# Methods for Oil Spill Tracking Leading to Accelerated Containment and Cleanup

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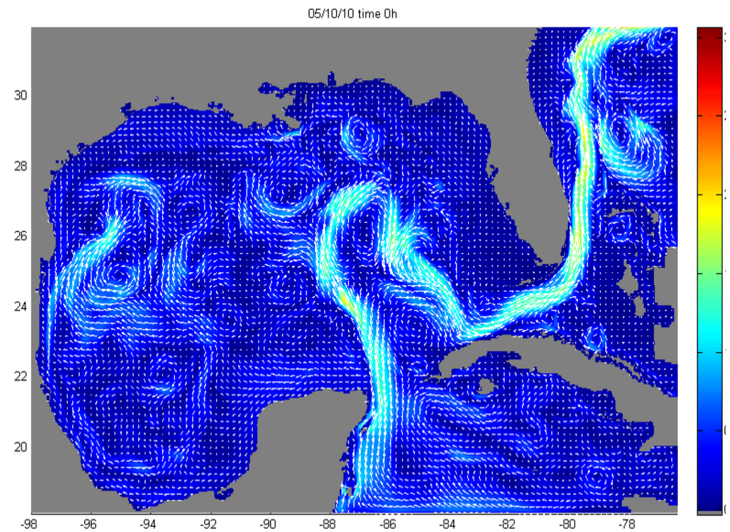
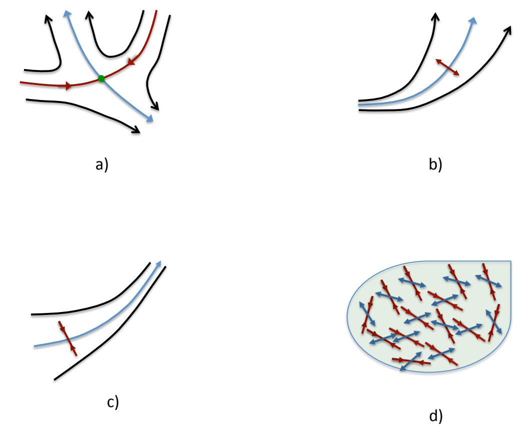
# *Introduction*

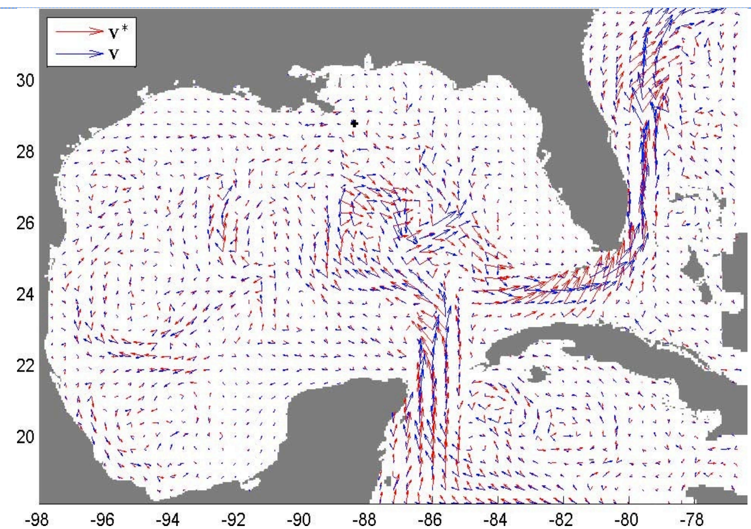
- Focus: Dynamical Systems (Lagrangian) methods for tracking and mitigation
  of oil, gas, and subsurface bacterial populations.
- A method for detection of elliptic and hyperbolic zones in complex ocean flows.
  -enables robust prediction of oil slick evolution
- A study of the fate of deep-sea gas irruption and associated bacterial bloom.
  (with D. Valentine et al)
- A method for optimal deployment of clean-up vehicles based on prior modeled knowledge of oil slick distribution.

