Remost Sensing Assessment of Surface Oil Transport and Fate during Spills in the Gulf of Mexico

WAMOST (Weathering and Advection Model for Oil Spill Tracking)

BOEM Contract M12PC00003
Project Tasks & Scientific Personnel

- Task 1: Project management
  - Ian MacDonald, FSU

- Task 2: Surface Oil Distribution from Remote Sensing
  - Chuanmin Hu, USF (Optical Remote Sensing)
  - Oscar Garcia, FSU (SAR)
  - Samira Daneshgar Asl, FSU (SAR)

- Task 3: Oil Transport Chemical Modeling Model
  - Mark Reed, SINTEF
  - Jøgen Skancke, SINTEF

- Task 4: Ocean and Wind Forcing
  - Dmitry Dukhovskoy, FSU COAPS
  - Steve Morey, FSU COAPS

- Task 5: Mixing Processes and Wind Forcing
  - Mark Bourassa, FSU COAPS
Peer-Reviewed Publications (to date)

1. Clark M, Heath N, Bourassa MA. 2015. Quantification of Stokes drift as a mechanism for surface oil advection in the Gulf of Mexico. J Geophys Res. (accepted, pending minor revisions)
Task 1: Project Integration

**Deliverables**

- Remote sensing algorithms for assessing oil spills;
- Oil coverage data;
- Thickness categories

- Forcing fields;
- Evaluation metrics for model performance;
- Simulated fields of oil coverage

- Impact of physical factors on oil transport and character under various conditions

- Analysis of oil mixing across material boundaries;
- Methods for identification of material boundaries;
- Quantity estimate of permeability of the boundaries for surface oil

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**Task 2:** Surface Oil Distribution from Optical and SAR Data  
FSU, USF

**Task 3:** Oil Transport and Weathering Model, Surface Fields  
SINTEF, FSU

**Task 4:** Effects of Ocean and Wind Forcing  
SINTEF, FSU

**Task 5:** Mixing Processes and Oil Transport  
FSU

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Insights on influence of ocean, waves, and wind fields on oil drift

Simulated oil transport and coverage; Model error estimates

Analysis of SAR and Optical Data for coverage and characteristics of surfaced oil
Task 2: Characterize Surface Oil Distributions Using SAR and Optical Remote Sensing

Distribution of DWH surface oil from satellite remote sensing

From SAR (MacDonald et al., unpublished)

From MODIS/MERIS (Hu et al., 2011)

Calibration of surface oil thickness from AVIRIS (below)

Approach:
1. Spectral analysis in the visible, NIR, and shortwave NIR
2. Scaling-up from AVIRIS to MODIS/MERIS
Task 2a: Characterize Surface Oil Distributions Using Optical Remote Sensing

Top: Oil slicks detected by VIIRS but not by MODIST
Bottom: Oil slicks detected by MODIS A but not by VIIRS

- Sun glint strength determines whether thin oil can be observed or not
  > $10^{-5}$ sr$^{-1}$: yes
  < $10^{-6}$ sr$^{-1}$: no
(Sun and Hu, 2016)
Task 2a: Characterize Surface Oil Distributions Using Optical Remote Sensing

Surface oil volume maps derived from MODIS after using histogram-based AVIRIS calibration

Color legend shows oil volume in liters per MODIS 250-m pixel
Example showing the case for May 17, 2010. 18 other cases are available (Hu et al., 2016, submitted)
Task 2a: Characterize Surface Oil Distributions Using Optical Remote Sensing

Surface oil thickness classes derived from MODIS after using histogram-based AVIRIS calibration

Color legend shows different oil thickness classes and other image features
Example showing the case for May 17, 2010. 18 other cases are available (Hu et al., 2016, submitted)
Task 2a: Characterize Surface Oil Distributions Using Optical Remote Sensing

Surface oil probability maps

0.1 means that 10% of that location is covered by oil of that thickness
Task 2a: Characterize Surface Oil Distributions Using Optical Remote Sensing

- Oil slick morphology characterized for different oil thickness classes derived from AVIRIS measurements of the DwH. (Sun et al. 2015).
- Thickness estimates obtained by processing AVIRIS images from a limited survey of DwH suggested a median thickness of 70 µm for emulsified oil (Sun, Hu et al. 2015).
- The DwH SAR data set was subsequently used to quantify “thin” (1 µm) and “thick” (70 µm) oil.

