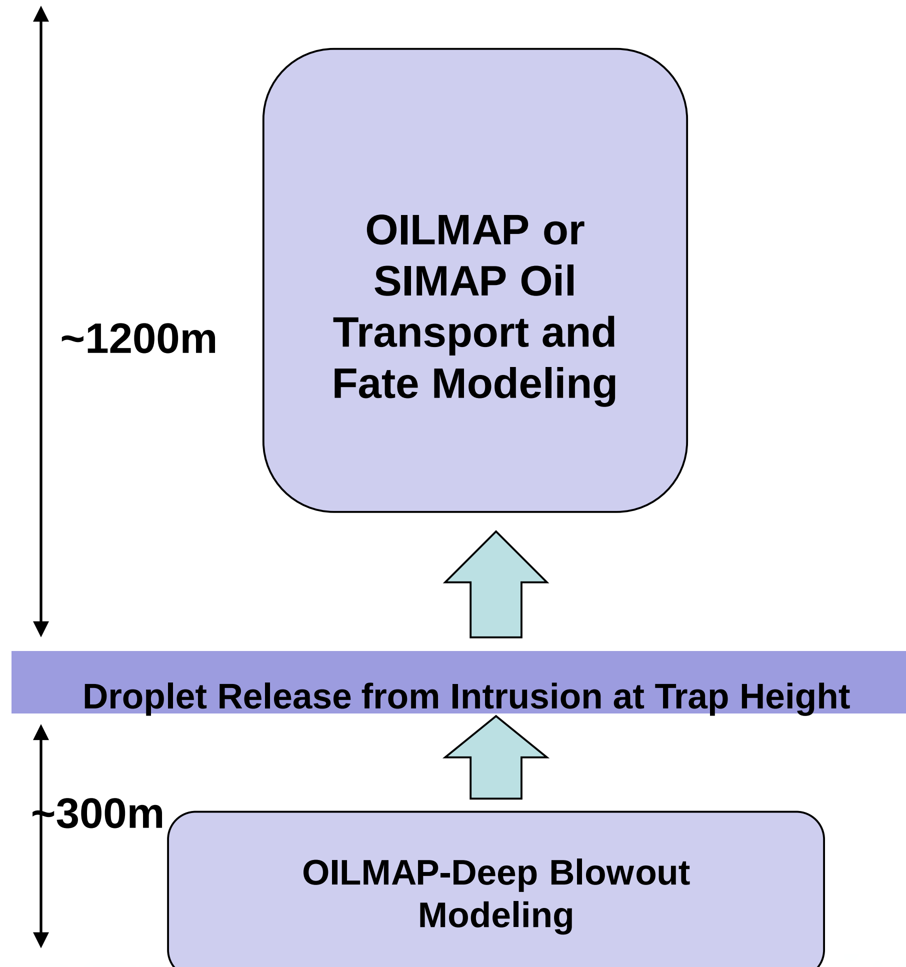
Member of the RPS Group plc since October 2011

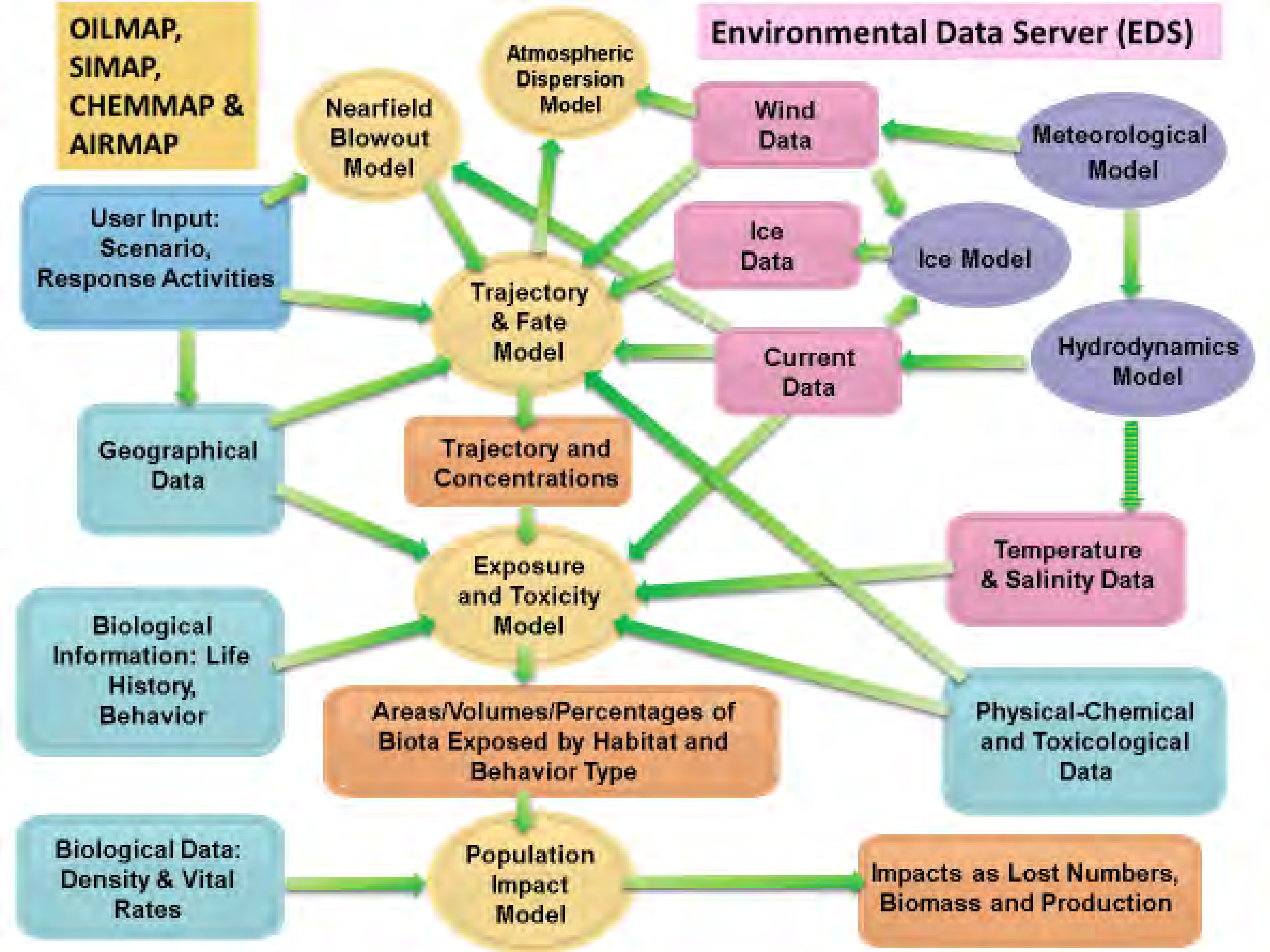
The OILMAP Family
...and a few relatives



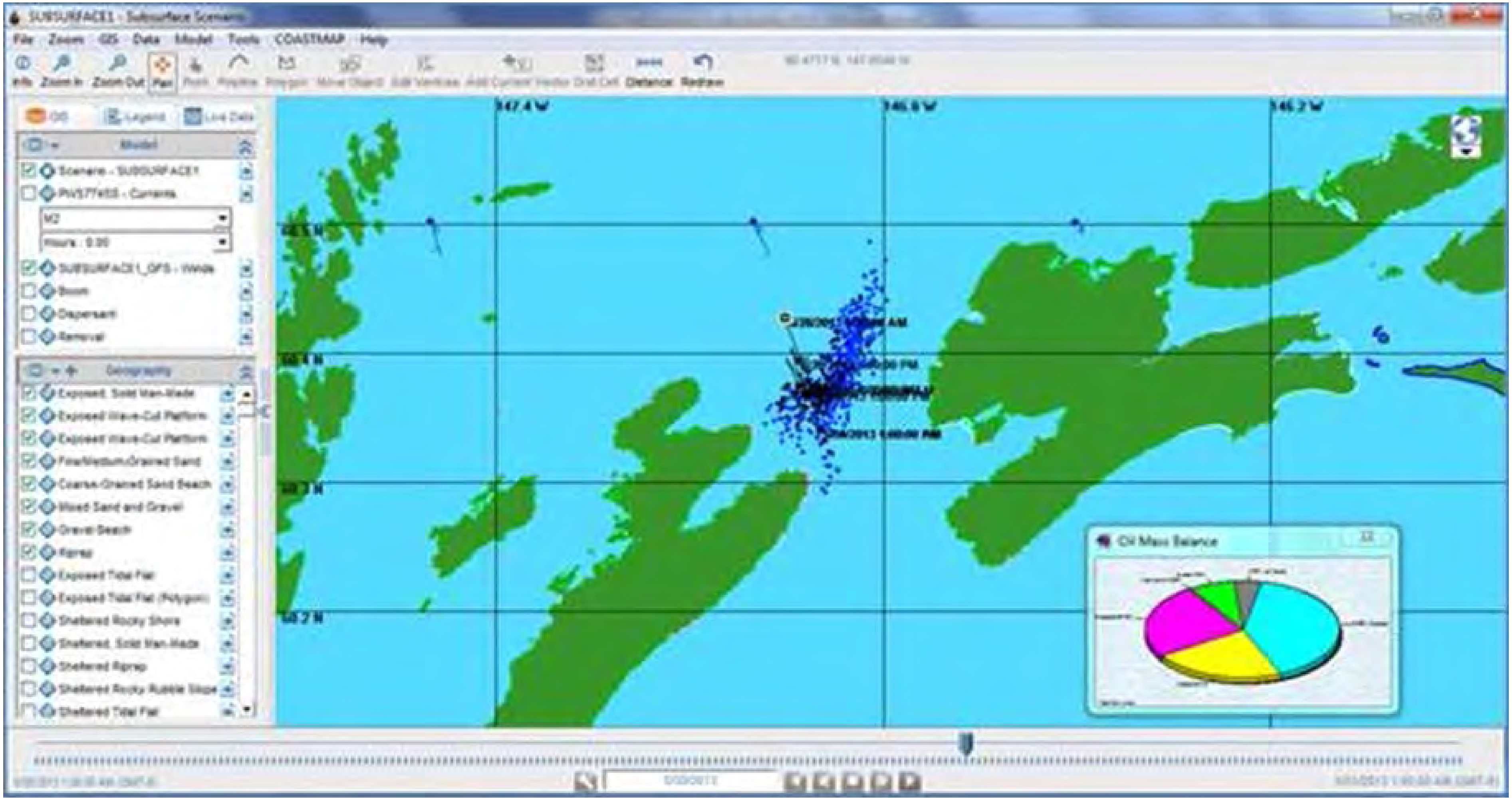
Modeling of the Near-field Blowout and Far-field Phases of an Oil and Gas Blowout





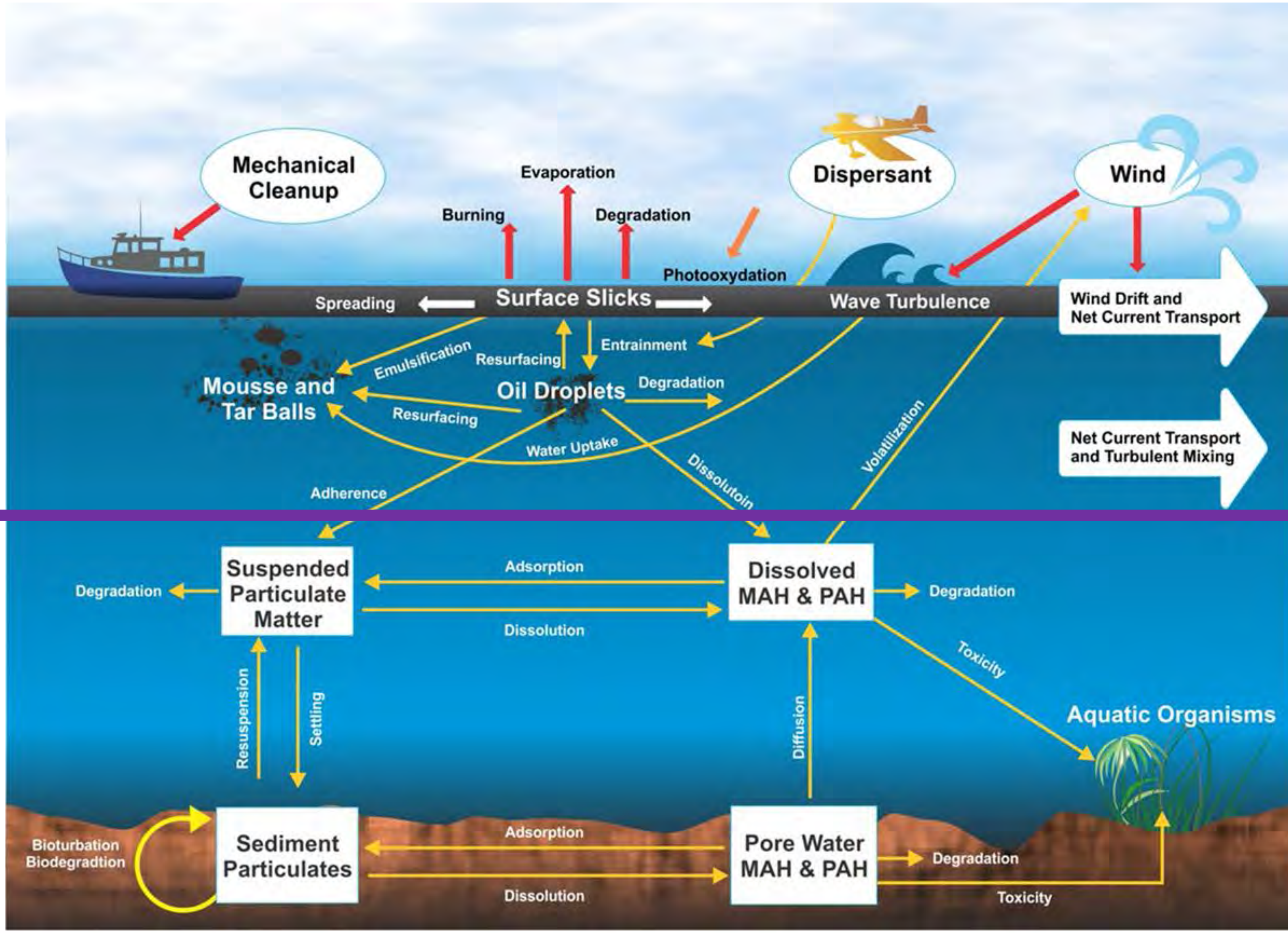

OILMAP, SIMAP, CHEMMAP & AIRMAP
Environmental Data Server (EDS)
Atmospheric Dispersion Model
Nearfield Blowout Model
Wind Data
Meteorological Model
User Input: Scenario, Response Activities
Ice Data
Ice Model
Trajectory & Fate Model
Current Data
Hydrodynamics Model
Geographical Data
Trajectory and Concentrations
Temperature & Salinity Data
Exposure and Toxicity Model
Biological Information: Life History, Behavior
Areas/Volumes/Percentages of Biota Exposed by Habitat and Behavior Type
Physical-Chemical and Toxicological Data
Biological Data: Density & Vital Rates
Population Impact Model
Impacts as Lost Numbers, Biomass and Production