# Lagrangian Approach

- Model: the HYbrid Coordinate Ocean Model (HYCOM).
- The HYCOM uses isopycnal coordinates in the deep stratified ocean, pressure coordinates in unstratified regions including the mixed layer, and terrain-following coordinates in shallow coastal regions.
- The simulations have 20 layers in the vertical 1/25deg ( 4 km) horizontal resolution and are forced with 6-hourly Navy Operational Global Atmospheric Prediction System (NOGAPS) winds



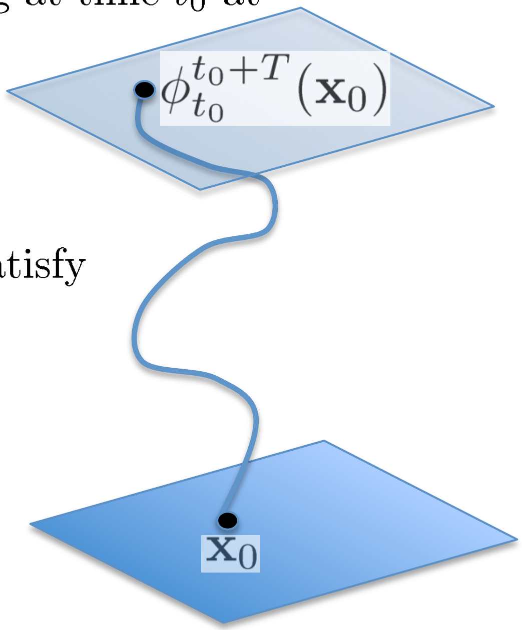

-Look for robust, hyperbolic structures Indicating:

- convergence,
- divergence and
- mixing

# Mesohyperbolicity

**Notation:**

- $\phi_{t_0}^{t+T}(\mathbf{x}_0)$ : the map of $A$ mapping the fluid particle starting at time $t_0$ at point $\mathbf{x}_0 \in \mathbb{R}$ to its position $\mathbf{x}$ at time $t_0 + T$.
- $D\phi_{t_0}^{t+T}(\mathbf{x}_0)$ is the Jacobian matrix $J(\mathbf{x}_0) = \partial \mathbf{x} / \partial \mathbf{x}_0$.




**Note:**

$\mathbf{v}$ is volume-preserving so the eigenvalues $\lambda_{1,2}(\mathbf{x}_0)$ of $J(\mathbf{x}_0)$ satisfy

$$\det(J(\mathbf{x}_0)) = \lambda_1(\mathbf{x}_0)\lambda_2(\mathbf{x}_0) = 1.$$

Thus, they are either real and

$$\lambda_1(\mathbf{x}_0) = 1/\lambda_2(\mathbf{x}_0)$$

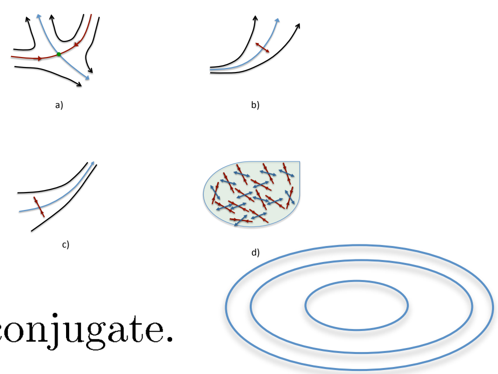
or complex conjugate on the unit circle,

$$|\lambda_{1,2}(\mathbf{x}_0)| = 1.$$

A trajectory starting at $\mathbf{x}_0$ is

*mesohyperbolic* if $\lambda_{1,2}(\mathbf{x}_0)$ are real and

*mesoelliptic* if the eigenvalues are complex conjugate.