AVIRIS-derived oil thickness (left) and Red-Green-Blue true color maps (from Clark et al., 2010)
Task 2a: Characterize Surface Oil Distributions Using Synthetic Aperture Radar

- Satellite SAR image processing was performed using TCNNA algorithm (Garcia-Pineda, Zimmer et al. 2009, Garcia-Pineda, MacDonald et al. 2010)
- TCNNA is an in-house developed algorithm which employs satellite and meteorological variables, and textural analysis to extract oil features from RADAR images.
- Each SAR pixel is classified as feature or non-feature and to reproduce, pixel by pixel, classifications an expert human analyst would evaluate whether a given group of pixels belongs to a feature.

For WAMOST, additional routines were developed to output multiple values corresponding to apparent oil thickness categories.
Mapping Surface Oil with SAR—
~950 Natural Seep Zones
A total of 176 SAR images comprise a consistent sample of oil-covered water during the DWH episode (24 April - 08 August 2010). Preliminary results shown next are based on 141 of these images.
Task 2a: Oil Emulsion Detection Algorithm

- A publication for WAMOST (Garcia-Pineda, MacDonald et al. 2013) describes the development of the Oil Emulsion Detection Algorithm.
- The Deepwater Horizon spill generated large areas of rainbow sheen and smaller regions of emulsified oil.
- Comparison of aerial photos and surface samples with SAR images found that emulsion produced a radar signature with intermediate intensity between unoiled water and floating sheen.
- This signature was used to segment areas of oil emulsion in 60 SAR images, which were applied to a time-series analysis of the spill.
Surface volume animation: 12-h best estimate from SAR

Total Volume (m³): 2673
Total Area (km²): 1641
Average Volume ($m^3/km^2$)

- **Cell Average**
  - 0.02 - 0.10
  - 0.19 - 0.29
  - 0.44 - 0.61
  - 0.84 - 1.13
  - 1.56 - 2.28

- **Vol ($m^3/km^2$)**
  - 0.11 - 0.18
  - 0.30 - 0.43
  - 0.62 - 0.83
  - 1.14 - 1.55
  - 2.29 - 4.06

Footprint Average Volume ($m^3$): 22619
Footprint Average Area ($km^2$): 11804
Time Series of DWH Oil
Oil-Covered Water—all thicknesses

![Graph showing the time series of DWH Oil oil-covered water in km² over time from 24 April to 2 August.]
Time Series of DWH Oil
Oil-Covered Water—Thick Oil (~70 µm)
Time Series of DWH Oil
Daily SAR Volume of Surface Oil

![Graph showing the daily SAR volume of surface oil from 24th April to 2nd August, with peaks on 6 May, 23rd May, 18th June, and 18th July. The graph indicates a significant increase in oil volume on these dates.](image-url)
DWH Surface Oil Animation

LOUISIANA
MISSISSIPPI
ALABAMA
GEORGIA
FLORIDA

APR24_12Z

<table>
<thead>
<tr>
<th>Vol (m³/km²)</th>
<th>0.1 - 0.39</th>
<th>0.75 - 1.2</th>
<th>1.8 - 2.6</th>
<th>3.9 - 6.4</th>
<th>12 - 17</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.4 - 0.74</td>
<td>1.3 - 1.7</td>
<td>2.7 - 3.8</td>
<td>6.5 - 11</td>
<td>18 - 25</td>
</tr>
</tbody>
</table>

Total Volume (m³): 2673
Total Area (km²): 1641
Published results delineated the average distribution of DWH surface oil volume (MacDonald, Garcia Pineda et al. 2015) in units of m³/km².

A time-series of the data showed the strong effect of winds in reducing the visible volume of surface oil.