OILMAP: Trajectory & Fate Model for Response Planning

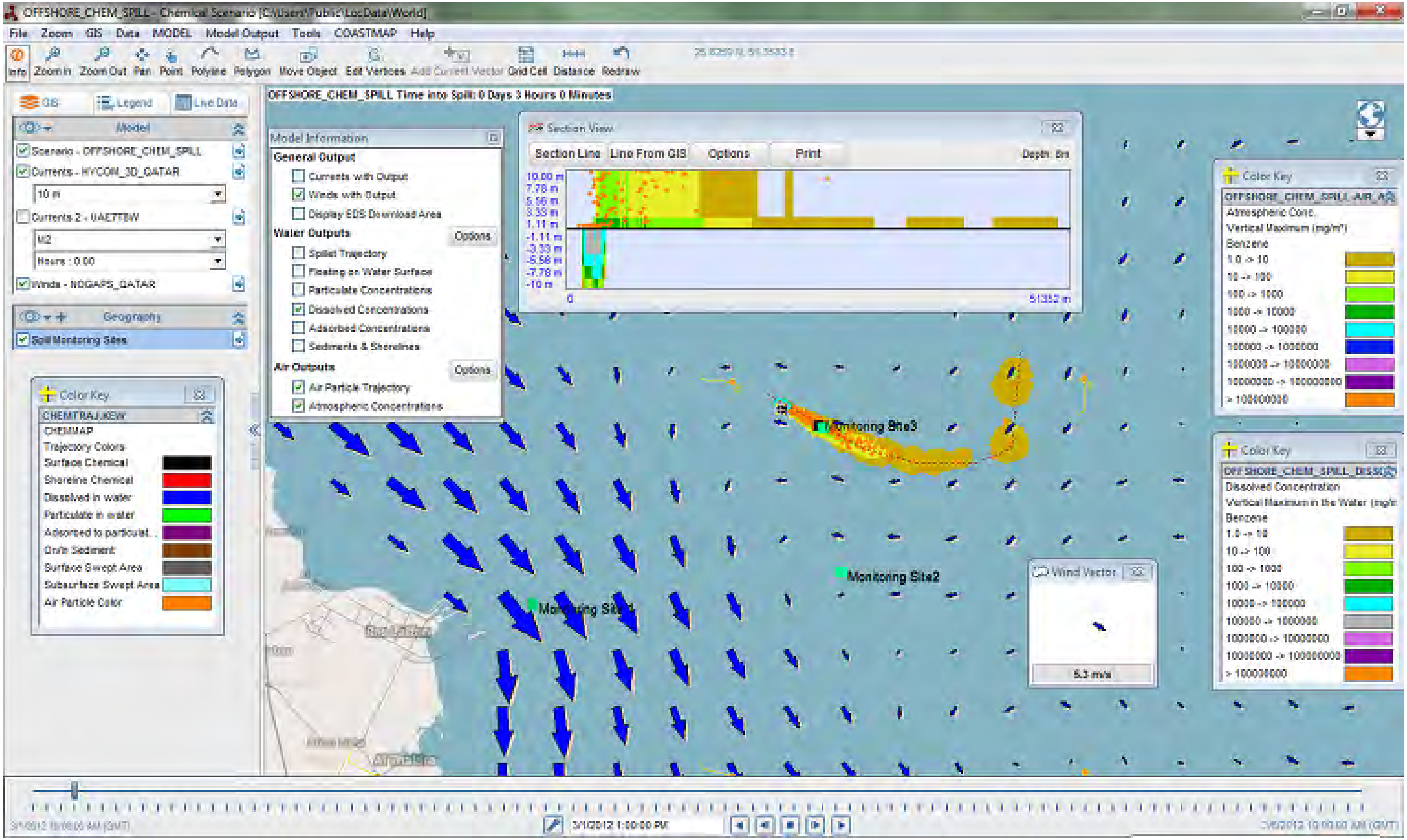


SIMAP: Trajectory, Fate & Exposure Models for Risk & Impact Assessment, NRDA

SIMAP

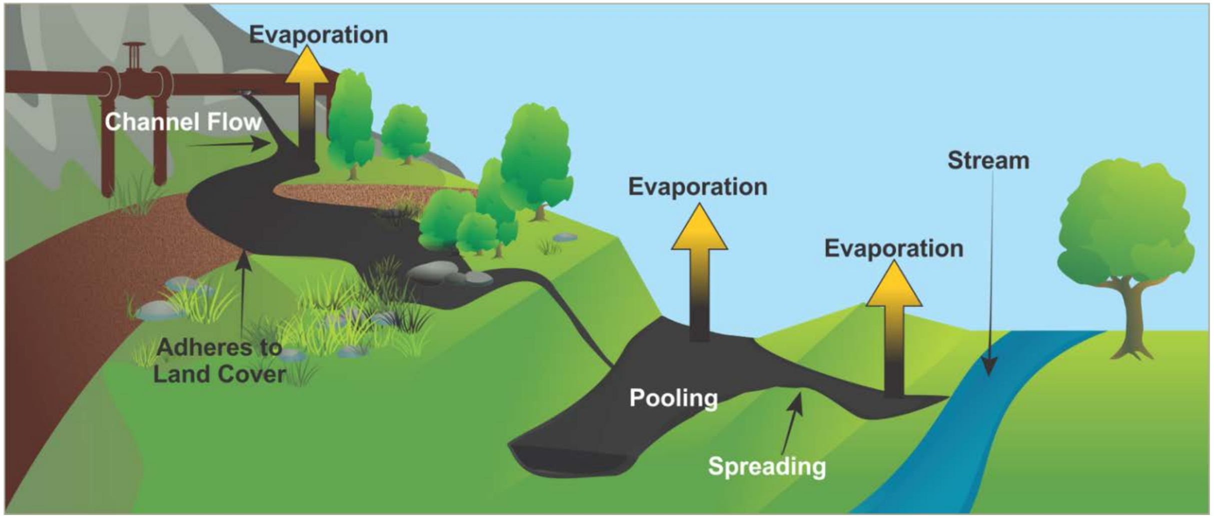


CHEMMAP Trajectory and Fate Model and AIRMAP

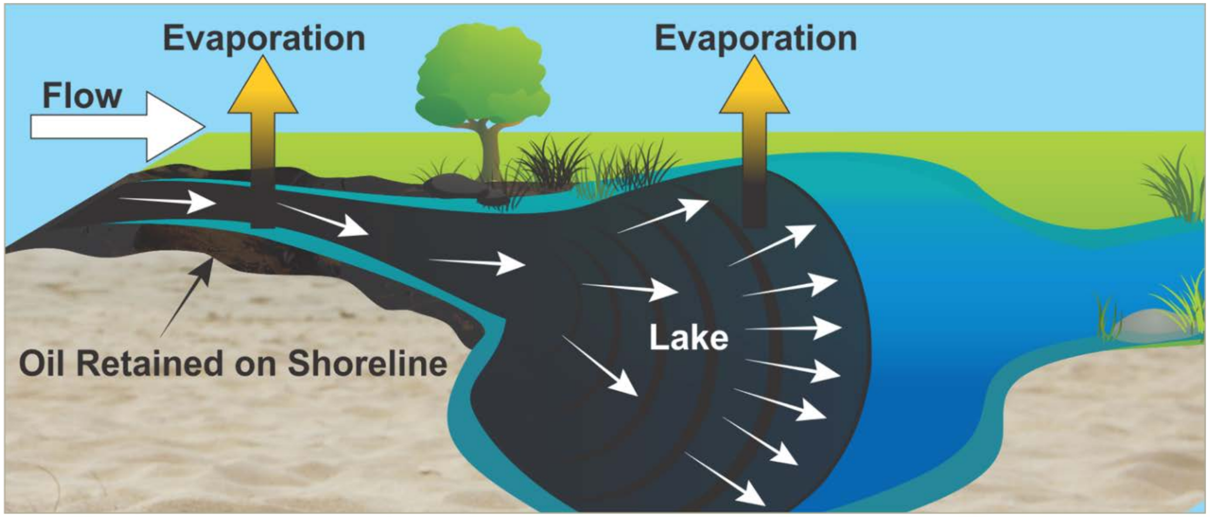


OILMAPLand - 2D Trajectory and Fate

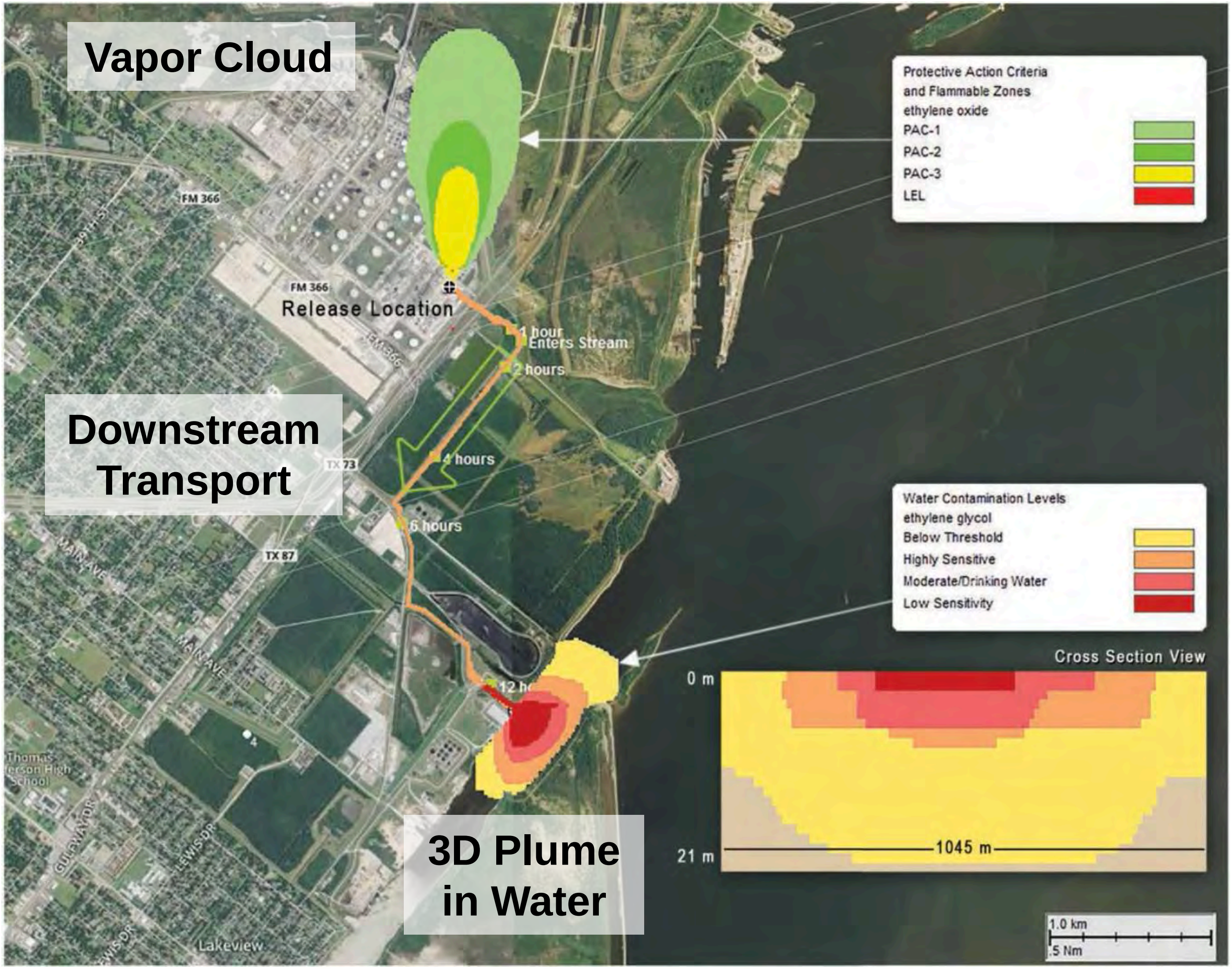
Modeled Processes – Overland Flow



Modeled Processes – Surface Water Network



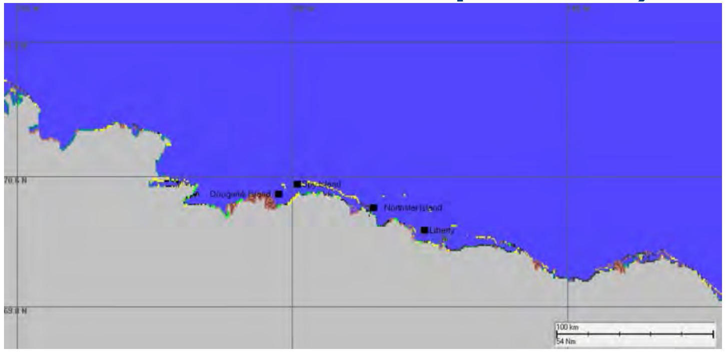
Chemical Spills (e.g., from a Chemical Plant Potential Effects: Air, Land, and Estuary



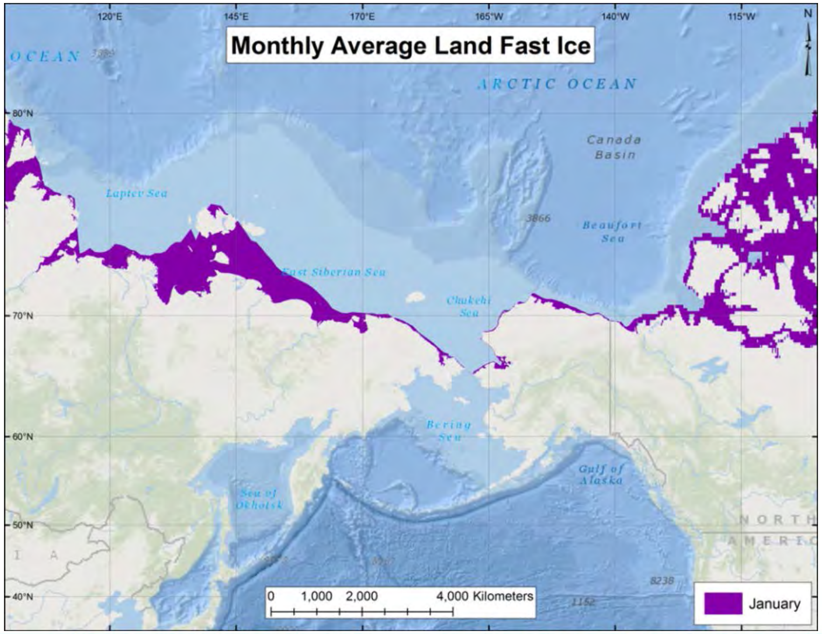
RPS

Physical Fate and Exposure Modeling Approach & Discretization

- Movements of oil/chemical & organisms tracked in space and time as parcels (Lagrangian elements, LEs, ‘spillets”)
  - Floating slicks, weathered oil
  - Droplets/particulates &
  - organisms in the water
  - Dissolved
  - In/on sediments & shorelines



- Model uses grids to define
  - Bathymetry
  - Habitats
  - Temperature, Salinity
  - Current vectors
  - Mobile ice cover & vectors
  - Landfast Ice cover



- **Results also gridded**

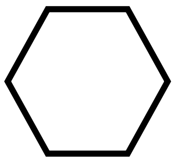
Volatile Components of Oil Modeled Separately; In SIMAP: Soluble and Semi-Soluble vs Insoluble

C-C-C-C-C-C

Aliphatics:

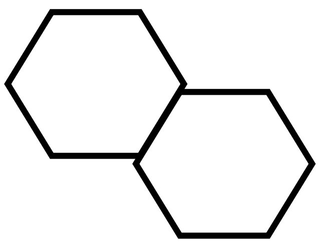
- Alkanes – C12-C23 – volatile, negligible solubility
- Alkanes $\leq$ C12 & Cyclics – volatile & soluble

∑



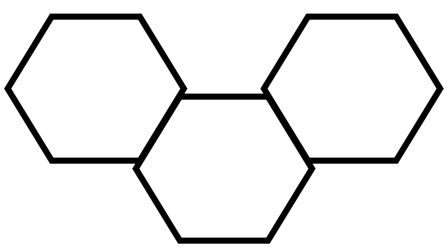
Monoaromatic Hydrocarbons (MAHs)

- Benzene, Toluene, Ethylbenzene and Xylenes = BTEX – highly soluble, highly volatile, moderately toxic
- Alkyl-substituted Benzenes – soluble, less volatile, more toxic



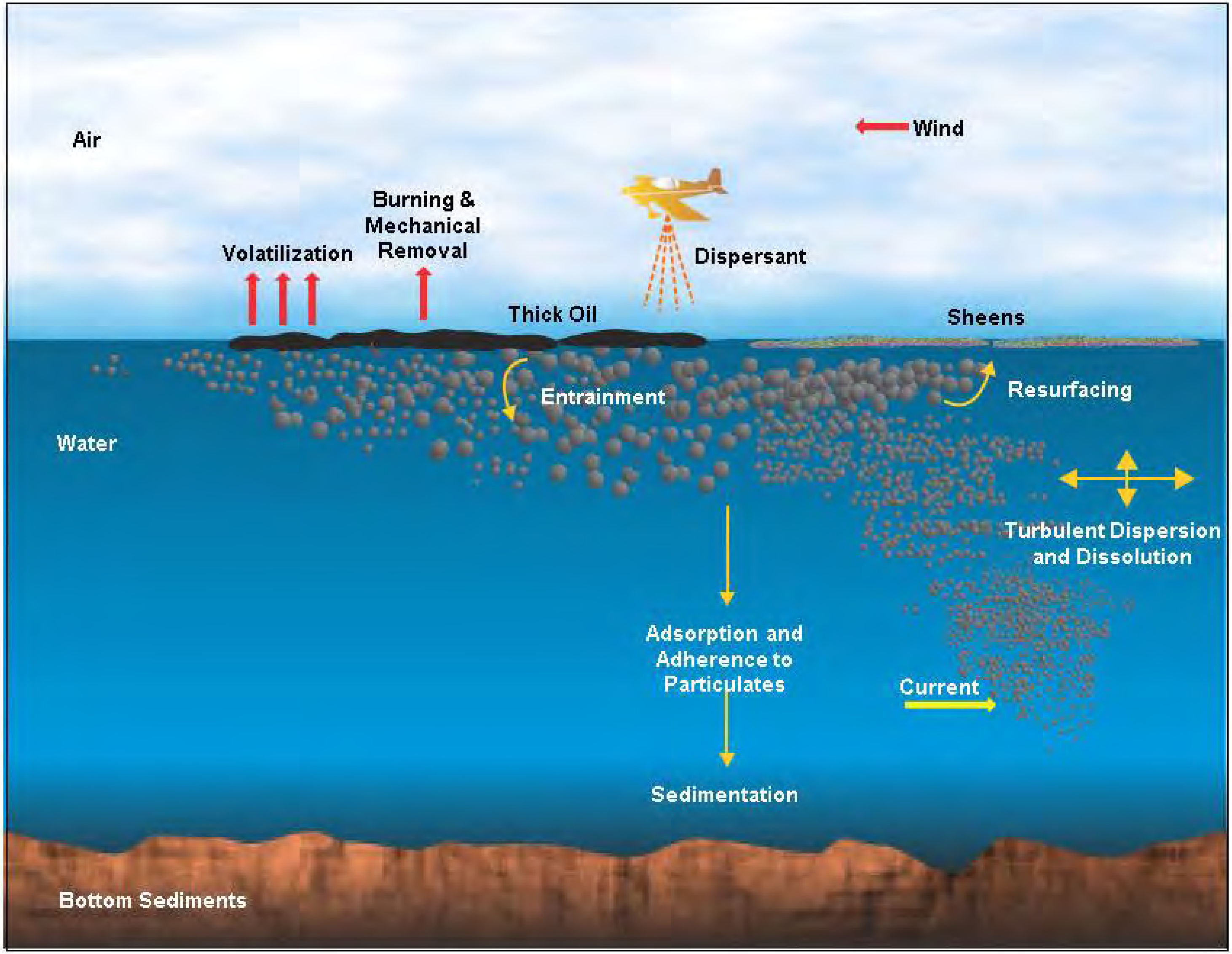
Polynuclear Aromatic Hydrocarbons (PAHs)

- Naphthalenes (2-ring PAHs)
  - soluble, less volatile, more toxic
  - with more alkyl chains, less soluble but more toxic
- 3 ring PAHs – semi-soluble, most toxic fractions
  - Phenanthrenes
  - Fluorenes
  - Dibenzothiophenes