# Mesohyperbolicity

**Theorem** A trajectory is mesohyperbolic on interval $[t_0, t_0 + T]$ provided

$$(T^2 \det \nabla \mathbf{v}^*(\mathbf{x}_0, t_0, T) - 4) \det \nabla \mathbf{v}^*(\mathbf{x}_0, t_0, T) > 0$$

and mesoelliptic if

$$(T^2 \det \nabla \mathbf{v}^*(\mathbf{x}_0, t_0, T) - 4) \det \nabla \mathbf{v}^*(\mathbf{x}_0, t_0, T) < 0$$

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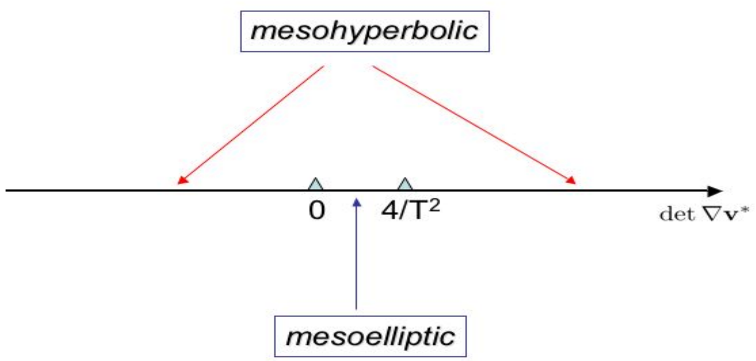
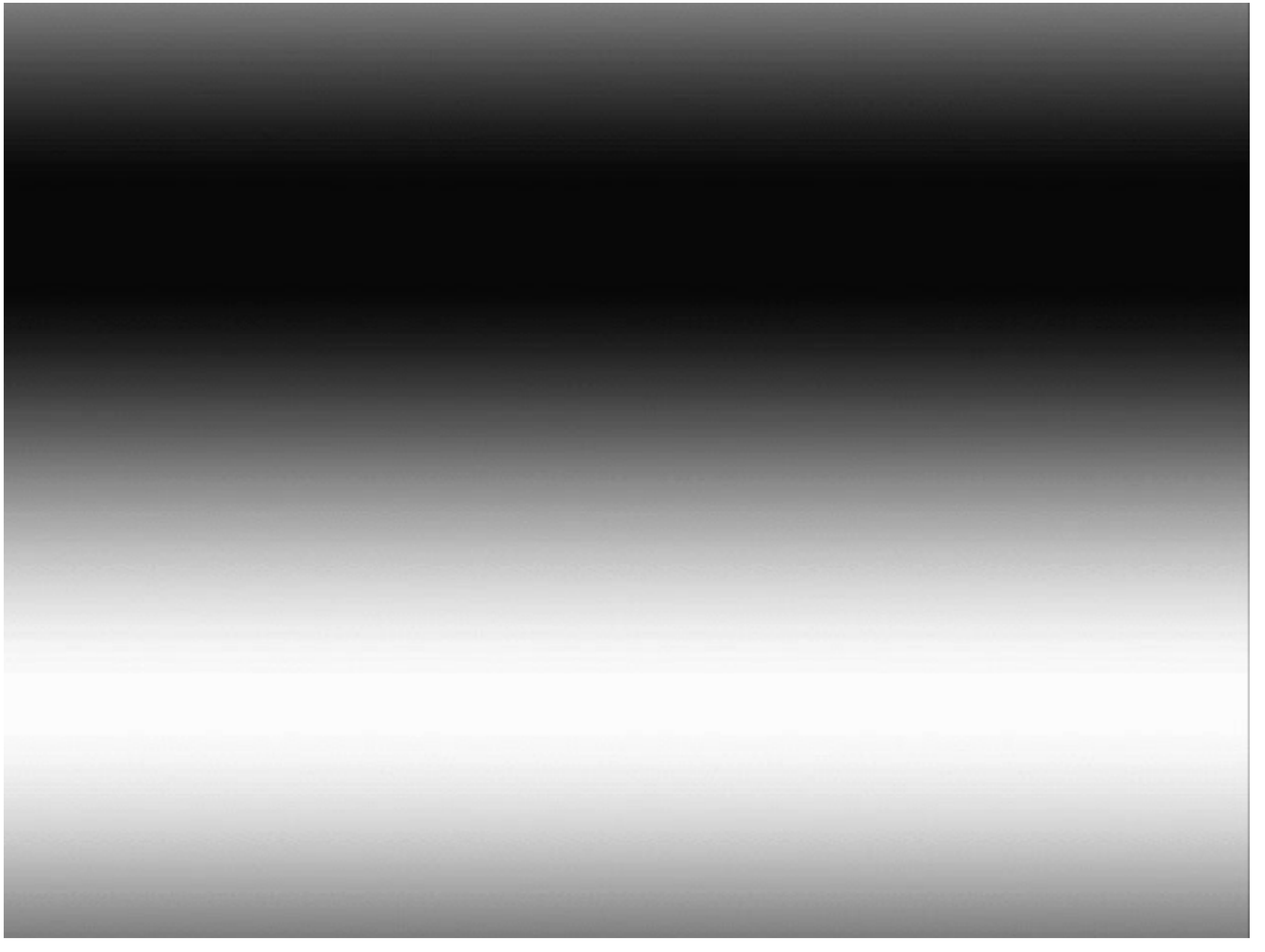