Results indicate a reduction in volume (21%) during the June-July phase of the spill was accompanied by an increase in area (49%).
Task 3: Surface-oil Transport and Weathering Model, Forcing Fields

Objectives

- Develop a surface-oil transport and weathering model for the Gulf of Mexico.
- Compile and assess oceanographic and atmospheric forcing fields for the oil model.
- Develop validation metrics for quantifying model performance.
- Parameterize the oil transport and weathering model based on validation metrics and the remotely-sensed surface oil data.
OSCAR (Oil Spill Contingency and Response)  
SINTEF-Norway

Inputs
- Oil type
- Spill rate, location, Special conditions
- Response specifications
- Coastline
- Bathymetry
- Currents
- Waves
- Wind speed
- Sea temperature
- Sea ice coverage
- Biological resources

Processes
- Drifting
- Spreading
- Evaporation
- Photo-oxidation*
- Emulsification
- Natural dispersion
- Dissolution
- Degradation
- Sediment interactions:
  - Water column and seafloor
  - Droplets and WAF
- Stranding
- Response actions:
  - Chemical dispersion
  - Mechanical recovery
  - Burning*

Outputs
- Oil mass balance, Geographical distributions, Properties, Biological implications
OSCAR has previously been run with a surface or subsea release of fresh crude oil or petroleum product.

Weathering algorithms calculate the further behavior and fate of the oil.

For the WAMOST project, OSCAR was modified to permit starting the model from a given spatial distribution of oil on the sea surface, with an estimated thickness, age and weathering history.

This work required two innovations:
1. Establishing a setup start-state in the software for pre-weathered oil slicks
2. Modifying the I/O of OSCAR to output parameters required for determining weathering state of the DwH oil.

A version of OSCAR available to the academic community has been released.
**Task 3: Dispersant Effects on DwH Oil**

- OSCAR model simulation of surface oil from DwH.
- Without dispersants, the volume of the spill is relatively consistent through July, when installation of the capping stack reduced the discharge rate.
Task 3: Dispersant Effects on DwH Oil

- Modelled with dispersant application, the surface oil volume and mass decreases sharply in July.
- This coincides with increased subsurface treatment with Corexit.
- Result is consistent with WAMOST results obtained from SAR observations.
Questions

Ian MacDonald,
Florida State University
Task 3: Forcing fields, ocean currents

The Naval Oceanographic Office Operational Prediction system for the Gulf of Mexico and Caribbean (AmSeas)

- Navy Coastal Ocean Model (NCOM), 1/36° (~3 km), 40 vertical levels (sigma-z level)
- Atmospheric forcing: Navy’s COAMPS model
- Assimilation: all quality controlled observations including satellite SST and altimetry, as well as profile T and S data using NCODA system
- Data available via NOMADS: 3hr May 08 2010 – present – not the entire DwH time period.

HYCOM + NCODA Gulf of Mexico 1/25° Analysis/Reanalysis (GOMl0.04)

- HYbrid Coordinate Ocean Model (HYCOM), 1/25° (~4 km), 20 vertical hybrid (isopycnic/sigma/z-level) levels
- Atmospheric forcing: NOGAPS (20.1, 31.0), CFSR (50.1)
- Assimilation: all quality controlled observations including satellite SST and altimetry, as well as profile T and S data using NCODA system
- Analysis runs 31.0 (3 DVAR): Apr 2009 – 2014
Differences in HYCOM and NCOM shear may be due to vertical grid, wind forcing, or turbulence closure.
Task 3: Assessment of the NCOM-AmSeas and HYCOM-GOMI0.04

- Sea Surface Height (SSH):
  *Models vs CCAR altimetry*
  *Loop Current (LC) front*

- Sea Surface Temperature (SST):
  *Models vs SAMOS ship data*
  *ARGO floats*
  *(www.nodc.noaa.gov/deepwaterhorizon/insitu.html)*

- Sea Surface Salinity (SSS) and salinity profiles:
  *Satellite Ocean Color Index (USF)*
  *ARGO floats*
Task 3: Demeaned SSH fields (m) from CCAR, NCOM AmSeas and HYCOM GOMI0.04 Time-Averaged Over May 12 – 19 of 2010
Task 3: LC and LCE Fronts in NCOM and HYCOM

Maximum Northern Extent of the LC

- CCAR
- AmSeas (NCOM)
- GOM10.04 (HYCOM)

MHD(HYCOM) - MHD(NCOM)