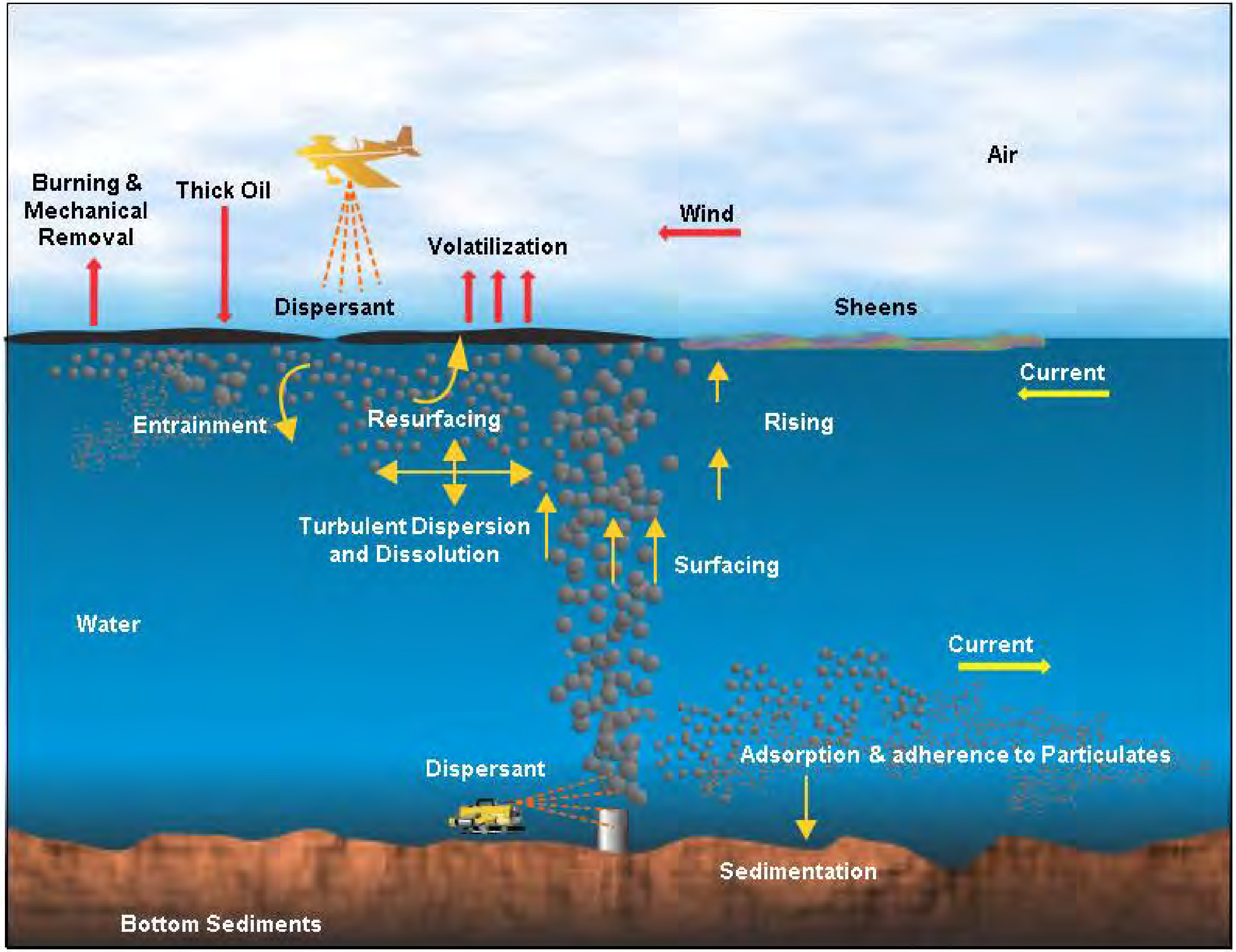


- 4-ring PAHs – fluoranthenes, pyrenes, chrysenes
- larger PAHs insoluble

Important Processes Determining Exposure



Important Processes Determining Exposure

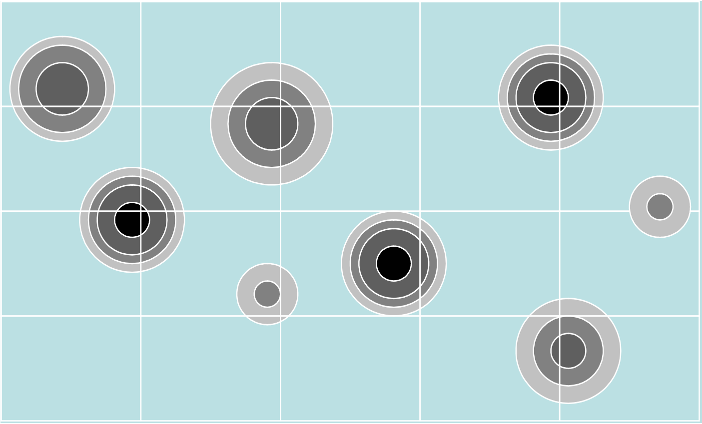


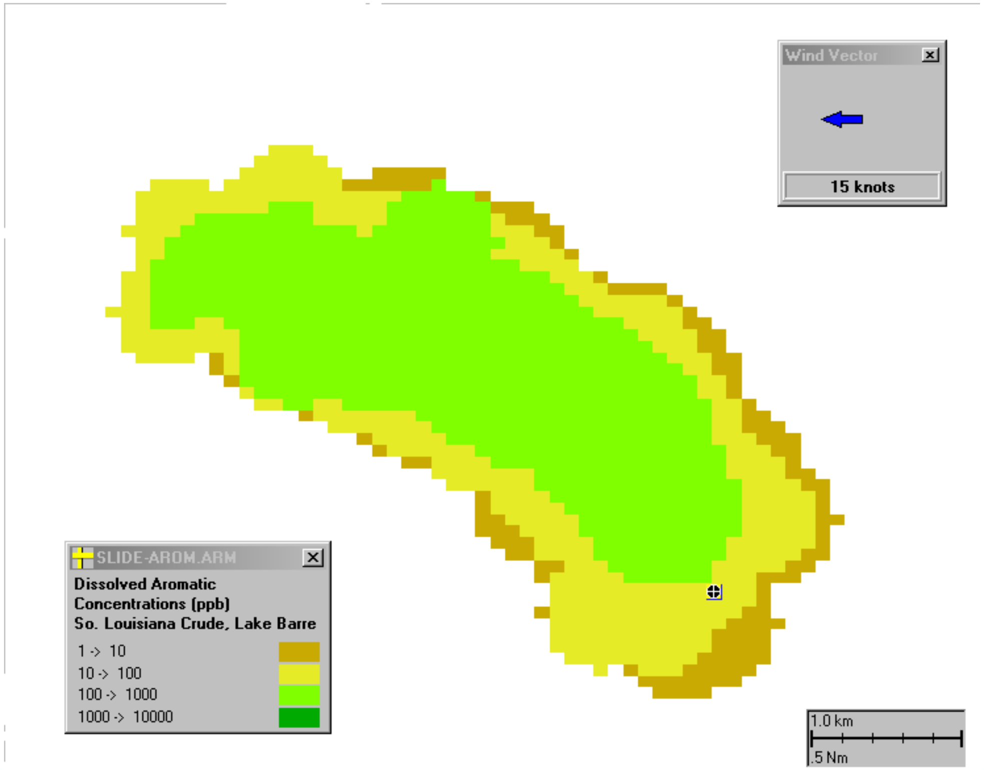
Response Modeling

- Model accounts for
  - Surface dispersant application
  - Booming
  - Mechanical removal (off water and shorelines)
  - In situ burning
  - Subsea dispersant use via OILMAP-Deep
- User specifies
  - Location of response actions (GIS polygon)
  - Time window
  - Efficiency/Amount per time
  - Failure thresholds (wind, waves, minimum thickness)

Lagrangian →Outputs as Concentrations

Floating Oil & In-Water Concentrations





Horizontal cross section of LEs with Gaussian distributions of mass around each LE, projected into a grid

Wildlife Exposure & Effects Model

- Calculate area swept by oil > threshold thickness
- French McCay (2009, 2016) developed surface oil thickness thresholds based on experimental and field data:
  - Lethal threshold: 10 g/m^2
  - Sublethal threshold: 1 g/m^2
- Probability of Exposure
  - Habitats occupied
  - Behavior – likelihood of intersection oil at water surface

Activity-based Exposure Model: Fish and Invertebrates

- Organisms classified by behavior
  - Swimming
    - Vertical zone
    - Diel migration
    - Speed
  - Drift with currents
  - Stationary (benthic)

- Movements of organisms are tracked using Lagrangian Elements to calculate exposure of individuals

Acute toxic effects a function of dose

- **Exposure duration – while concentration > threshold**
- **Mean concentration during exposure duration**

Biological Effects Model Outputs

- Mortality by behavior group, species and life stage, as:
  - Equivalent area or volume of 100% loss = Σ (Fractional loss in each area/volume)
  - Percentage of population in defined area
  - (If pre-spill abundance known)
    - Numbers
    - Biomass (kg)
- Future impacts
  - Production forgone = growth that would have been produced over remaining lifetime if there had not been a spill
  - Catch loss (yield foregone) for fished species

SIMAP Model Validation

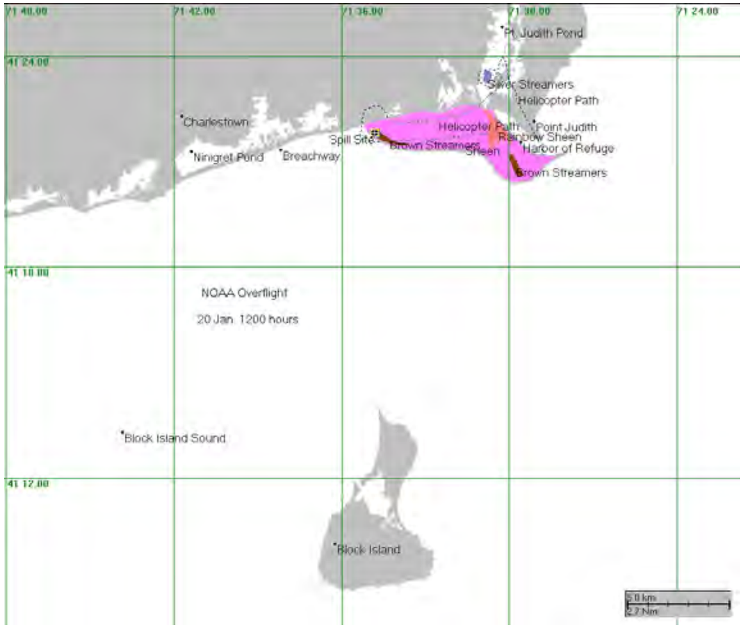
- Developed over 3 decades, several peer reviews, validation studies
- Derived from CERCLA Type A model (French et al. 1996); also referred to in OPA 90 NRDA regulations
- *Exxon Valdez* Oil Spill (French McCay 2004)
- *North Cape* Oil Spill (French McCay 2003)
- 20 spills (French McCay and Rowe, 2004)
- Test spills designed to verify algorithms (French and Rines 1997; French et al. 1997; Payne et al. 2007; French McCay et al. 2007)
- Deepwater Horizon (DWH) oil spill in support of the Natural Resource Damage Assessment (NRDA) – NOAA (Spaulding et al. 2015, 2017; French McCay et al. 2015, 2016, 2018) and as part of validation study for BOEM risk assessment project (French McCay et al., 2018a,b,c)

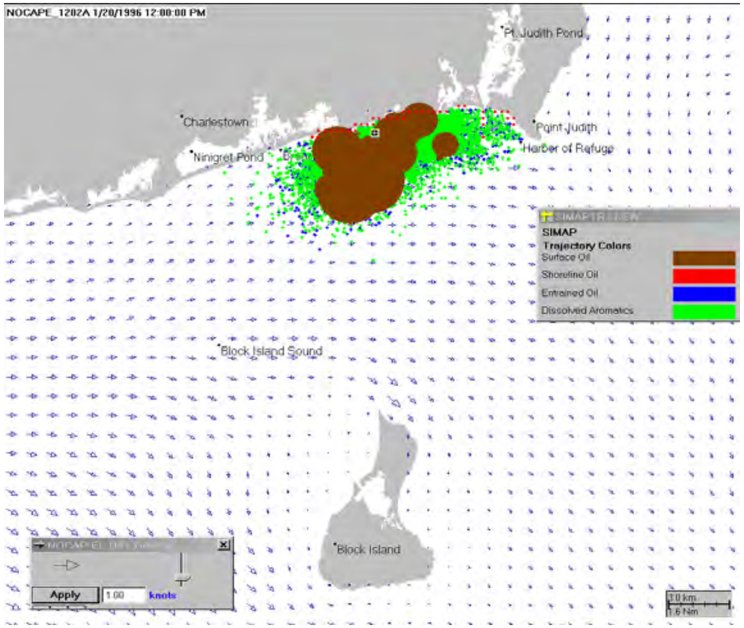
North Cape Oil Spill

- USA, Rhode Island coast, 19 January 1996
- 828,000 gal (2,682 tonnes) of No. 2 (light) fuel oil
- Entrained by heavy surf causing large impact to aquatic organisms

Surface Oil at 16 Hours After Spill

Observed – Modeled

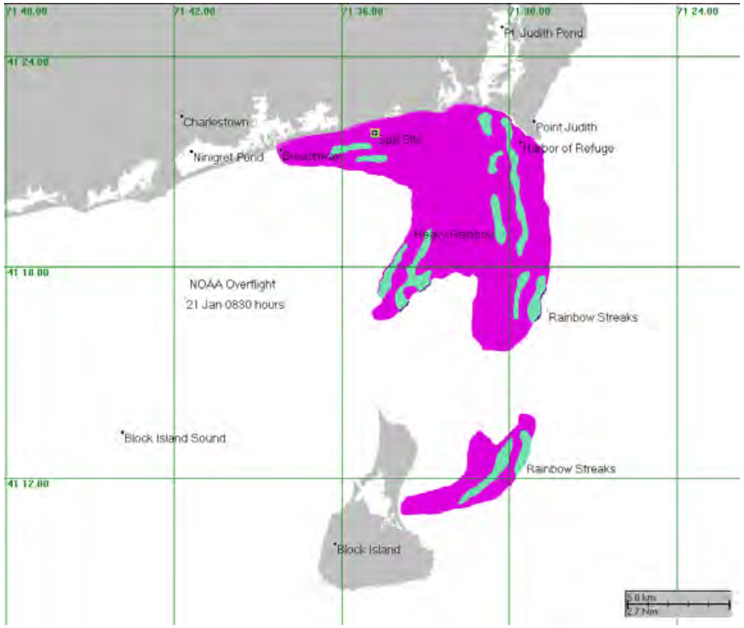


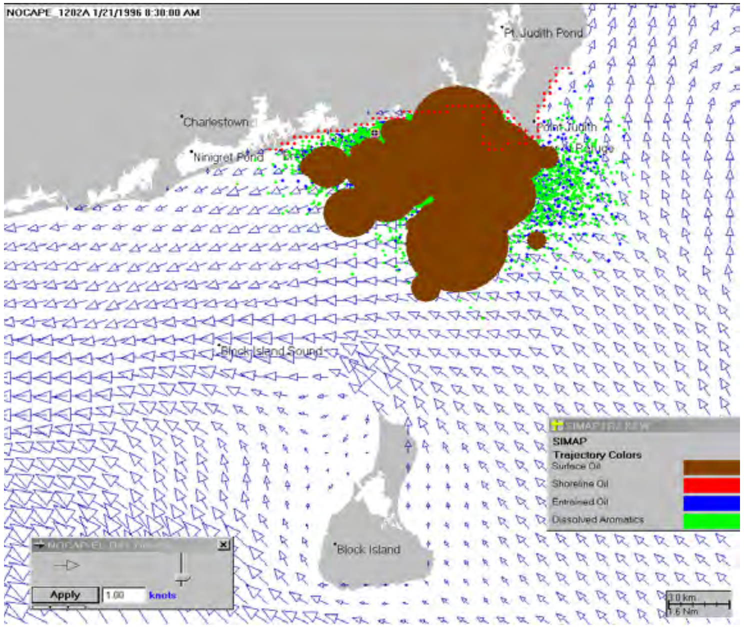


RPS

Surface Oil at 36 Hours After Spill

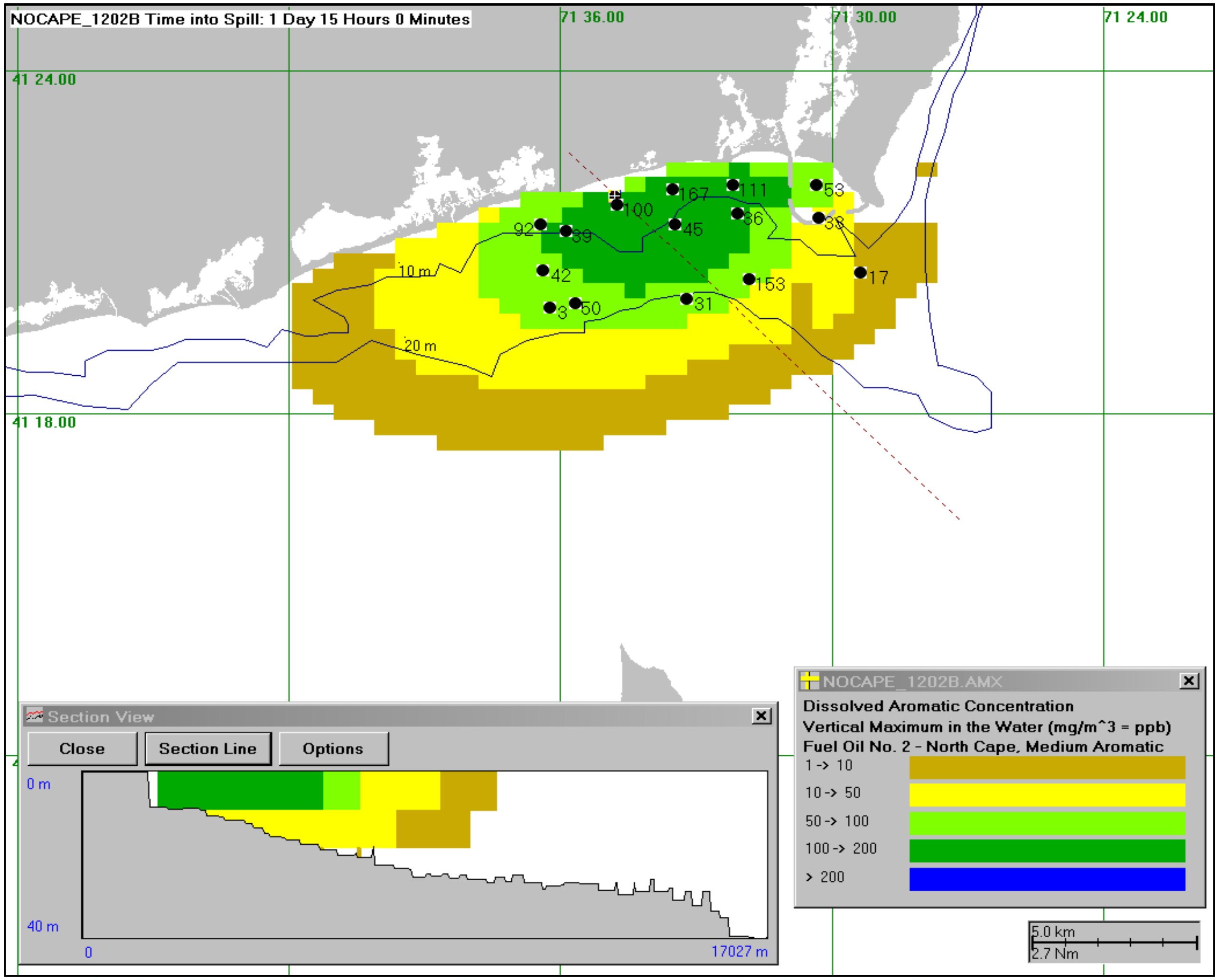
Observed – Modeled





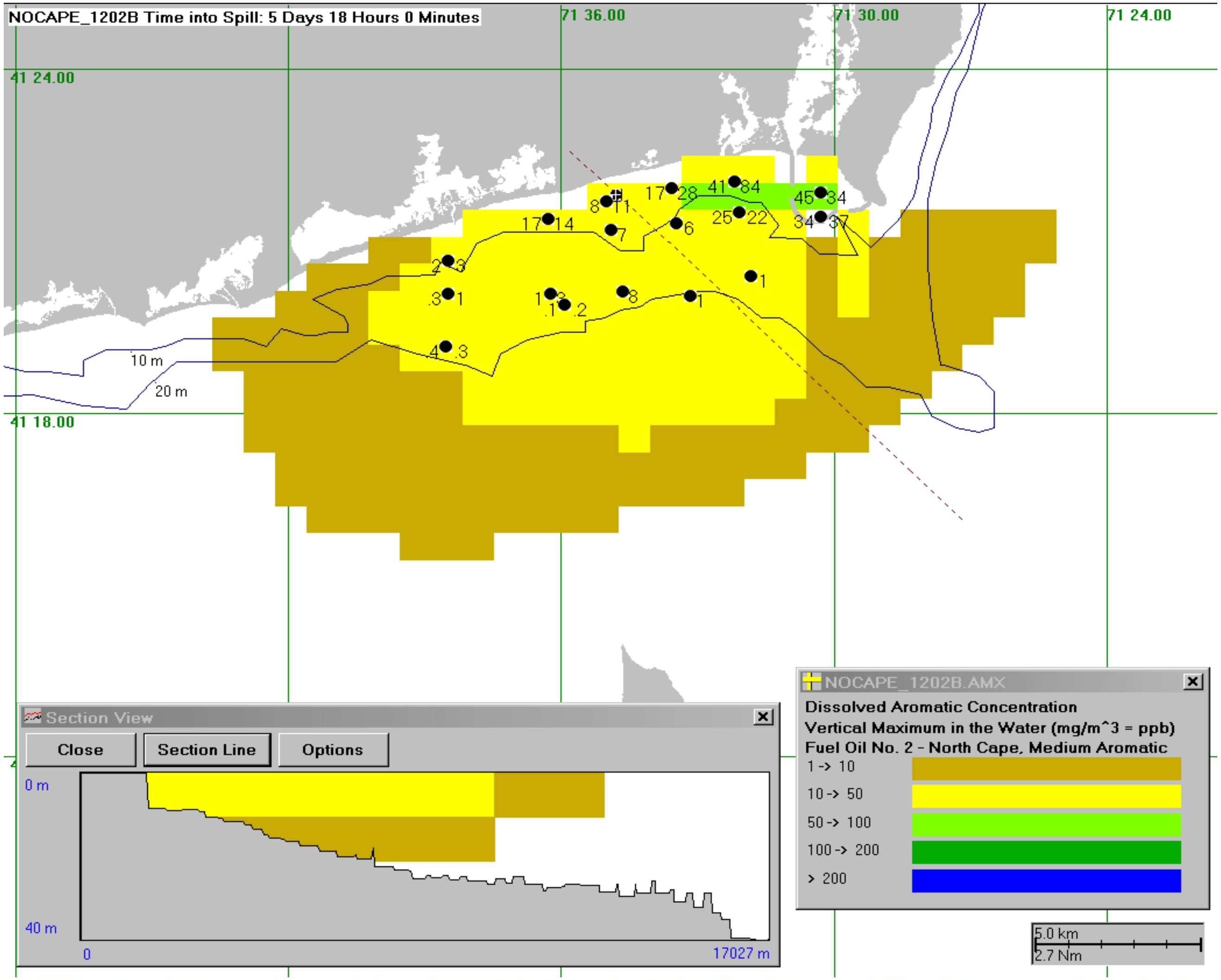
Dissolved Aromatic Concentrations at 40 Hours After Spill