HYCOM “better”
NCOM “better”
The mean is -0.03

Modified Hausdorff Distances between LC fronts (model – CCAR)

Good
Bad
Task 3: Representation of the Near-surface Ocean Circulation in HYCOM GOMI0.04 Analysis (20.1 and 31.0) and Reanalysis (50.1) Datasets
Task 3: Sea Surface Salinity in the Models vs Ship Observations During the DwH Oil Spill Event

- SST and SSS fields from the analysis data sets are compared to the ship observations collected in the area during the DwH spill event.
- The data were provided by the Shipboard Automated Meteorological and Oceanographic System (SAMOS).
Task 3: SST in the Models vs Ship Observations

NCOM

HYCOM
Task 3: T/S Profiles from the Models vs ARGO Floats

5/24/10

5/26/10

5/30/10

8/16/10
Task 3: SSS Fronts in NCOM-AmSeas and HYCOM-GOML0.04

Top: SSS from NCOM-AmSeas 7-day composite: August 1, 2010
Bottom: SSS from HYCOM-GOML0.04 7-day composite: August 1, 2010

Ocean Color Index 7-day composite: August 1, 2010
Task 3: Comparison of Simulated River Plumes Using Chl-a (ocean color index)

NCOM-AmSeas

HYCOM-GOMI0.04

Chl-a (mg/m³)

Spatial correlation between model SSS and Chl-a

Mean MHD for OCI – HYCOM and OCI-NCOM
Task 3: Summary: NCOM-AmSeas vs HYCOM-GOMI0.04

● SSH:
  ✓ Both models represent timing, location and shape of anticyclonic eddies and the Loop Current fairly well compared to CCAR data
  ✓ There is less agreement between the model and altimeter data on position and shape of cyclonic eddies and smaller scale features
  ✓ Fronts of the LC and LC eddies are accurately simulated in both models. On average, HYCOM has a slightly better representation of the fronts compared to NCOM.

● SSS and vertical profiles:
  ✓ From OCI analysis, NCOM has a better representation of the river plume near the coast compared to HYCOM. Specifically, HYCOM has a more dispersed river plume and its low salinity water spreads farther offshore than in the NCOM forecast.
  ✓ Overall, the vertical T and S profiles in both model analyses match the ARGO floats (except for the cases when ARGO float was close to a mesoscale feature).

● SST:
  ✓ Both models demonstrate good agreement with ship observations. HYCOM has a slightly better correlation with ship data.

● Velocity fields:
  ✓ In the deep ocean: strongly influenced by mesoscale eddies
  ✓ In the shallow regions: winds control ocean circulation
  ✓ HYCOM has a stronger vertical shear in the upper layers
For oil simulation, the near-surface ocean currents should be dynamically consistent with the wind field to avoid possible discrepancies between the wind fields and surface currents (largely influenced by winds) forcing the oil simulation.

In case when ocean surface currents are from a numerical simulation, such consistency is provided when atmospheric fields forcing the ocean model are used to derive the near-surface winds.

Considered wind fields for oil simulations:

<table>
<thead>
<tr>
<th>Wind Data</th>
<th>Temporal Resolution</th>
<th>Spatial Resolution</th>
<th>Spatial Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS)</td>
<td>3 hr</td>
<td>0.2°</td>
<td>120°W–60°W, 0°N–32°N</td>
</tr>
<tr>
<td>NCEP Climate Forecast System Reanalysis (CFSR)</td>
<td>1 hr</td>
<td>0.25°</td>
<td>Global</td>
</tr>
<tr>
<td>Navy Operational Global Atmospheric Prediction System (NOGAPS)</td>
<td>3 hr</td>
<td>0.5°</td>
<td>Global</td>
</tr>
<tr>
<td>Cross-Calibrated Multi-Platform Ocean Surface Wind Vectors (CCMP)</td>
<td>6 hr</td>
<td>0.25°</td>
<td>0°W–360°W, 78.7°S–78.7°N</td>
</tr>
</tbody>
</table>

Analysis:

- The RMS difference
- Wind speed bias
- Wind vector difference
- Timing and structure of fronts
- Comparison to NDBC observations

Needs validation

Validated in Wallcraft et al., 2009; Sharp et al., 2015
Validated in Wallcraft et al., 2009
Validated in Atlas et al., 2009
The frontal structure is similar between CCMP and COAMPS.

COAMPS has much larger wind speeds ahead of the front.

In contrast, CCMP has stronger winds behind the front.

Interestingly, CCMP also has a wind speed maximum located over the oil slick area that is not seen in the COAMPS wind vector plot.
Task 4: Wind Forcing: COAMPS vs CCMP winds

Average Wind Speed Bias and Wind Vector Difference (CCMP-COAMPS)

- The wind speed bias has a positive peak (~1.5 m/s) over the oil slick location, showing that CCMP winds > COAMPS on average.
- The wind vector difference highlights substantial changes in the v-comp of the wind.
- CCMP winds have better agreement with NDBC data in the oil affected regions.

- Radiometer wind retrievals are affected by oil because some of the assumptions of the retrieval algorithm fail due to altered surface emissivity and the dielectric constant.
- The oil slick introduces a wind speed bias into gridded products (CCMP and COAMPS) through compromised radiometer wind speed retrievals and reduced surface roughness.
Task 3: Summary, Validation of COAMPS

- In general, good agreement between COAMPS and CCMP winds
- The magnitudes, timing and features of wind fields are well captured
- The frontal structure is similar (but not exact)
- The low wind speed areas behind the front are stronger in CCMP
- The oil slick may introduce a wind speed bias into gridded products such as CCMP and COAMPS through compromised radiometer wind speed retrievals and reduced surface roughness
- CCMP wind speeds are in better agreement with NDBC buoy wind speeds than COAMPS within the oil slick.
- COAMPS winds have noticeable negative bias (~1.5 m/s) in wind speeds over the oil slick compared to the CCMP and NDBC data
Considered Metrics:

1) Absolute Deviation (absolute difference of the areas inside the contours)

2) RMSD

3) Mean Displacement (MD)

4) Hausdorff Distance (HD)

5) Modified Hausdorff Distance (MHD)

Root Mean Square Deviation

\[ \text{RMSD} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} d_i(A,B)^2} \]

Mean Displacement

\[
\begin{align*}
\bar{D}_A &= \frac{1}{n} \sum_{i=1}^{n} h_i d(a_i, P_0), \\
\bar{D}_B &= \frac{1}{m} \sum_{i=1}^{m} g_i d(b_i, P_0), \\
D_{MDSD}(A,B) &= |\bar{D}_A - \bar{D}_B|,
\end{align*}
\]

Modified Hausdorff Distance

\[ d_{MH}(A, B) = \max \left\{ \frac{1}{|A|} \sum_{a \in A} d(a, B), \frac{1}{|B|} \sum_{b \in B} d(A, b) \right\} \]

where \( d(a, B) = \min_{b \in B} d(a, b) \) and similarly for \( d(A, b) \).

All metrics were analyzed and subjected to sensitivity and robustness tests. The study has been published in Dukhovskoy et al., 2015.

Examples of application of MHD to geophysical fields are given in Dukhovskoy et al., 2015; Hiester et al., 2016;
Several metrics have been considered for a quantitative skill assessment of oil drift models (Mean Displacement, Weighted Mean Displacement, Hausdorff Distance, Modified Hausdorff Distance):

- All metrics demonstrate the ability to identify differences in the shape of the oil spill and oil fraction coverage among the model experiments.
- The RMSD rankings often are not consistent with other validation metrics. It also has high sensitivity to noise.
- In the considered cases, the rotation and translation of the oil fields were negligibly small. Thus the Mean Displacement and Weighted Mean Displacement metrics agreed well with the topological metrics (HD and MHD).
- The Mean Displacement method cannot penalize differences in the shapes’ rotation or translation relative to each other. Not very robust to noise.
- Skill metrics are somewhat sensitive to the choice of a contour that bounds compared fields.