Model Agreed with Measured Concentrations



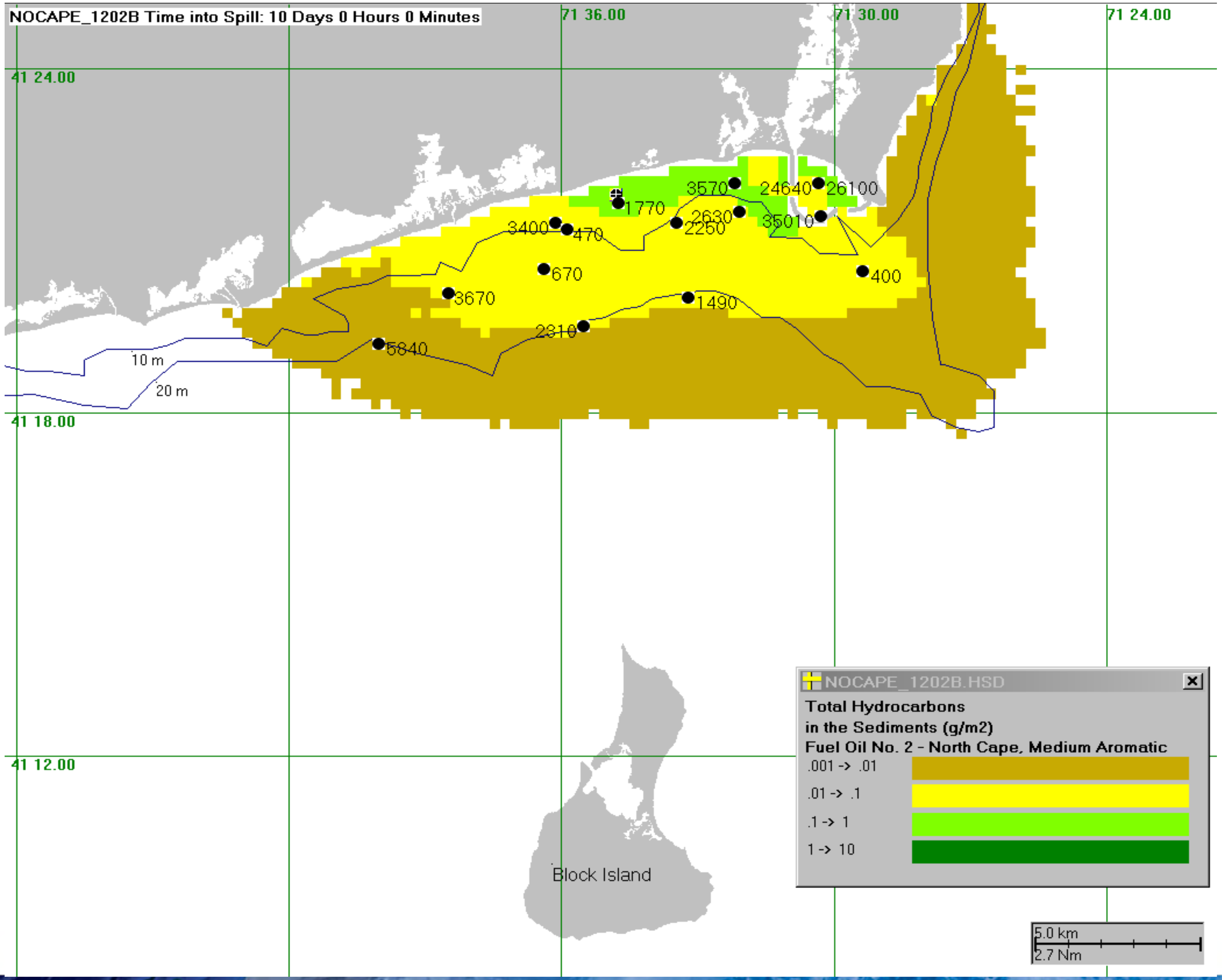
Dissolved Aromatic Concentrations at 138 Hours After Spill

Model Agreed with Measured Concentrations



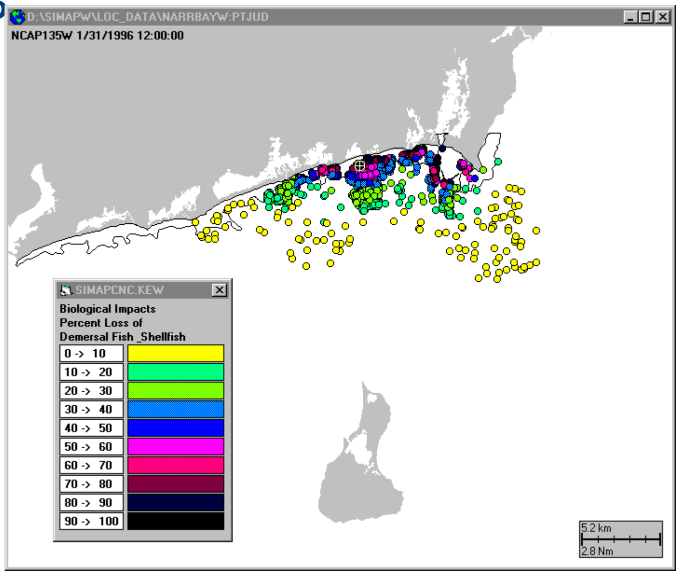
Total Hydrocarbons in Sediments at 10 Days After Spill

Model Agreed with Measured Concentrations



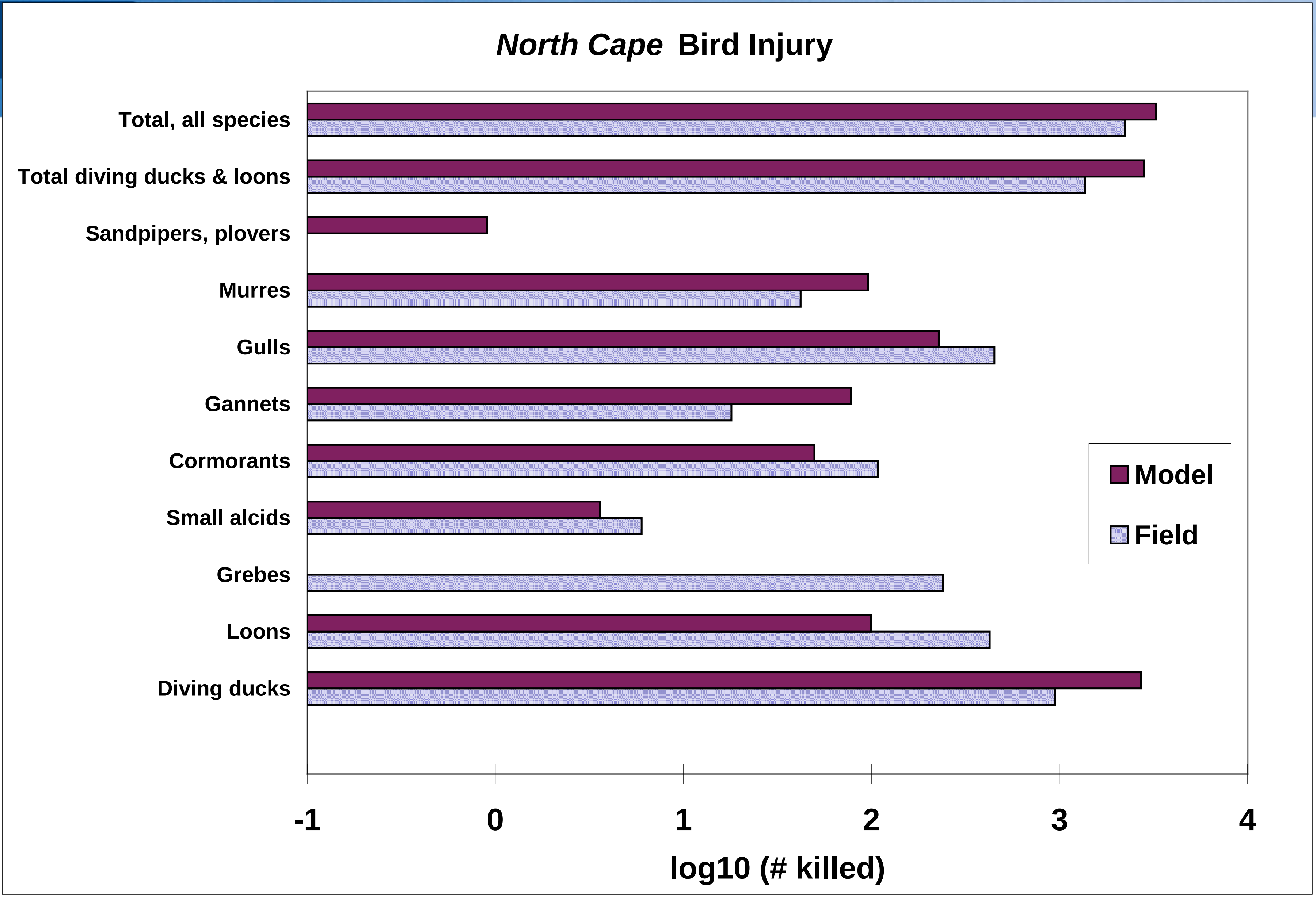
Biological Model

- Validation: Lobsters
  - Field-based estimate 9 million
  - Model estimate 8.3 million
    - (using best estimate of toxicity)
  - Stranded dead lobsters on beaches: 3 million (so at least this many killed)



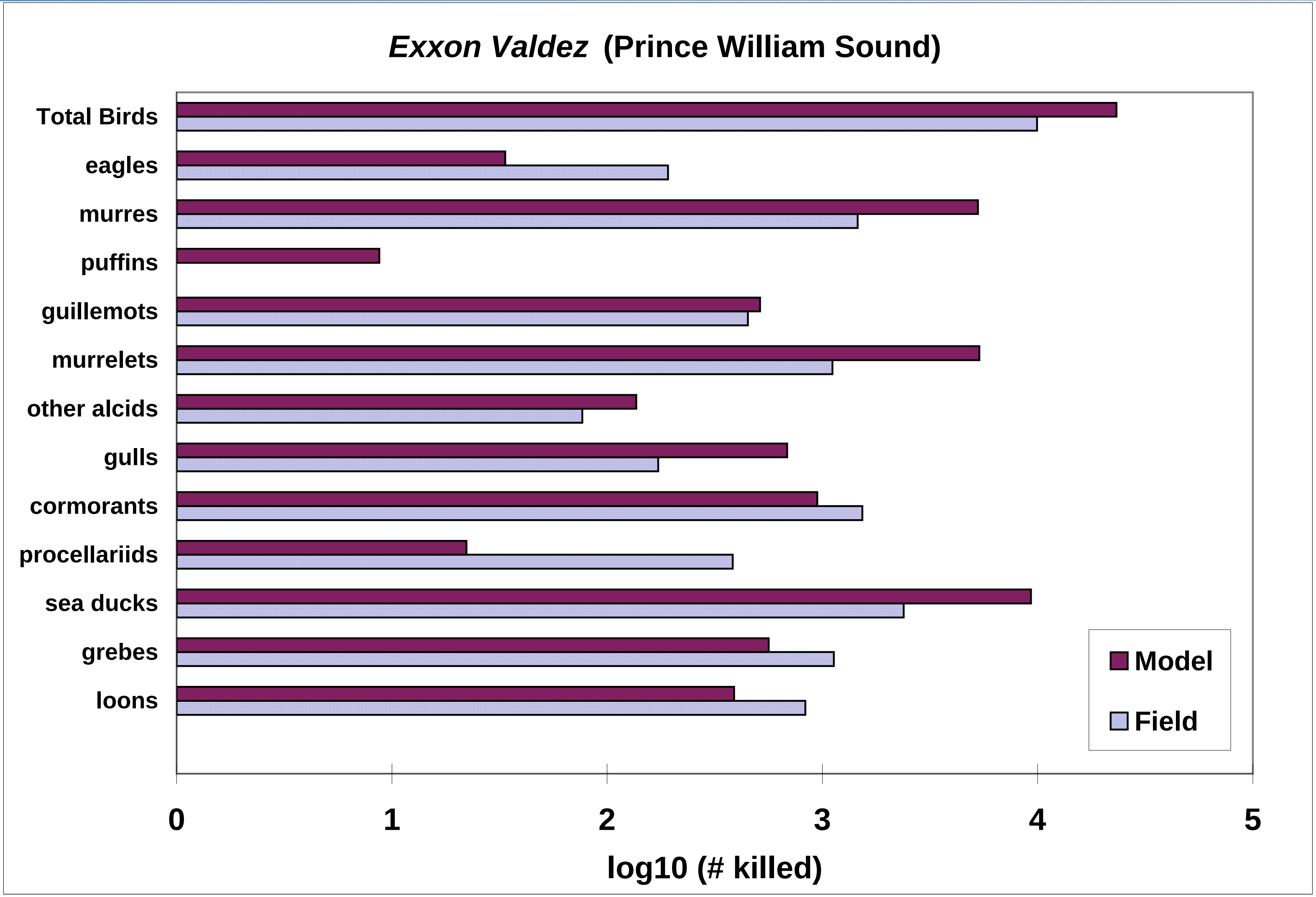
- Used validated model for injury quantification for fish and invertebrates

French McCay 2003 Mar. Poll. Bull. 47: 341–359.



French McCay 2003 Mar. Poll. Bull. 47: 341–359.