- **The skill metric based on the Modified Hausdorff Distance is deemed to be the most appropriate for current study**
- The MHD metric is employed as an objective measure for the proximity of the numerical solution to observations or other control field. Low MHD score indicates good resemblance of the simulated oil spill to the control field.
Task 3: COAPS Surface Oil Drift Model

Realistic application of the MHD to the surface oil model evaluation and adjustment is demonstrated for the sensitivity runs with a surface oil drift model. Each particle represents some volume of oil (estimated from the number of particles released per time step).

Surface oil drift model: Oil is simulated as Lagrangian particles advected by ocean currents, winds, and (optionally) waves.

- Surface currents: 1/25° Gulf of Mexico HYCOM Analysis/Reanalysis
- Winds: CFSR, CCMP
- Wind drift parameterization (options):
  - 3.5% of the wind speed
  - Wind-dependent wind coefficient or user-specified constant value (e.g., 20° to the right of the wind vector)
- Laplacian diffusion of oil particles is parameterized as a random walk
- Half-life: Oil particles are removed randomly based on a prescribed half-life
Task 3: Testing MHD: Sensitivity Oil Model Experiments with Varying Parameters

The MHD-based ranking of the simulations correctly identifies the case with the parameter value close to the control run.

MHD scores (vertical axis) from the sensitivity experiments

The MHD scores (vertical axis) from the sensitivity experiments.
Task 3: Estimation of Half-life from SAR Observations and Oil Drift Model by Minimizing MHD Score

The MHD technique is employed to estimate half-life of surface oil particles from SAR observations by running sensitivity experiments with the oil drift model.

Contours of the time-integrated surface oil volume (0.09 m$^3$/km$^2$), May 23, 2010, 00Z from the simulations with varying half-life and SAR.

Time-integrated SAR/TCNNA surface oil volume (m$^3$/km$^2$), May 23, 2010, 00Z.

Skill metric scores for surface oil volume from the simulations with varying half-life parameter and SAR/TCNNA data.
Task 4: Effects of Wind Forcing on Oil Drift

Oil drift is estimated as the vector sum of the surface drift component due to wind (W) and the surface current component (U).

Surface drift component due to wind (W):

\[ aW \cos(\theta) \]

Wind deflection angles as a function of wind speed:

- \( \theta = 25^\circ \exp \left(-10^{-8} \frac{W^3}{v g}\right) \)
- \( \theta = 22^\circ - 6.3 (W - 4)^{1/2} \) (Neumann, 1959)
- \( \theta = 34^\circ - 7.5 (W)^{1/2} \) (Witting, 1909)

Deflection angle form Samuels et al. (1982)

\[ \theta = 25^\circ \exp \left(-10^{-8} W^3/v g\right) \]

- Numerical experiments with the surface oil drift model indicate high sensitivity of the oil transport to the wind factor.
- Winds play important role in transporting oil towards the coast.
Surface Oil Drift Model Hindcasts with Varying Wind Coefficient

- $C_w = 0.00875$
- $C_w = 0.035$
- $C_w = 0.0525$
- $C_w = 0.0875$
Task 4: “Surface Current” in a Model

Vertical layers in HYCOM GOM10.04

Approximation of the vertical temperature structure in a model

The top-most layer is 3 m thick

- Ocean “surface” currents from hydrodynamic models may be represented by very different depth-averaged velocity fields from the top-most layer. Depending on vertical grid and mixing parameterization in the surface layer velocity model, the accuracy of such an approximation may vary substantially across the models.

- Presumably, the hydrodynamic models with higher near-surface discretization and better physics would have a closer approximation of the true surface current. Thus, oil drift models forced with these surface currents may need reduced wind factor.

- Numerical sensitivity experiments with different forcing fields demonstrate that the optimal set of wind parameters that would fit all oil drift models cannot be derived. The set of wind parameters should be derived for an individual surface oil model depending on the surface current forcing fields.
Oil dampens the roughness of the surface

- Capillary waves and wind waves were not observed for surface stresses typical of wind < \( \sim 8 \text{m} \cdot \text{s}^{-1} \).
- Highly damped at greater wind speeds

Oil causes

- Lower surface stress and greater surface winds
- A different balance between wind, roughness, and stress
- Weaker ocean Ekman transport
- Highly reduced latent heat flux from water (more from hydrocarbons)
- Greater near surface temperatures \( \rightarrow \) Stronger stratification
- Modification of waves
- Damping of capillary waves and wind waves
- Allows swell (long waves generated from distant winds) to propagate
Task 5: Goals and Objectives

The goal of this part of the project is to investigate the possible existence of barriers to surface oil transport and whether they may be inferred from readily obtainable observational data.