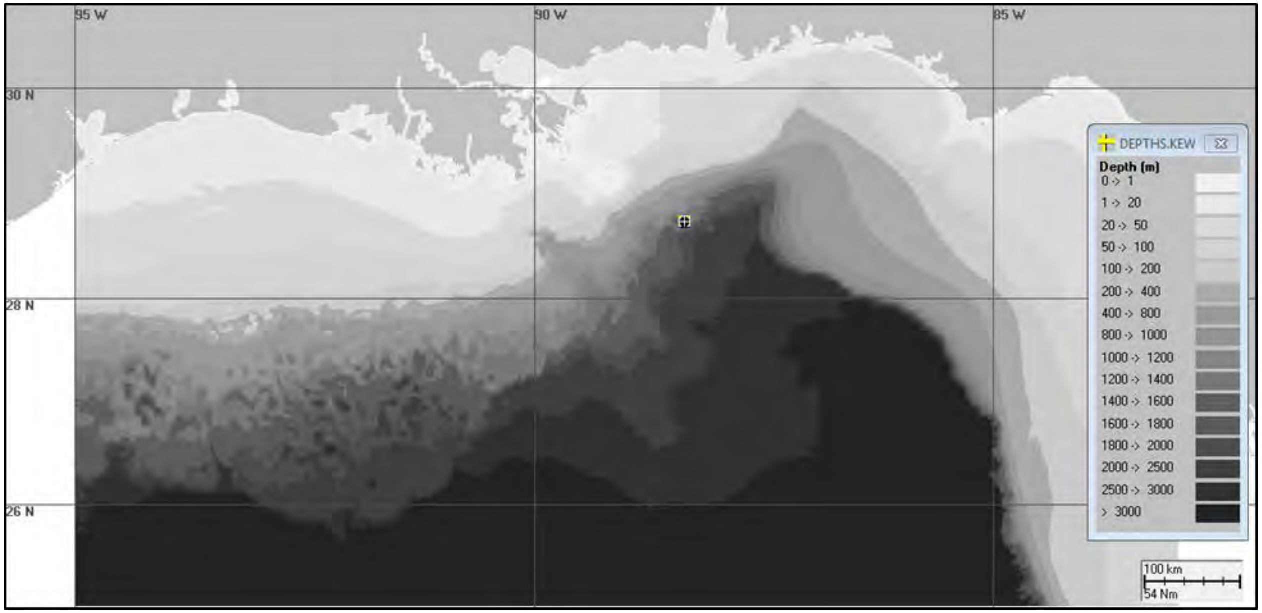
Validation – EVOS – Birds



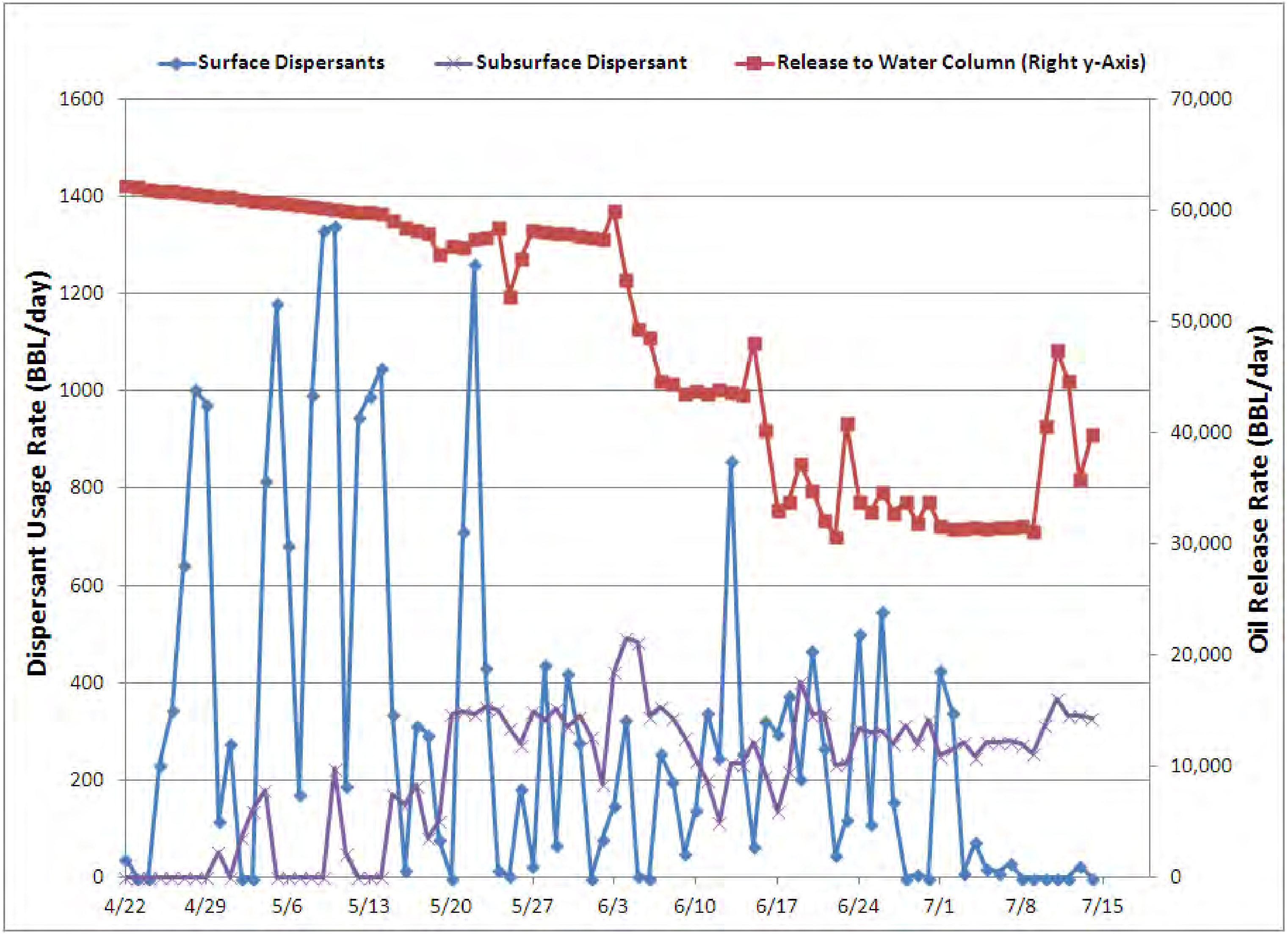
French McCay 2004 Envir. Tox & Chem

Deepwater Horizon Oil Spill

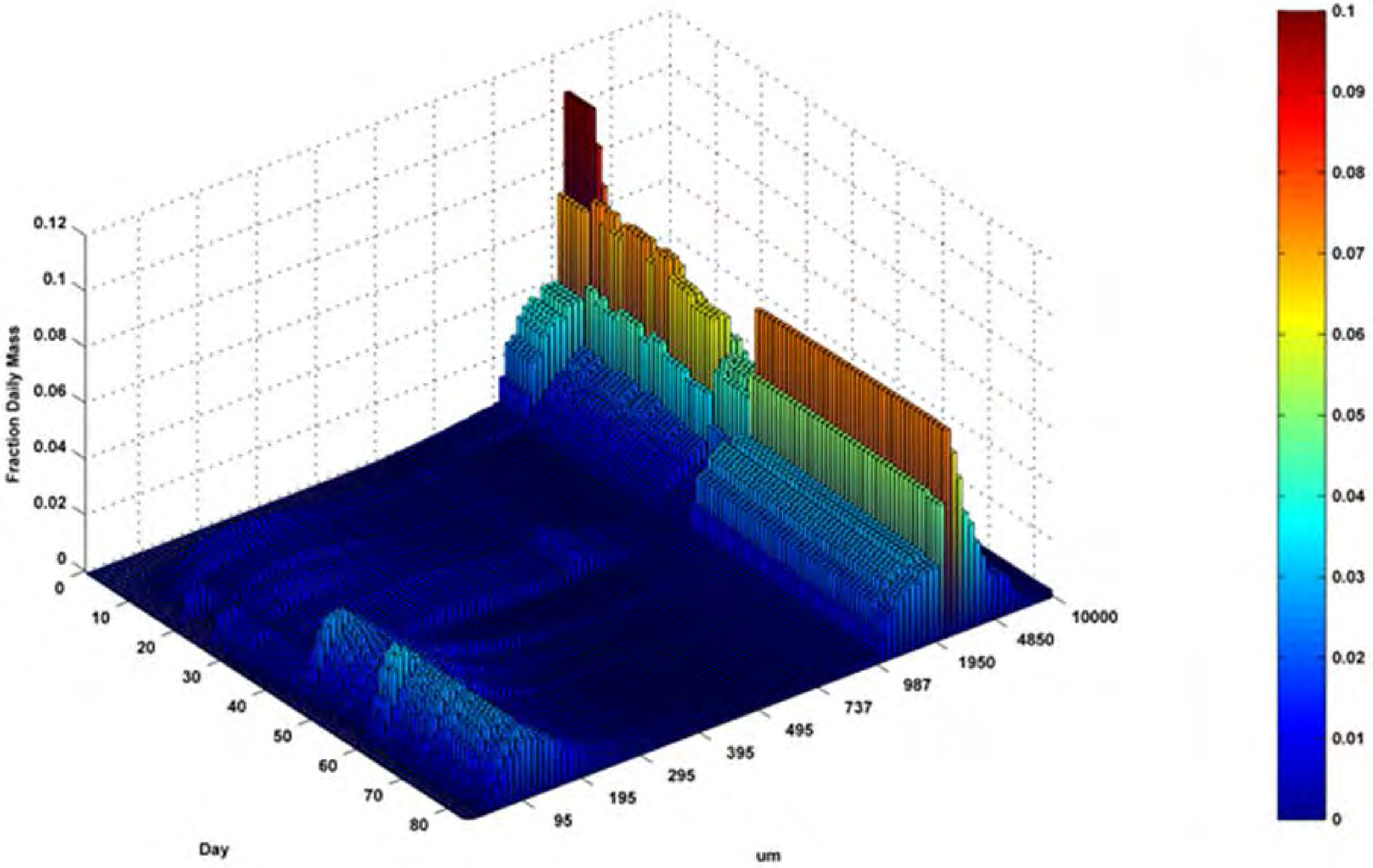
- April 22 – July 15, 2010 in NE Gulf of Mexico
- ~205 million gallons (government estimate)
- Response:
  - **Mechanical removal and In-Situ Burning**
  - **Surface and subsea application of dispersants**



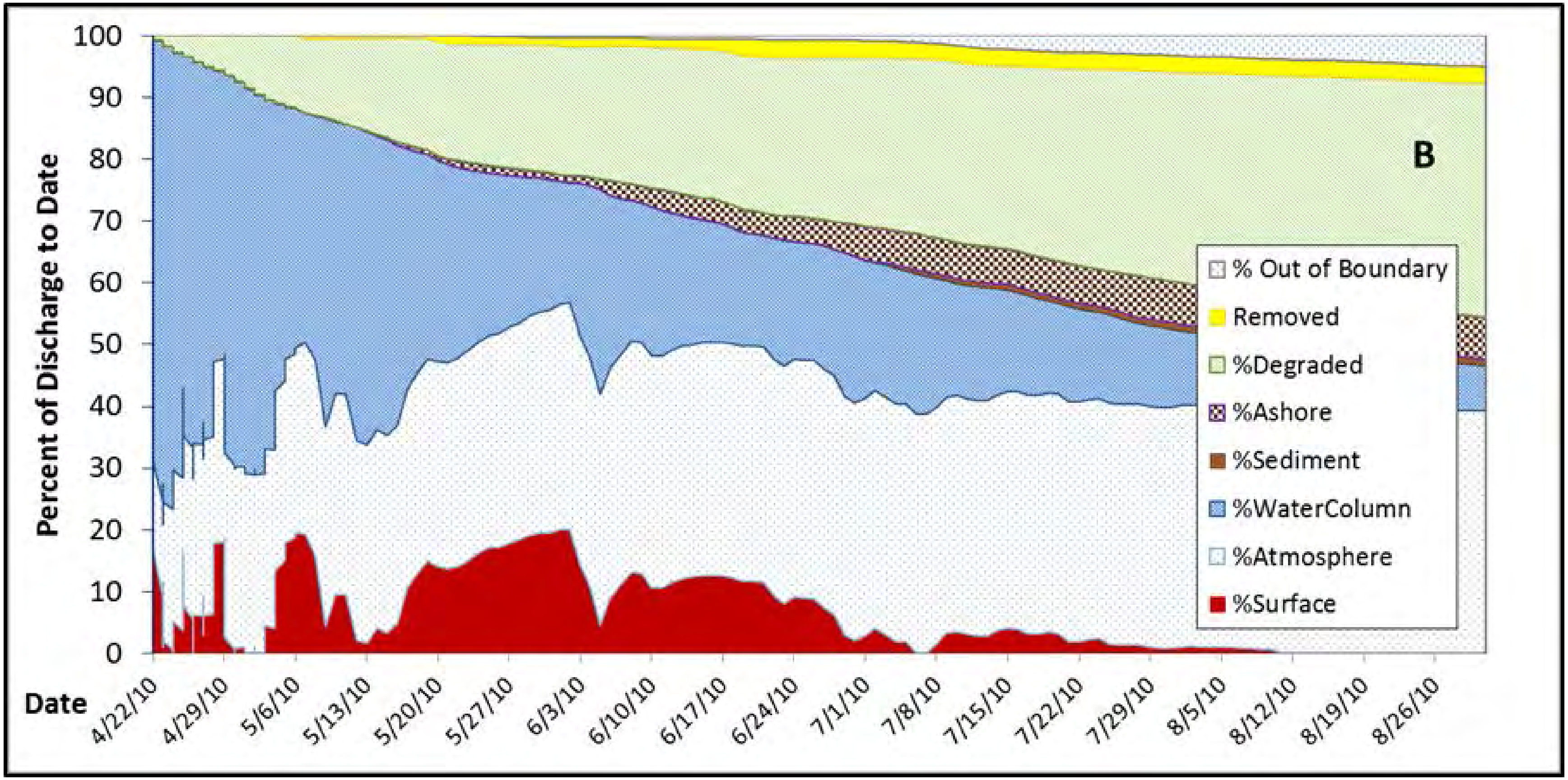
Daily Oil Flow Rate to Environment & Dispersants by Date (Lehr et al. / Government Estimates)



Droplet sizes – Volume Fraction by Day

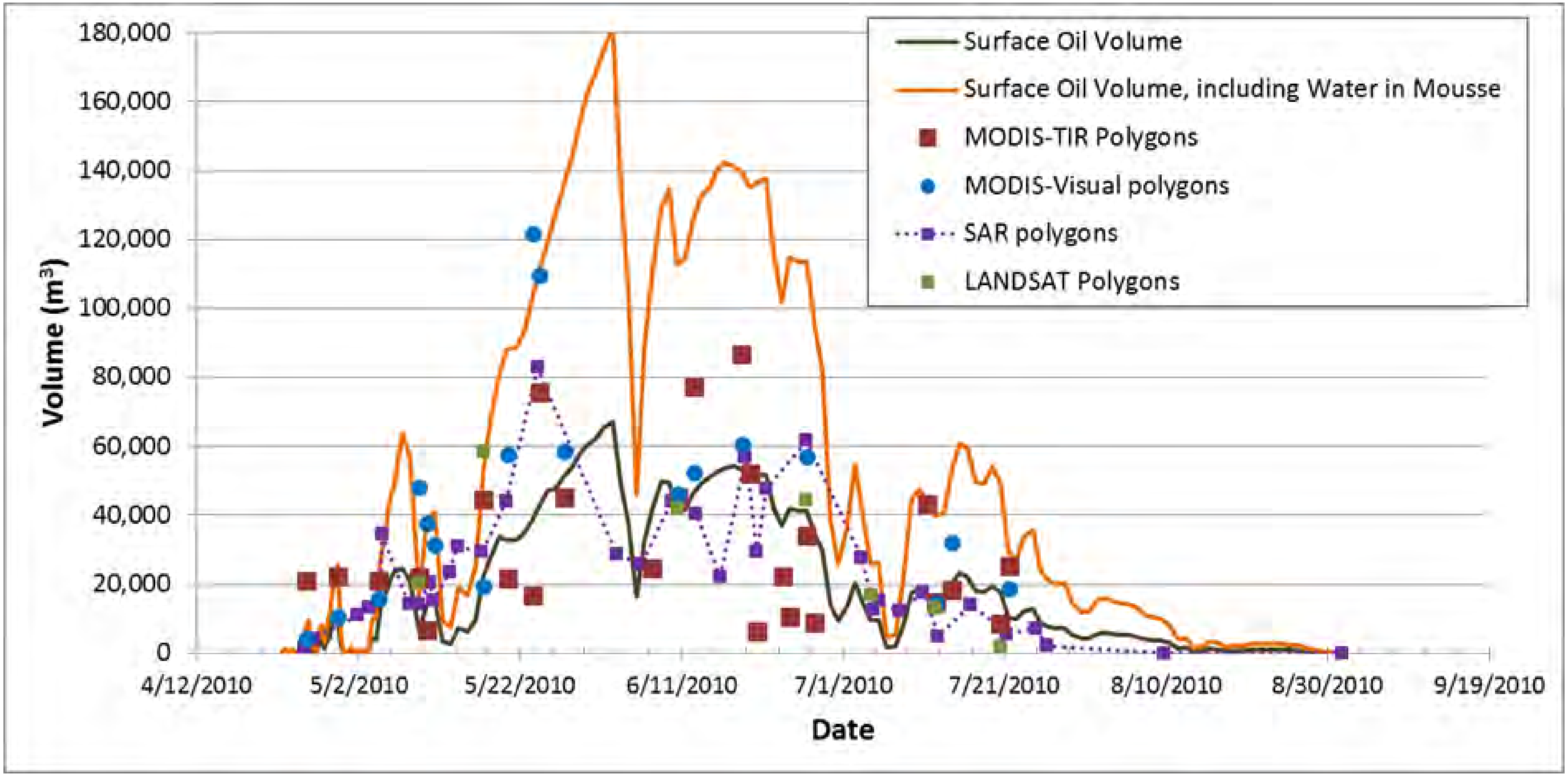


Overall Mass Balance – DWH



Reflects discharged amount over time, dispersant application at depth, winds

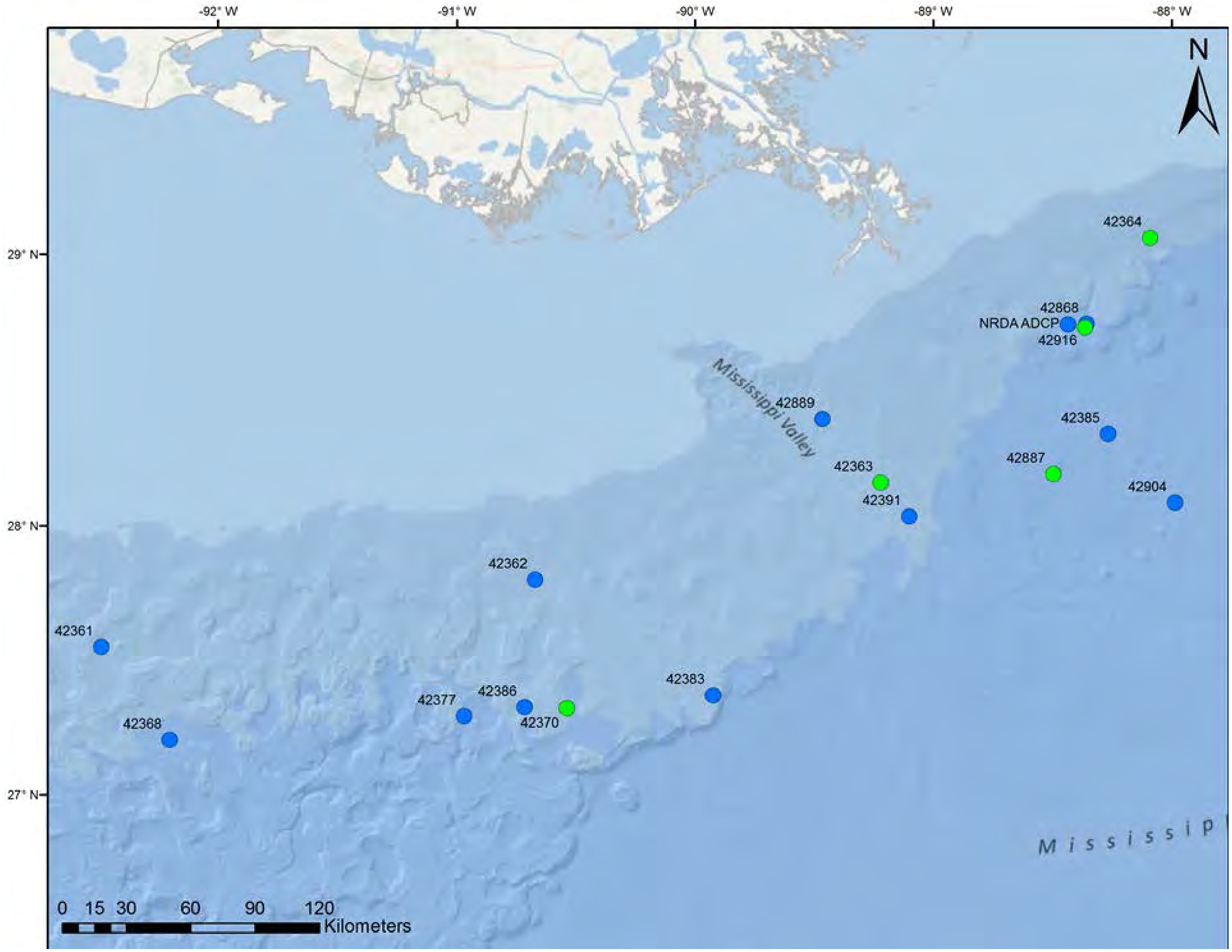
Validation Against Surface Oil Estimates Based on Remote Sensing



Uncertainties in Transport: Currents and Winds Used

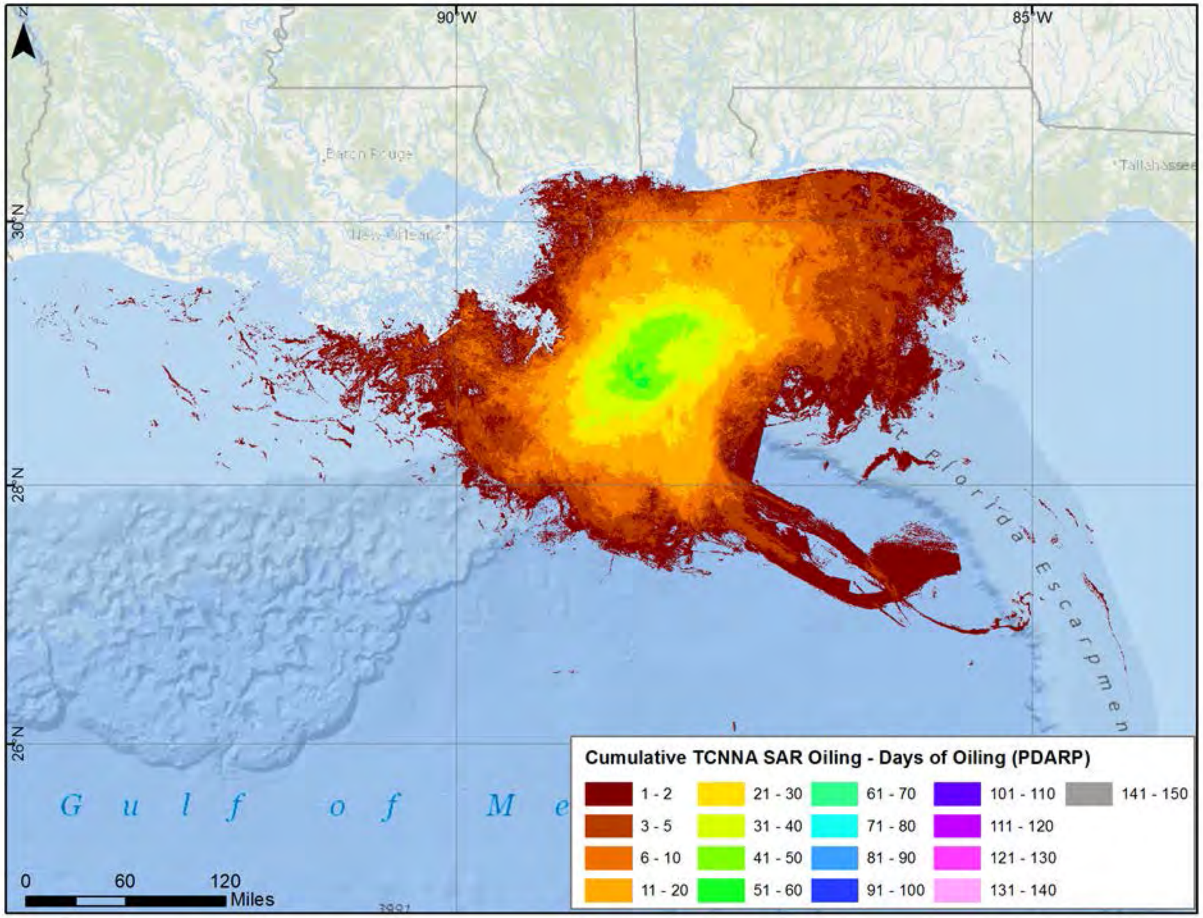
- Hydrodynamics (all very different)
  - ADCPs – measured currents, interpolated – best trajectory below 40 m
  - NGOM (NOAA, real time) – not correct directions below 40 m
  - NCOM (US Navy, NRL, real time) – not correct directions below 40 m
  - HYCOM (US Navy, NRL, real time) – not correct directions below 40 m
  - HYCOM (US Navy, NRL, reanalysis) – similar to FSU version
  - HYCOM (FSU, reanalysis) – best above 40 m, OK below
  - SABGOM (ROMS) – too fast below 40 m
  - IAS ROMs (ROMS) – too fast below 40 m
- Winds (all fairly similar)
  - NOAA: NARR, NAM, CFSR
  - NOGAPS

ADCPs

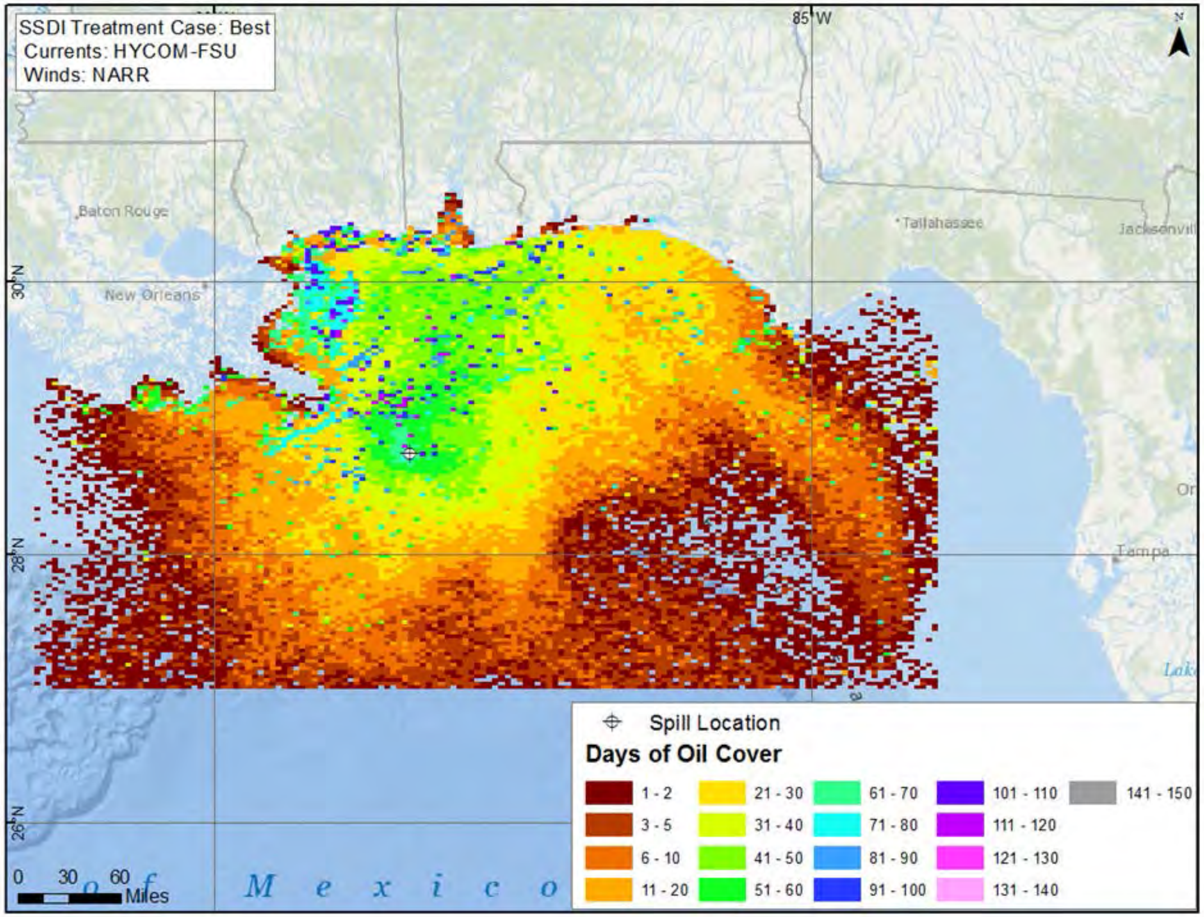


-92° W
-91° W
-90° W
-89° W
-88° W
29° N
28° N
27° N
N
42364
42868
NRDA ADCP
42916
Mississippi Valley
42889
42385
42887
42363
42904
42391
42362
42361
42383
42386
42377
42370
42368
Mississip
0 15 30 60 90 120
Kilometers

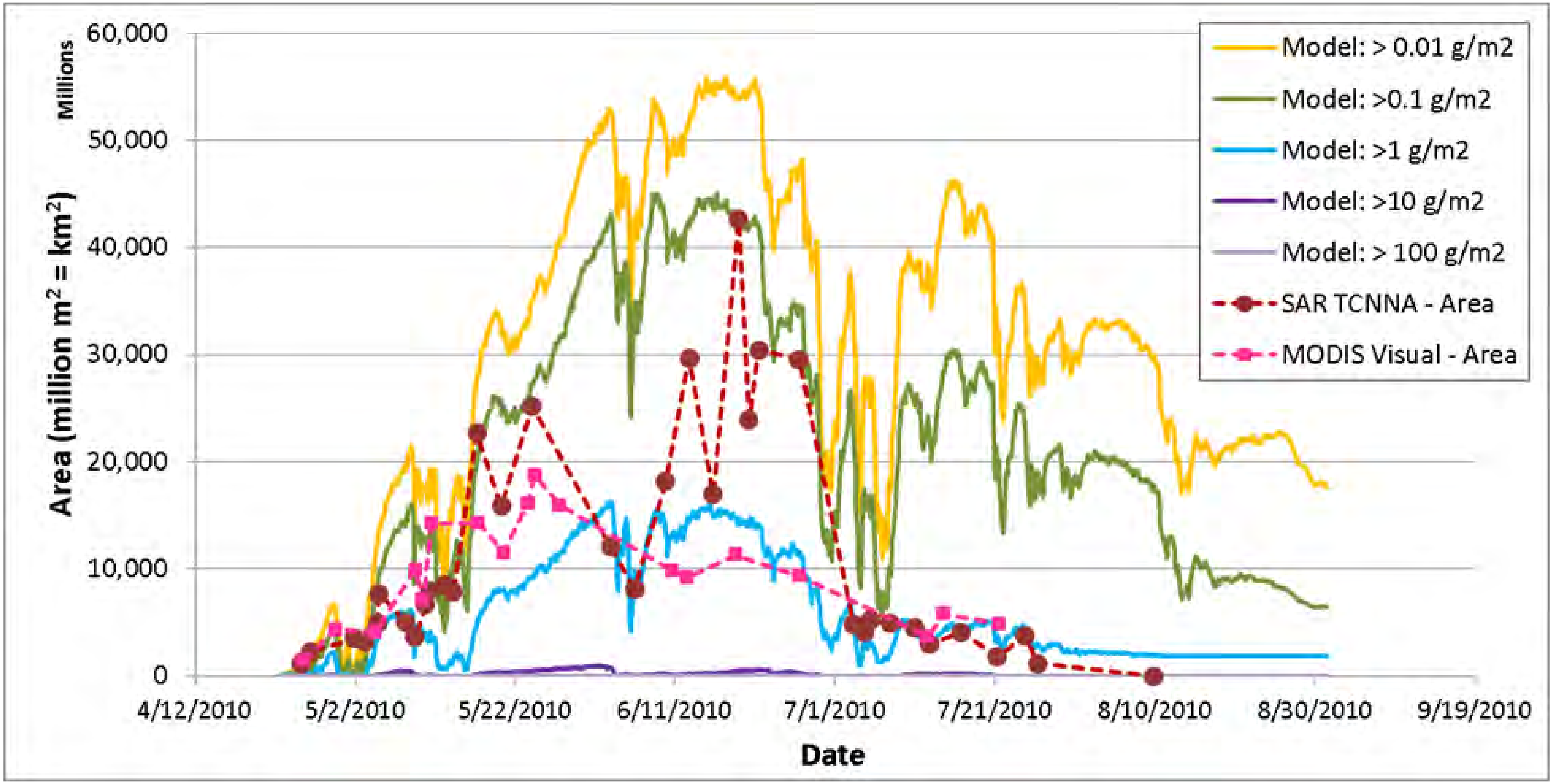
Surface Oil Distribution – SAR Based



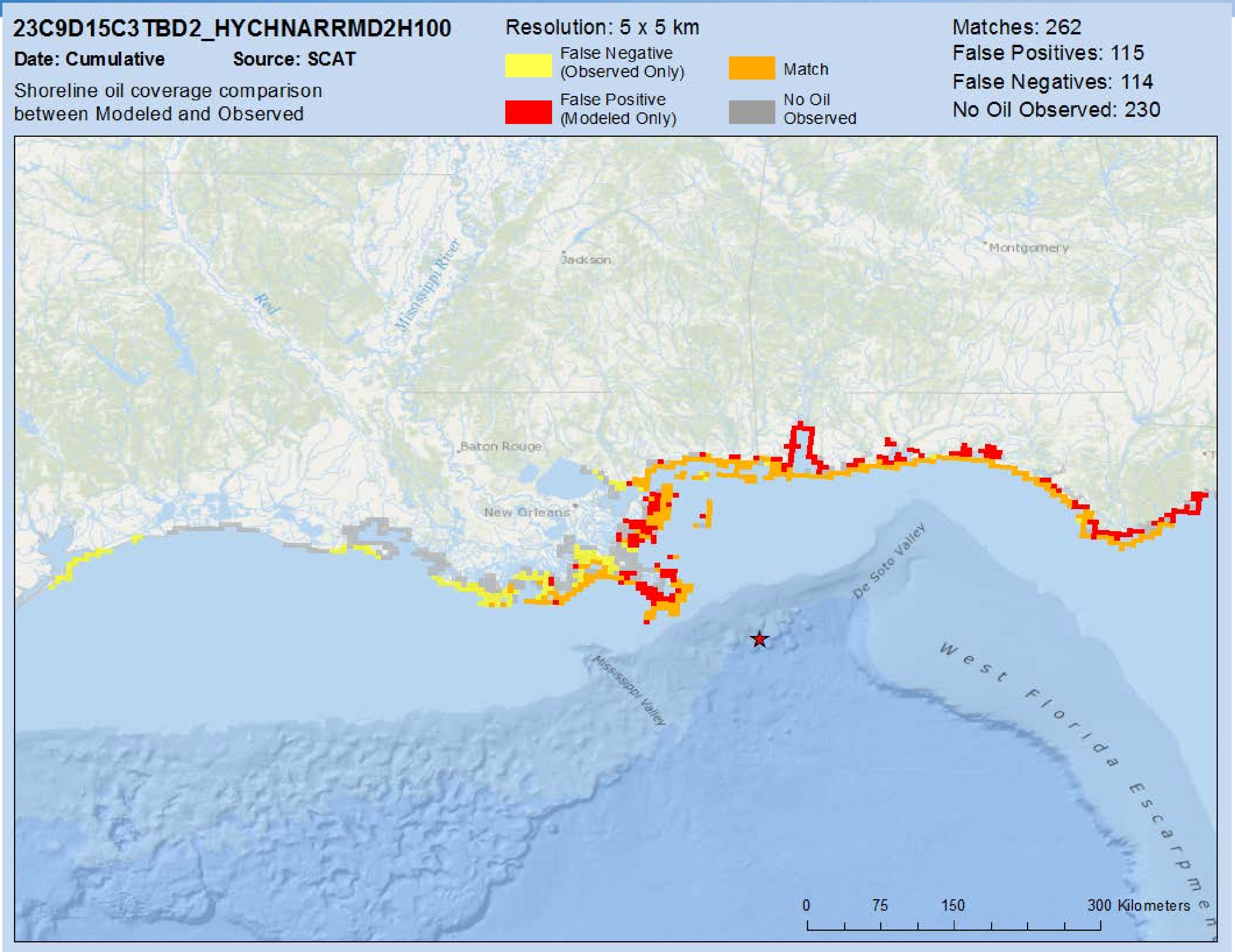
Surface Oil Distribution – Modeled



Surface Oil Area Covered by Oil



Shoreline Oil Distribution – HYCOM FSU

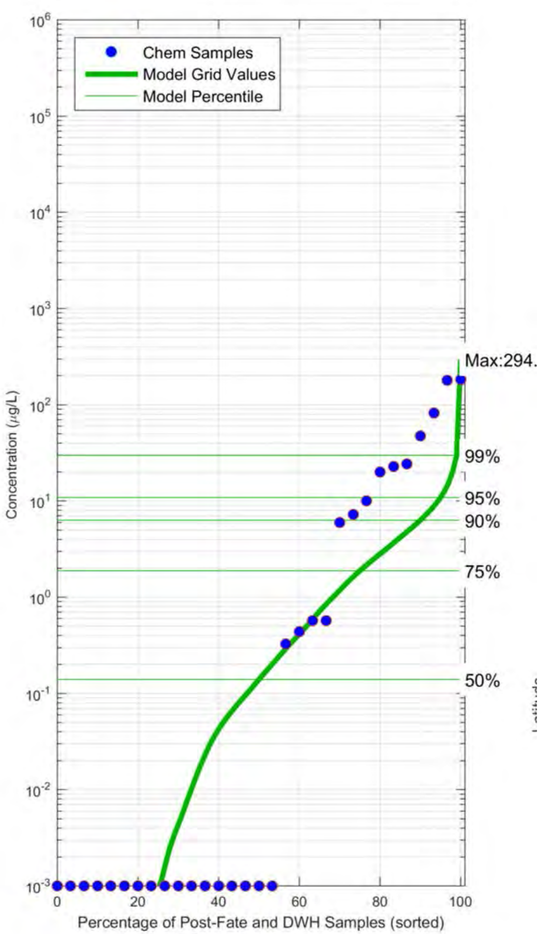


Comparison of the Modeled Concentrations to Field Measurements

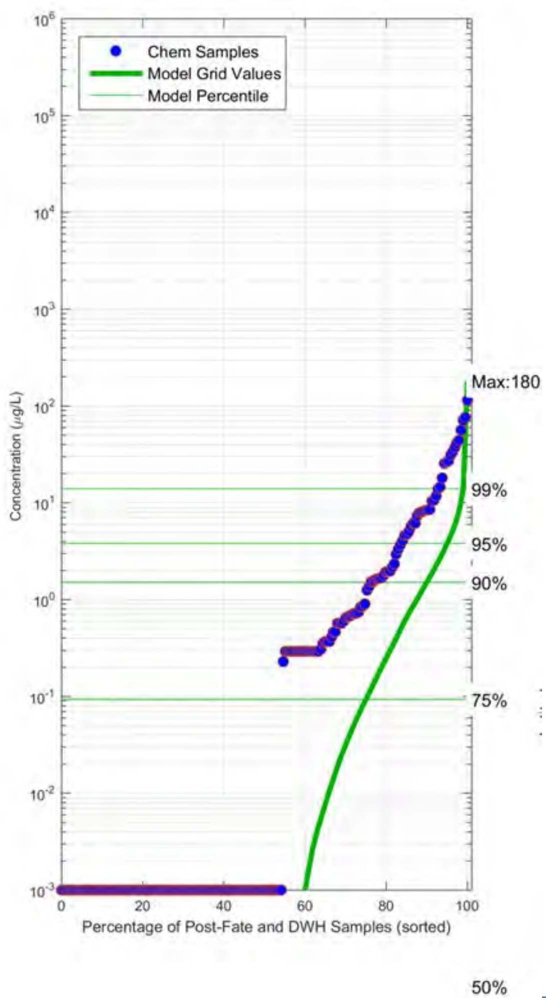
- Due to differences between modeled and actual field conditions and patchiness of observed chemistry – **displacement** between modeled and observed concentrations in both space and time
- Thus, direct overlay of chemistry measurements on the model was insufficient for evaluating if the concentrations produced by the model are reasonable.
- Results were plotted as probability distributions within a spatial (25 km by 25 km box centered on the wellhead) and time window, containing a population of chemistry samples.
  - Most sampling targeted deep plume within 12 km of wellhead
- **Good agreement of magnitudes of concentrations**

Comparison of ADCP Modeled Concentrations to Field Measurements: AR1 = BTEX, 800 – 1000 m

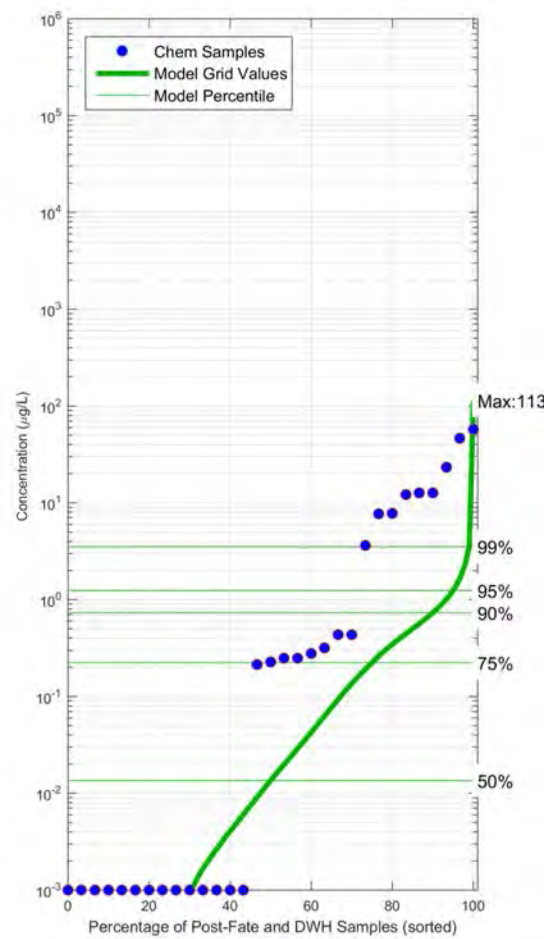
April 22 - May 26



May 26 – June 6

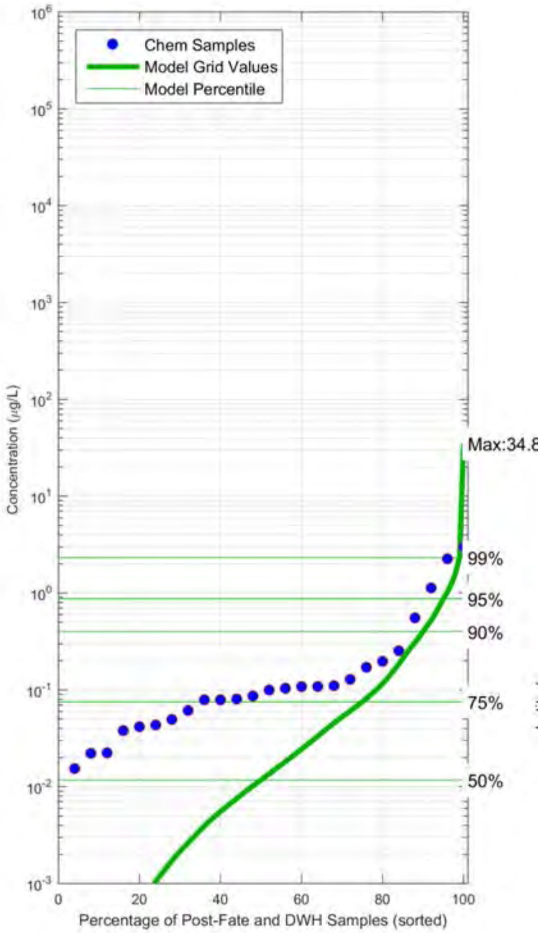


June 6 – July 15

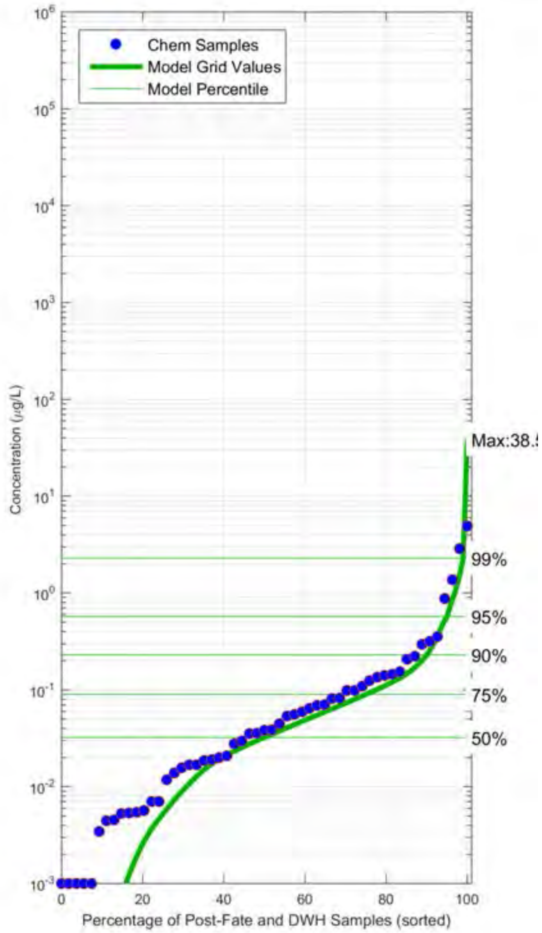


Comparison of ADCP Modeled Concentrations to Field Measurements: AR6, 800 – 1000 m