Specific Objectives:

1. Identify oceanographic features that may serve as barriers (or constraints) to surface oil transport.
2. Analyze the transport of oil across boundaries inferred from SSH, surface salinity, temperature or velocity fields.
3. Determine the critical strengths of any such boundaries for limiting cross-barrier oil transport.
A **material boundary** separates different bodies of fluids – the boundary always marks the same fluid material as the fluid **evolves in time**.

**Key Point:** Material boundaries are determined by analysis of the **time-dependent** flow field.

In a slowly evolving flow field, locations of dominant material boundaries may possibly be approximated by features (fronts) in instantaneous fields.

Should a readily-observable oceanographic field serve to approximately identify material boundaries, such a finding may aid in prediction of surface oil drift.
Task 5: Observations of Oceanic Fields

- Observations of (nearly) instantaneous fields of oceanographic variables are obtained only by satellite observations (in situ observations are too sparse to resolve mesoscale features).
- Radiometric sensors observe fields of surface temperature, surface color, and surface salinity (though presently lacking sufficient accuracy and resolution for these purposes).
  - Radiometric observations are heavily influenced by surface oil so inference of boundaries from these observations during an oil spill may be of limited practical use.
- Active microwave altimeters can detect SSH, but only at nadir (along-track observations).
  - SSH are sparse in time (10-35 days) and space (10-100km) cross-track spacing.
  - Statistical (gridding) or dynamical (assimilation into ocean models) methods are required to construct approximations of eddy-resolving SSH fields.
Task 5: Surface Oil Transport and Boundaries Inferred from SSH

- Material boundaries may approximately align with strong surface currents along fronts in a slowly-evolving ocean.
- SSH fronts indicate regions of strong geostrophic currents. Surface currents may have substantial ageostrophic components and deviate substantially from currents inferred from SSH.
- SSH fields from a data assimilating numerical model – The NRL HYCOM Gulf of Mexico Nowcast/Forecast model (hycom.org expt. 31.0) – are analyzed in conjunction with SAR TCNNA-derived surface oil coverage for the time period corresponding to the “tiger tail” formation (when oil was entrained into the Loop Current) in early-Mid May 2010.
SSH gradient and Loop Current position. The core of the Loop Current is approximated by the 17 cm SSH anomaly contour (following Leben, 2005) and by a Kalman Filtering technique that adjusts the position toward the SSH gradient maximum (Dukhovskoy et al., 2015).

Surface oil determined by SAR-TCNNA is outlined in yellow.

- During the tiger tail formation, oil drifted from the main slick toward the Loop Current. Oil can be seen crossing the Loop Current front (but there is uncertainty in the exact front location due to sparse altimeter observations).
- There is no barrier here to oil entering the Loop Current in which rapid transport over long distance could occur under conditions of slow oil degradation. Oil might be inhibited from crossing the Loop Current to the interior bulge where it would be largely retained.
Task 5: Surface Oil transport and Instantaneous Surface Velocity Fields

- Surface velocity can be approximated from SSH fields by explicitly adding ageostrophic components to geostrophic currents inferred from statistically gridded SSH (e.g., the OSCAR surface current product – not to be confused with the OSCAR oil model), or dynamically from an atmosphere-forced ocean model that assimilates satellite SSH (e.g., HYCOM).

- Oil transport during the tiger tail formation time period is analyzed with two diagnostics derived from instantaneous velocity fields obtained from HYCOM: the Okubo-Weiss parameter and surface relative vorticity.
Task 5: Okubo-Weiss Parameter

**Okubo-Weiss parameter** is derived from deformation and relative rotation in the surface velocity field. Strong negative values may indicate eddies.

Surface oil determined by SAR-TCNNA is outlined in black.

- The Okubo-Weiss parameter produces a very noisy field. No structures in the field appear to be related to movement of the surface oil.
Surface relative vorticity.

Surface oil determined by SAR-TCNNA is outlined in black.