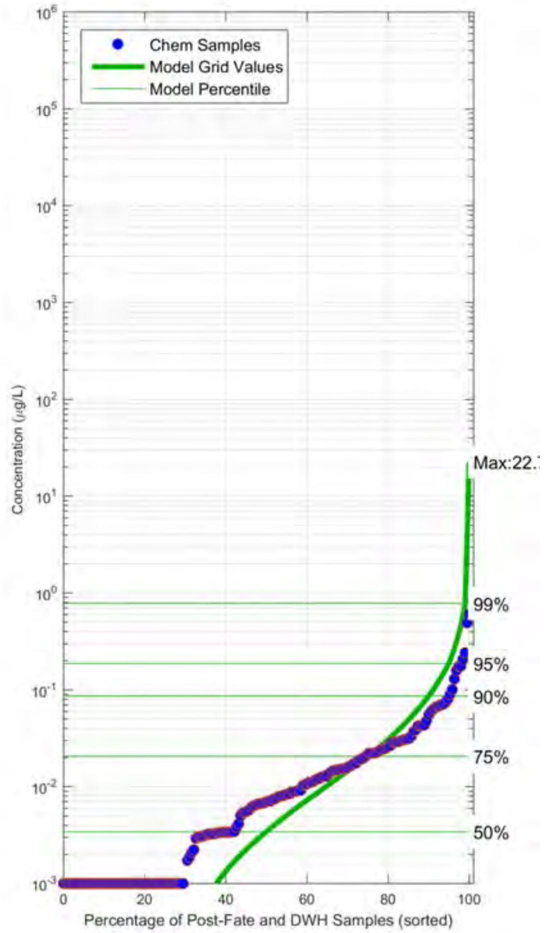
April 22 - May 26



May 26 – June 6



June 6 – July 15



Spill Risk Approach

Risk = (*probability of spill*) X (*consequences*)

Spill Probability

Oil or hazardous material type
Spill size and duration
Location
Season/environmental conditions

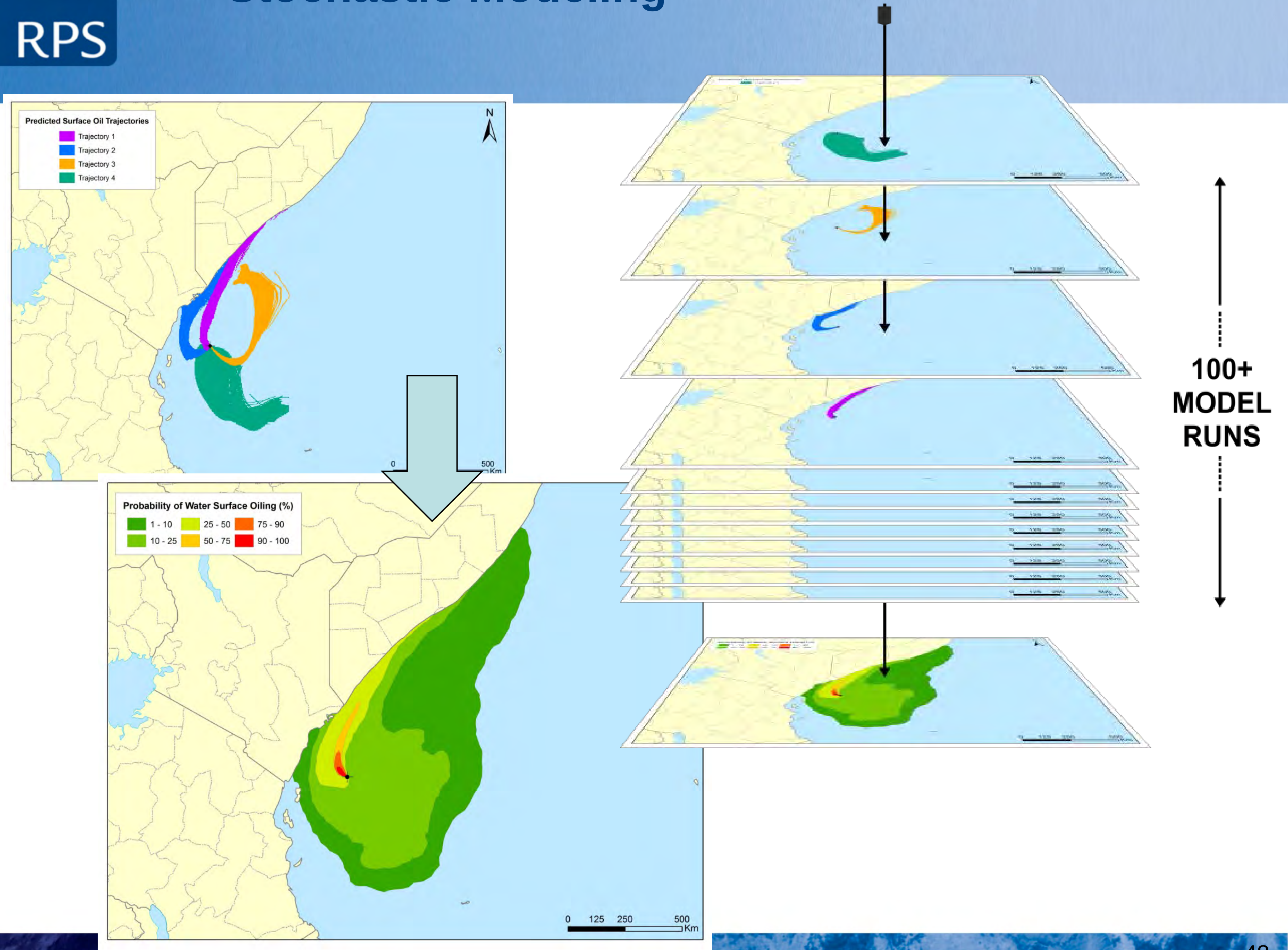
Spill consequences

Shorelines/Habitats
Wildlife (birds, mammals, turtles)
Fish and invertebrates
Socioeconomic resources

Stochastic Modeling

- **Quantifies**
  - Probability of contamination above threshold of concern
  - Mean (50th) and other (e.g., 99th) percentile degrees of contamination by location around the spill site
- **Uses**
  - Response planning
  - Environmental / Ecological Risk Assessment
  - Identification of worst case scenario for
    - Floating oil exposure
    - Shoreline oiling
    - Water column exposure

Stochastic Modeling



Potential Oil Trajectories and Surface Oil Exposure from Hypothetical Discharges in the Chukchi and Beaufort Seas

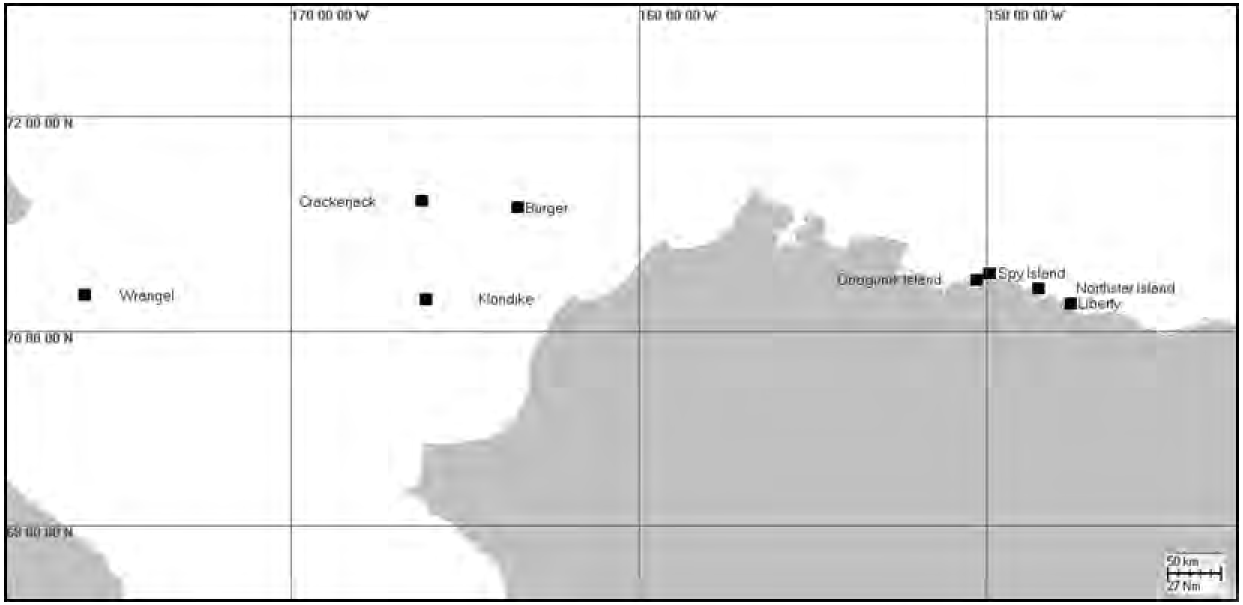
US Fish and Wildlife Service (USFWS) evaluated potential overlaps of oil spill trajectories from hypothetical spills with polar bear and other marine mammal distribution, habitat and usage maps (with Ryan Wilson, USFWS and Craig Perham, now @ BOEM)

Publications:

- Wilson, Ryan R., Craig Perham, Deborah P. French-McCay, Richard Balouskus, 2018. Potential impacts of offshore oil spills on polar bears in the Chukchi Sea. Environmental Pollution 235: 652-659.
- French McCay, D., R. Balouskus, J. Ducharme, M. Schroeder Gearon, Y. Kim, S. Zamorski, Z.Li, and J. Rowe, 2017. Potential Oil Trajectories and Surface Oil Exposure from Hypothetical Discharges in the Chukchi and Beaufort Seas. Proceedings of the 40th AMOP Technical Seminar on Environmental Contamination and Response, Emergencies Science Division, Environment Canada, Ottawa, ON, Canada.
- French-McCay, D.P., T. Tajalli-Bakhsh, K. Jayko, M. L. Spaulding, and Z. Li, 2018. Validation of oil spill transport and fate modeling in Arctic ice. Arctic Science 4: 71–97.
- French McCay, D., T. Tajalli Bakhsh, and M.L. Spaulding, 2017. Evaluation of Oil Spill Modeling in Ice Against In Situ Drifter Data from the Beaufort Sea In: Proceedings, International Oil Spill Conference, May 2017, Paper 2017-356, American Petroleum Institute, Washington, DC.

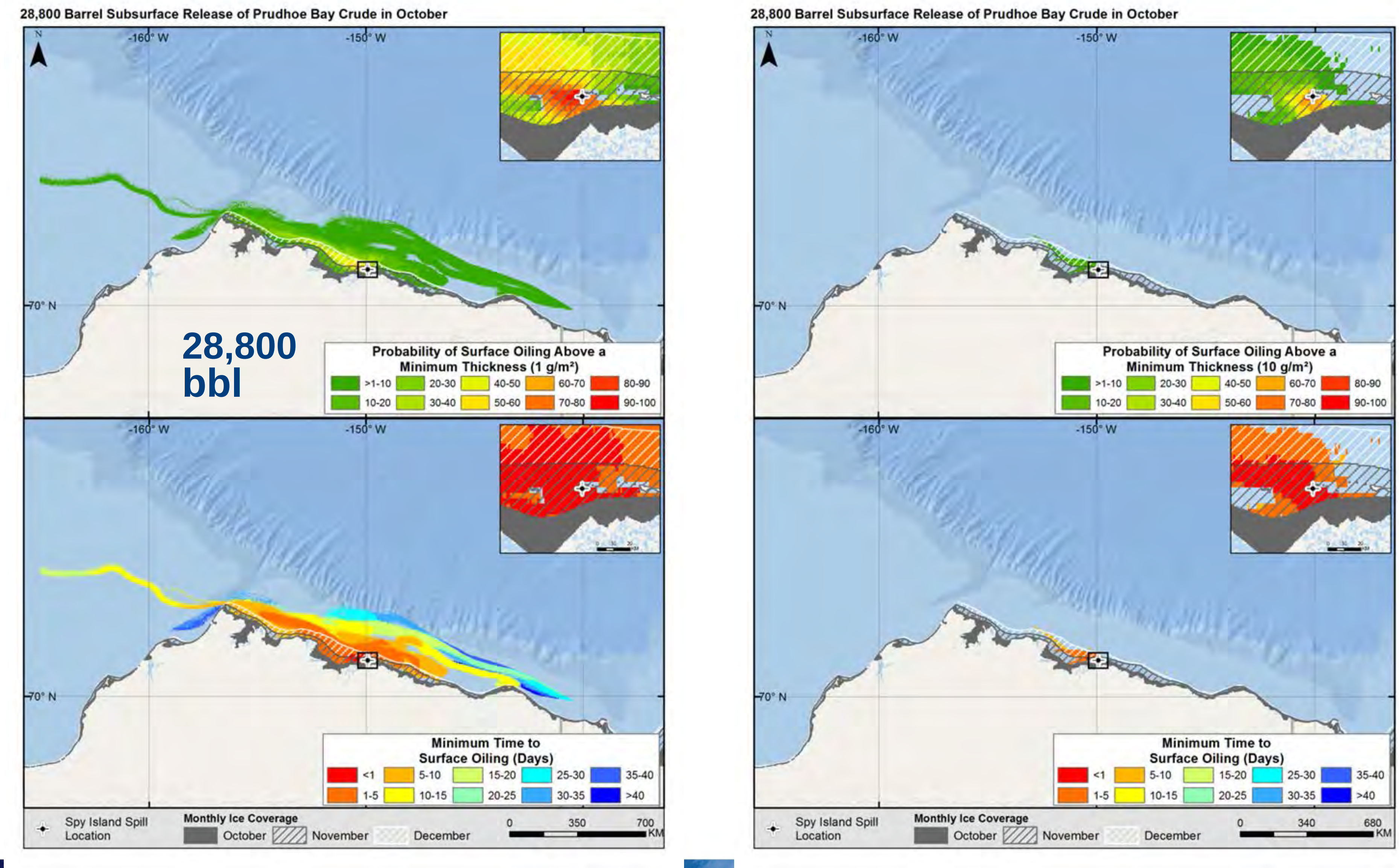
Oil Spill Scenarios: Spill Sites, Discharge Rates, Durations, Oil Type

- Beaufort Sea (6-day pipeline discharges at sea floor)
  - **Spy Island; 4,800 bbl/day (Prudhoe Bay, medium crude)**
  - **Spy Island; 110 bbl/day (Prudhoe Bay, medium crude)**
  - **Northstar Island; 4,800 bbl/day (light crude)**
  - **Liberty; 4,800 bbl/day (heavy crude)**
- Chukchi Sea (blowouts: medium crude, 25,000 bbl/day for 30 days)
  - **Burger**
  - **Klondike**
  - **Crackerjack**
  - **Wrangel**
- **Spill Start in October**



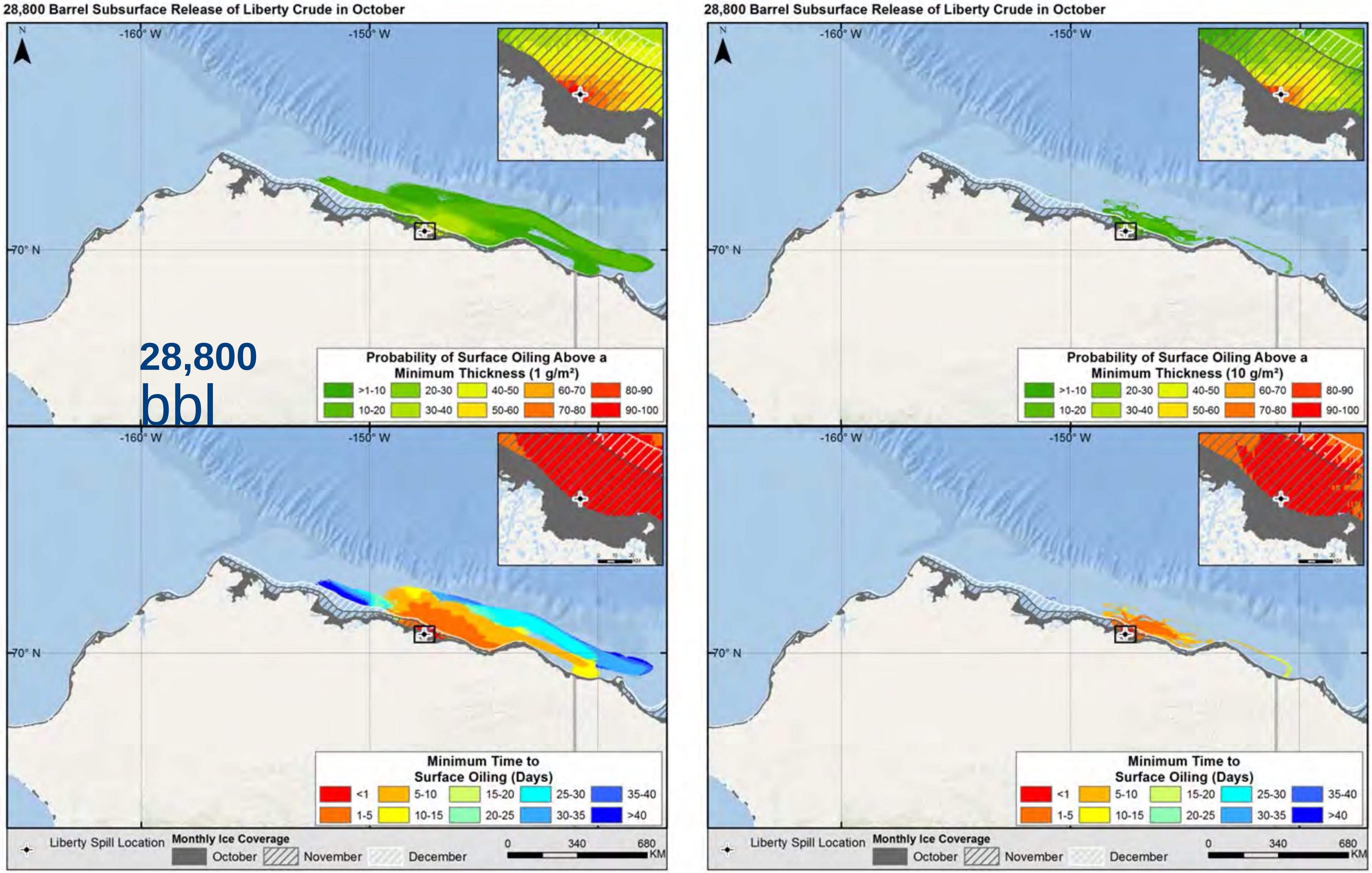
28,000 bbl spill

Probability of Surface Oiling & Time of First Arrival for ≥1 g/m² (Left) or ≥10 g/m² (Right) Oil Cover at Spy Island



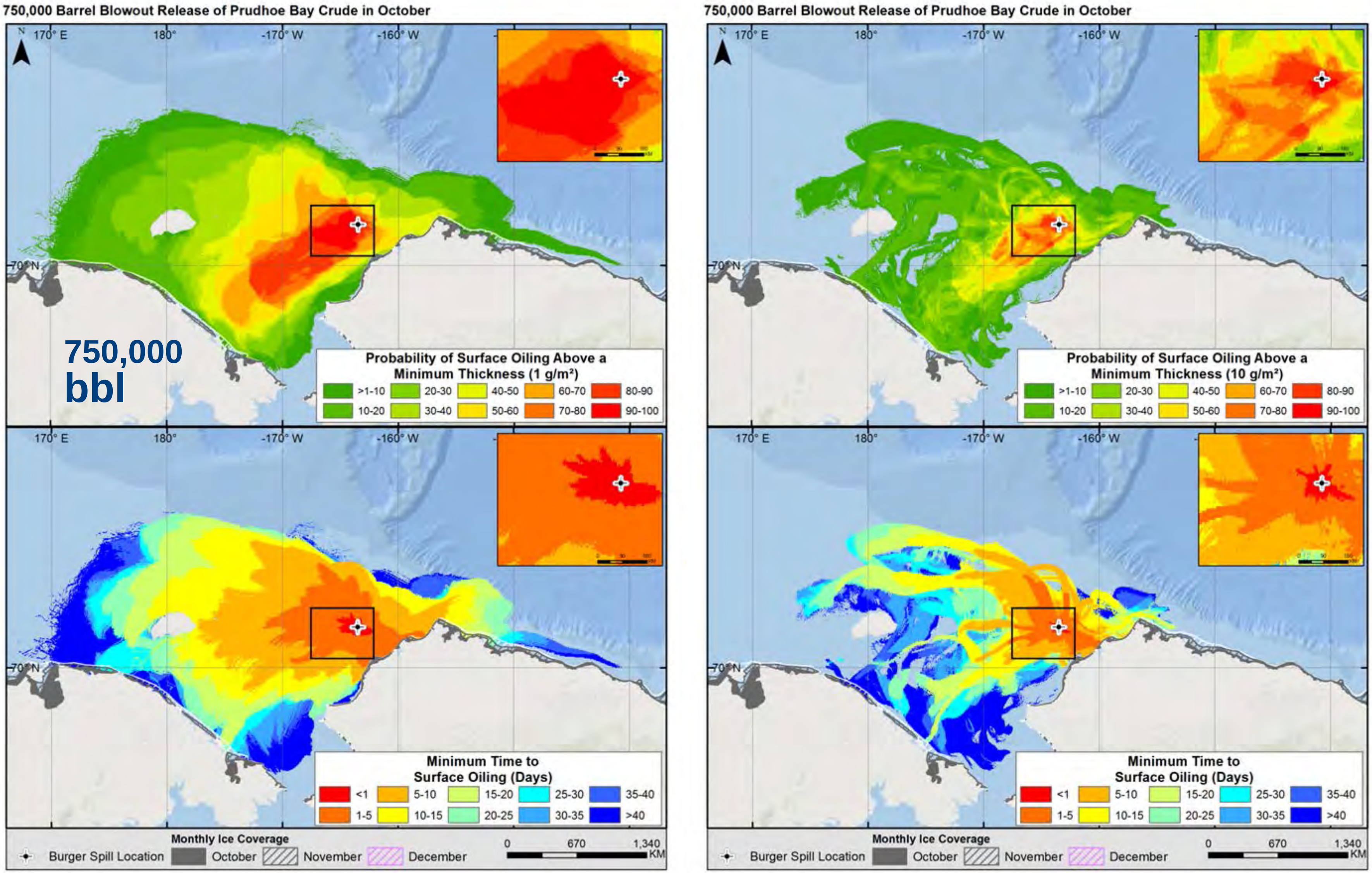
28,000 bbl spill

Probability of Surface Oiling & Time of First Arrival for ≥1 g/m^2 (Left) or ≥10 g/m^2 (Right) Oil Cover at Liberty



75,000,000 bbl spill

Probability of Surface Oiling & Time of First Arrival for ≥1 g/m² (Left) or ≥10 g/m² (Right) Oil Cover at Burger



Consider These are Worst Case Discharges

- Hypothetical spills modeled here were very large, worst case scenarios.
- Also, worst conditions for persistence of surface oil in the environment were evaluated: a spill occurring or to continuing into the ice freeze up season (i.e., occurring during October).
- The probability of such a spill occurring would be extremely low.
- Results from smaller spills and in other seasons would result in much less surface oil exposure.
- Need to consider Risk: These results should be considered in view of the joint probabilities of such a spill occurring and of the projected consequences.

Comparative Risk Assessment (CRA) Study

- Oil Fate and Exposure – Deep Sea Blowout With and Without Subsea Dispersant Injection Treatment (SSDI)
- Compared various response options
  - **No intervention**
  - **Mechanical only**
  - **Mechanical & In-Situ Burning & Surface Dispersant (MBSD)**
  - **MBSD & SSDI**
  - **SSDI-only**
- 3 papers in press Marine Pollution Bulletin
- API Sponsored
- Included a Technical Advisory Committee (TAC) of Responders and Subject Matter Experts (SMEs)

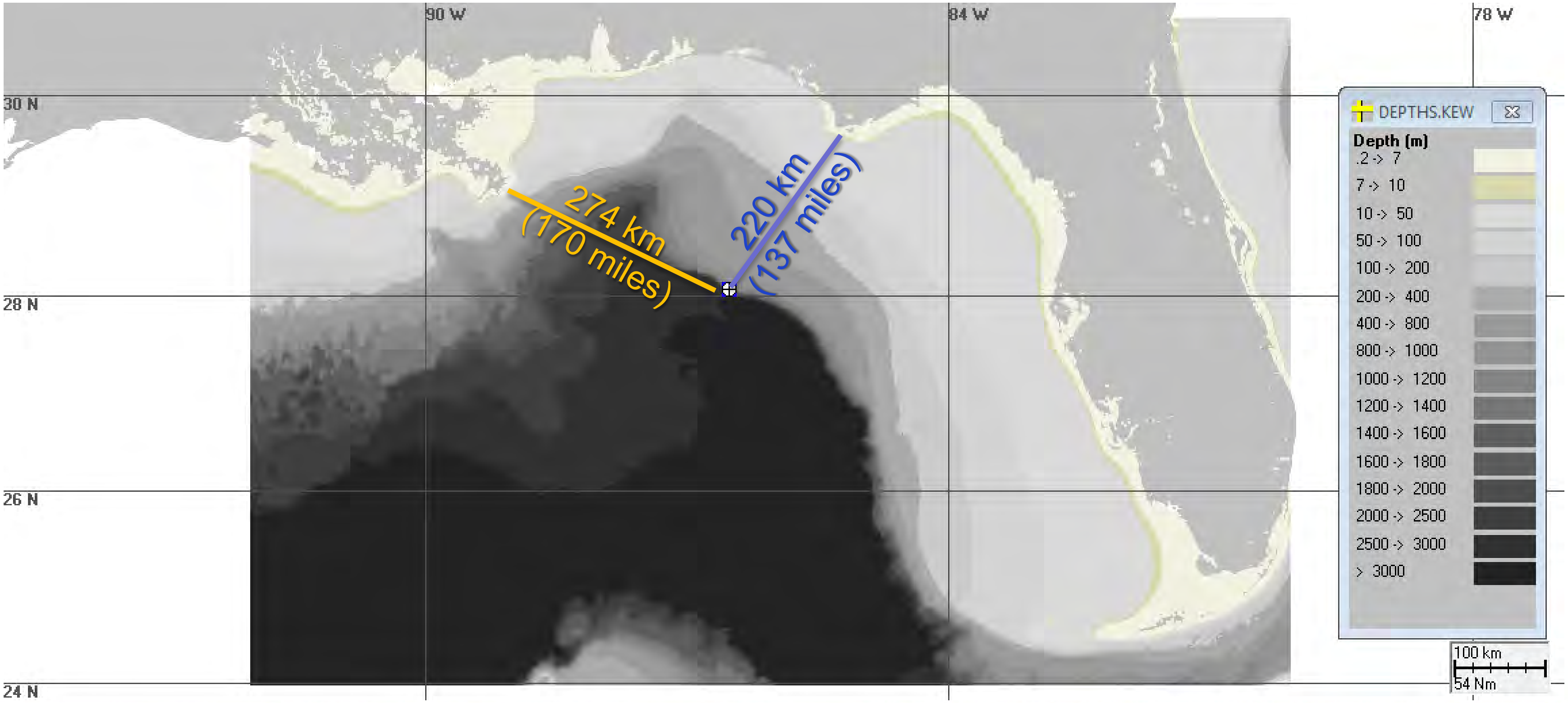
Comparative Risk Assessment (CRA)

Oil Release Rate	45,000 bbl/day
Release Duration	21 days
Release Depth	1400 m
Crude oil density	API = 34.2

274 km
(170 miles)

220 km
(137 miles)

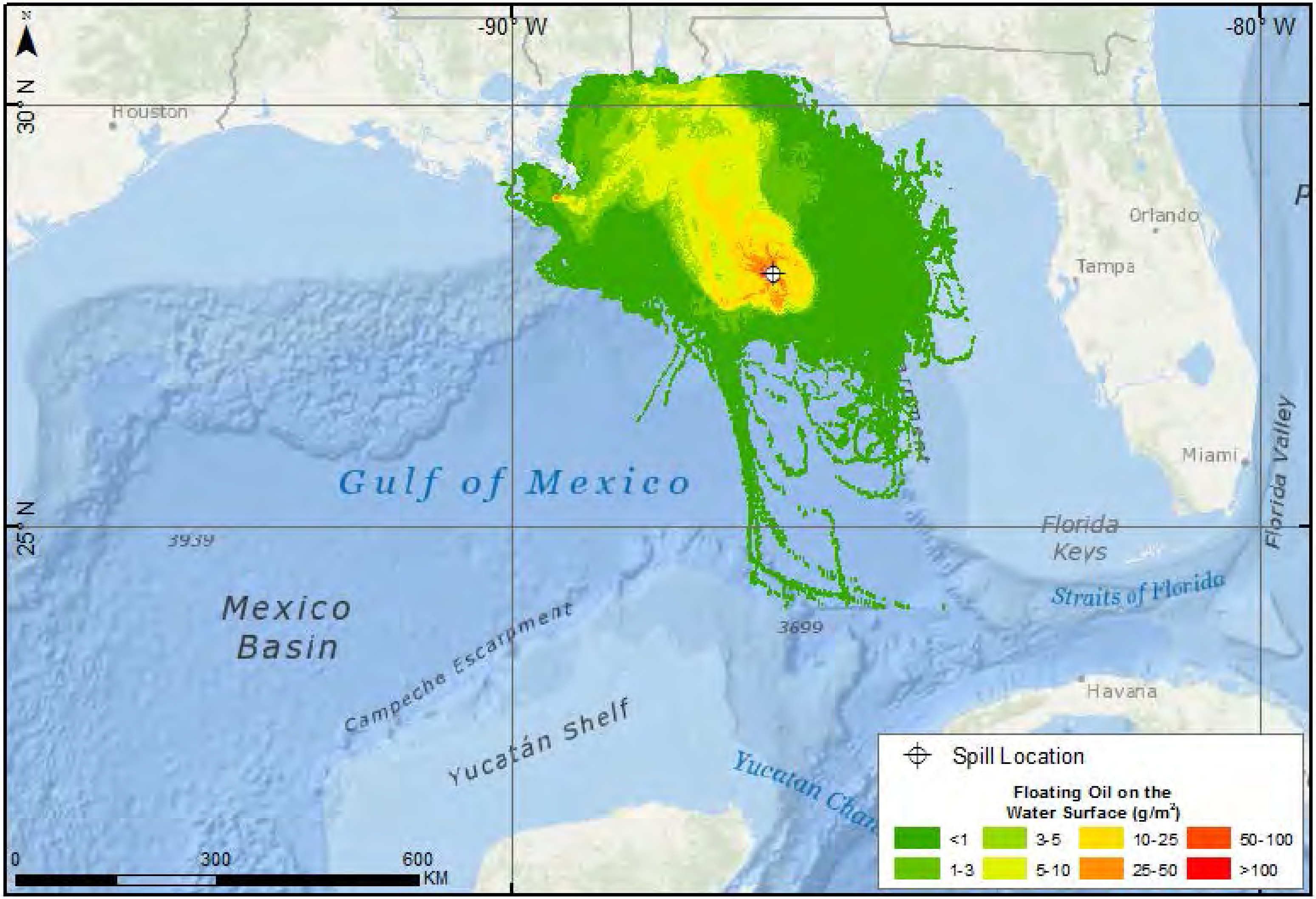
- **Currents – Naval Research Lab HYCOM**
- **Winds – NOAA NCEP CFSR hourly**



No Intervention – 5th Surface & 97th Shoreline Oil of 100 Runs Starting at Randomly-Selected Dates: Maximum Exposure on Water Surface (at any time)

Averaged g/m^2 in ~1km^2 grid cells

Run 36: Spill Start: 2008 Dec 5, 12:08 UTC



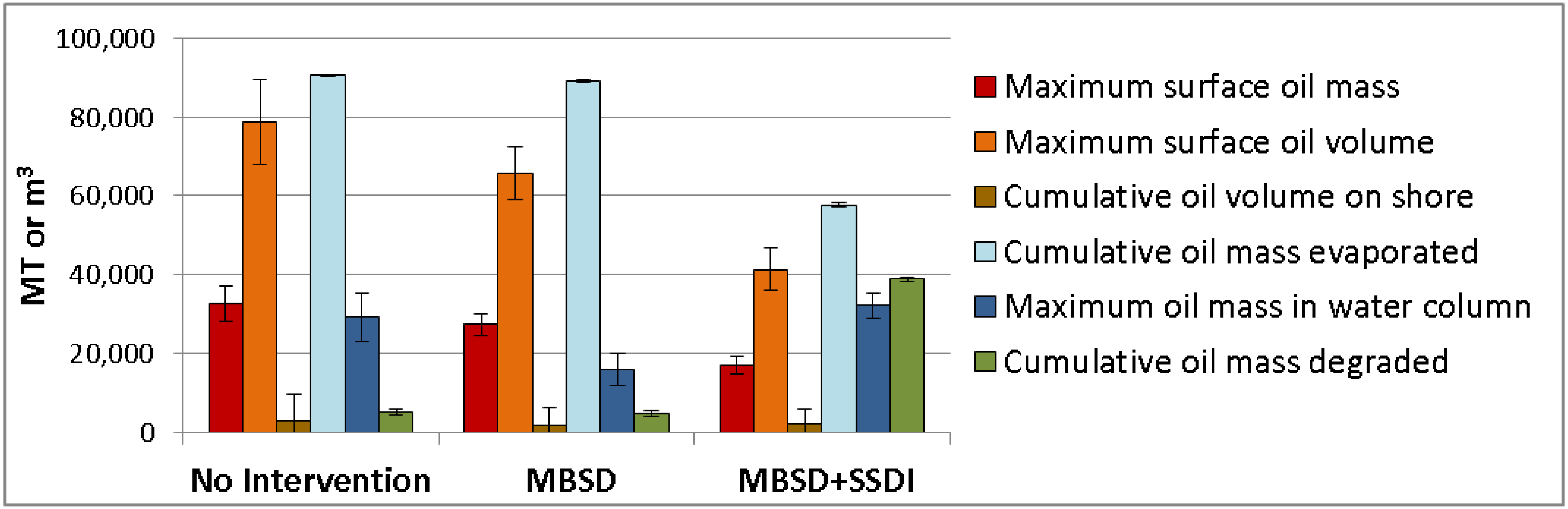
RPS

Results of CRA Study

Uncertainty – Environmental Conditions: Summary of Exposure Metrics for 100 Model Runs, Randomizing Start Date and Time

Mean (Coefficient of Variation = SD/Mean)

Due to Environmental Conditions



RPS

Conclusions of CRA Study

The Model-Predictions Show

- **Mechanical and *in situ* burning only removed a small fraction of the oil that would otherwise have been floating or evaporate.**
- **Compared to the No-Intervention and MBSD cases, SSDI has the potential to substantially**
  - **Reduce the amount of oil and mousse on the water surface and on the shoreline**
  - **Increase dissolution rate of soluble & semi-soluble hydrocarbons (BTEX, PAHs and soluble alkanes) and so their degradation rate**
  - **Increase weathering rate of rising oil such that floating oil contains much less soluble & semi-soluble aromatics (BTEX, PAHs)**
  - **Decrease VOC emissions to and concentrations in the atmosphere and human and wildlife exposure**
  - **Reduce the concentrations of PAHs in surface waters**
  - **Increase the concentrations of PAHs in deep water; however, densities of biota at depth are << than near surface**

Risk Assessment for BOEM: Similar Results & Conclusions

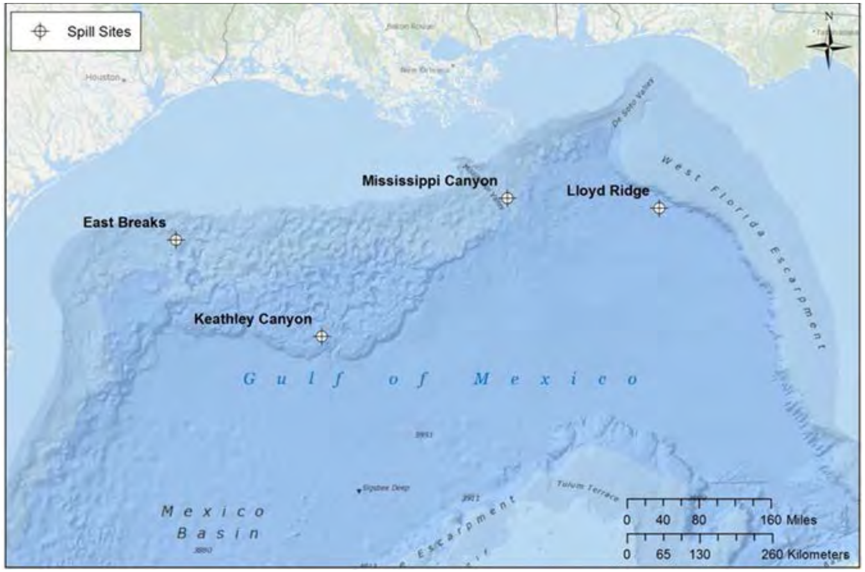
Spill Scenario

- 45,000 bbl/day over 30 days decreasing by 113.1 bbl/day
- Total Release = 1,300,802 bbl
- Simulation Length = 75 days

Parameters Considered

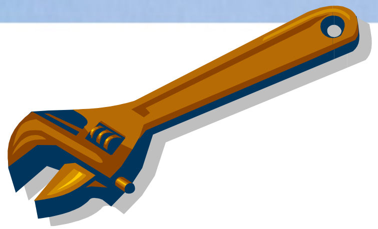
- 4 Release Locations (680 – 2,950 m depth)
- 2 GOR's (100 and 1,500 scf/stb)
- 2 Crude Oil types (light and medium)
- 3 Dispersant Options: none, 50% and 100% effectiveness
- 3 Hydrodynamic/wind model pairs
  - POM/ECMWF
  - ROMS/NARR
  - HYCOM/NARR

144 possible spill scenarios distilled to 72



Physical Parameters	Mars TLP 2004	Ship Shoal Block 269
Oil Type	Medium	Light
Pour Point (°C)	-28°	-42°
API Gravity	26.8	38.7
Density at 25°C (g/cm^3)	0.8817	0.8236
Viscosity (cP) @ 25°C	24	4

Conclusions – Models as Informative Tools



- Modeling results are useful to
  - Inform response planning
  - Assess risks
  - Scale the expected level of impact
- May use conservative assumptions to be protective of resources at risk
- **Quantitative**, based on best information
- Allows evaluation of alternatives and tradeoffs
  - Response options
  - Regulatory approaches

Contact Information

Deborah French McCay, Ph.D.

Director, Research and Model Development
RPS Ocean Science

South Kingstown, RI USA

Debbie.FrenchMcCay@rpsgroup.com
+1 (401) 789 - 6224 x331