- Surface relative vorticity more clearly highlights jets, which have a characteristic rapid change in sign of the vorticity on either side of the core of the jet. The Loop Current is well-defined.
- The tiger tail enters and crosses the core of the jet as inferred from relative vorticity.
- There are no obvious structures in the vorticity field along the observed transport pathway of the tiger tail. Such structures might simply not exist or not be evident due to uncertainties in the surface currents from the data assimilative model.
Lagrangian Coherent Structures (LCSs) are material boundaries.

LCS positions are determined through analysis of the time-evolving flow field over some finite time interval.

LCSs are ridges in the Finite Time Lyapunov Exponent (FTLE) field, which characterizes the rate of stretching of neighboring trajectories.

- LCSs determined from FTLE fields from forward-in-time trajectories are repelling.
- LCSs determined from FTLE fields from backward-in-time trajectories are attracting.

LCSs evolve in time. A location on one side of an LCS may at a later time be on the other side of the LCS (and LCSs continually form and disappear in an unstable flow field).
Surface oil transport and relationships to LCSs are studied using a simple surface oil drift model driven by the NRL HYCOM Gulf of Mexico Reanalysis (expt 50.1).

- This simulation has improved representation of river plumes allowing investigation of oil transport and salinity gradients.
- The time composite of simulated oil coverage agrees qualitatively well with SAR TCNNA time composites.
- The tiger tail feature forms in this simulation, but a couple of weeks later than observations.

Fraction of time period (24 April – 14 July 2010) that each .05° x .05° bin had oil present.
Task 5: Example of LCSs from an FTLE Field

Backward-in-time FTLE field computed from HYCOM surface velocity data 18-21 June 2010.

Attracting LCSs corresponding to the most dominant ridges in the FTLE field.
SSH Gradient and LCSs (purple – attracting, gray – repelling)

Oil (simulated oil Lagrangian elements shown in black) tends to collect and be transported along attracting LCSs.

LCSs are prevalent near the Loop Current, but are not aligned with instantaneous SSH gradients.

An LCS connecting the region of the main body of oil to the Loop Current forms a conduit for oil to be transported to the LC region.

(see Olacoaga and Heller PNAS 2012)
Surface Salinity Gradient and LCSs
(purple – attracting, gray – repelling)

Oil converges along strong surface salinity gradients.

Attracting LCSs are aligned with strong gradients – likely due to buoyancy-driven currents.

These structures strongly constrain oil transport, serving as near-barriers, but at times oil can cross these zones of strong salinity gradients (hence beaching of oil along the MS river Delta).

(see Kourafalou and Androulidakis JGR 2013)
Task 5: Main Points

- Material boundaries are defined through analysis of the time-evolving flow field.
- Attracting LCSs determined from ridges in backward-in-time FTLE fields computed from time-evolving surface velocity fields highlight preferential pathways for oil transport.
- LCSs (or any constraints to surface oil transport) are not readily apparent from observed SSH or derived geostrophic velocity fields.
- LCSs are useful analysis tools, but application to forecasting requires forecasts of currents from a hydrodynamic model. It would likely be more straightforward to simply run an oil drift model than computing FTLE fields and deriving LCSs.
- Strong surface salinity gradients seem to be significant constraints (but not impermeable barriers) to surface oil transport. Previous satellite observations of salinity (Aquarius) are not high enough resolution for these purposes, but the new SMAP mission should be investigated for potential utility to oil spill prediction.
Recommendations for Future Research

- Further investigation of the dynamics of near-surface velocity structure using newly available observational techniques leading to new parameterizations.
- Improve parameterization of wave effects on oil transport considering directional wave spectrum.
- Extend weathering and transport oil prediction capabilities for cold (temperate latitude winter or Arctic) conditions.
- Higher resolution salinity data from the new SMAP (Soil Moisture Active Passive) mission should be investigated for potential utility to oil spill prediction given the correspondence of salinity gradients and attracting LCSs.
- Improve technology for characterizing oil, including measuring oil thickness and volume, in the laboratory and the field and using remotely sensed data.
- Improve understanding of emulsification processes and how emulsified oil drifts differently from thin oil.