# Mixing in flows with simple time-dependence



# Finite-Time Dynamics

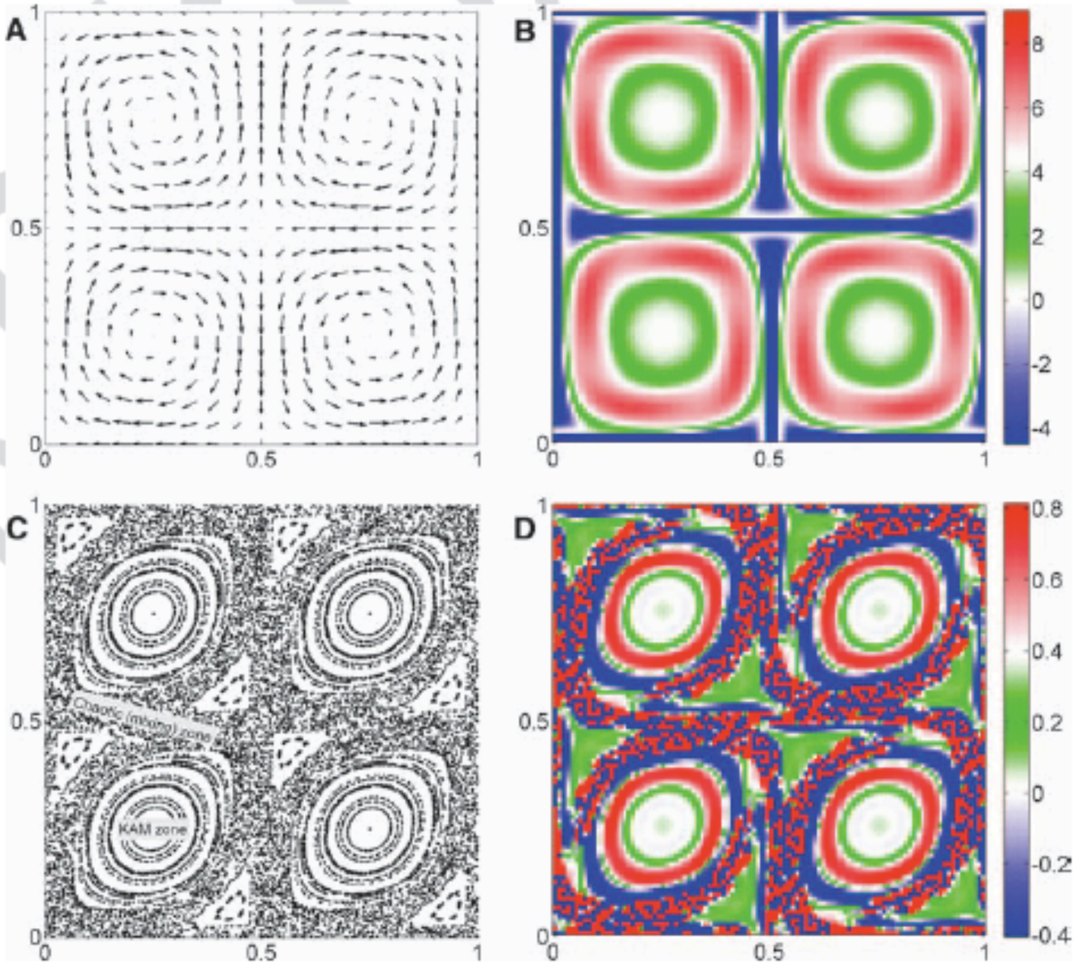
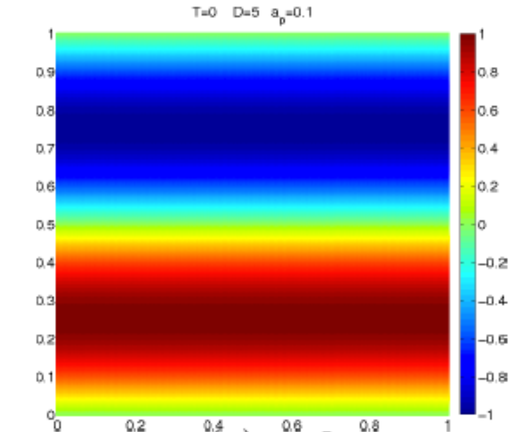
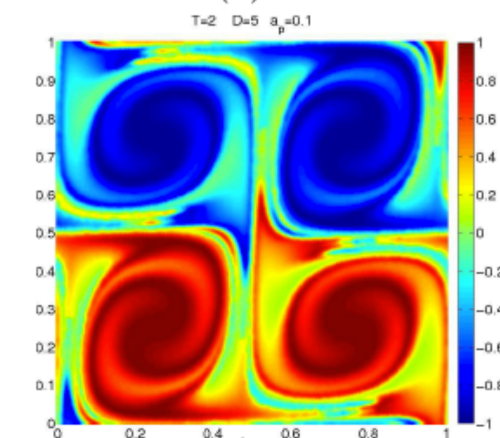


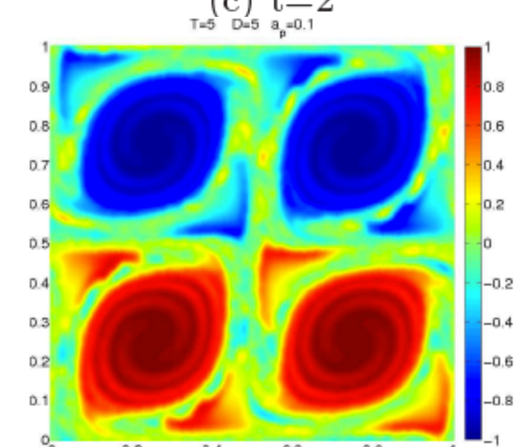

**Fig. 1.** (**A**) A cellular, divergence-free velocity field described in Eq. 6. (**B**) Hypergraph map for the velocity field shown in (A), for $T = 0.94248$. (**C**) Poincaré map for the time-periodic, divergence-free perturbation of the velocity field shown in (A) by a vector field described in Eq. 7, with $\epsilon = 0.1$. (**D**) Hypergraph map for the time-periodic velocity field whose Poincaré map is shown in (C), for $T = \pi$.




(a) t=0




(c) t=2




(f) t=5

# Gulf Oil Spill Prediction

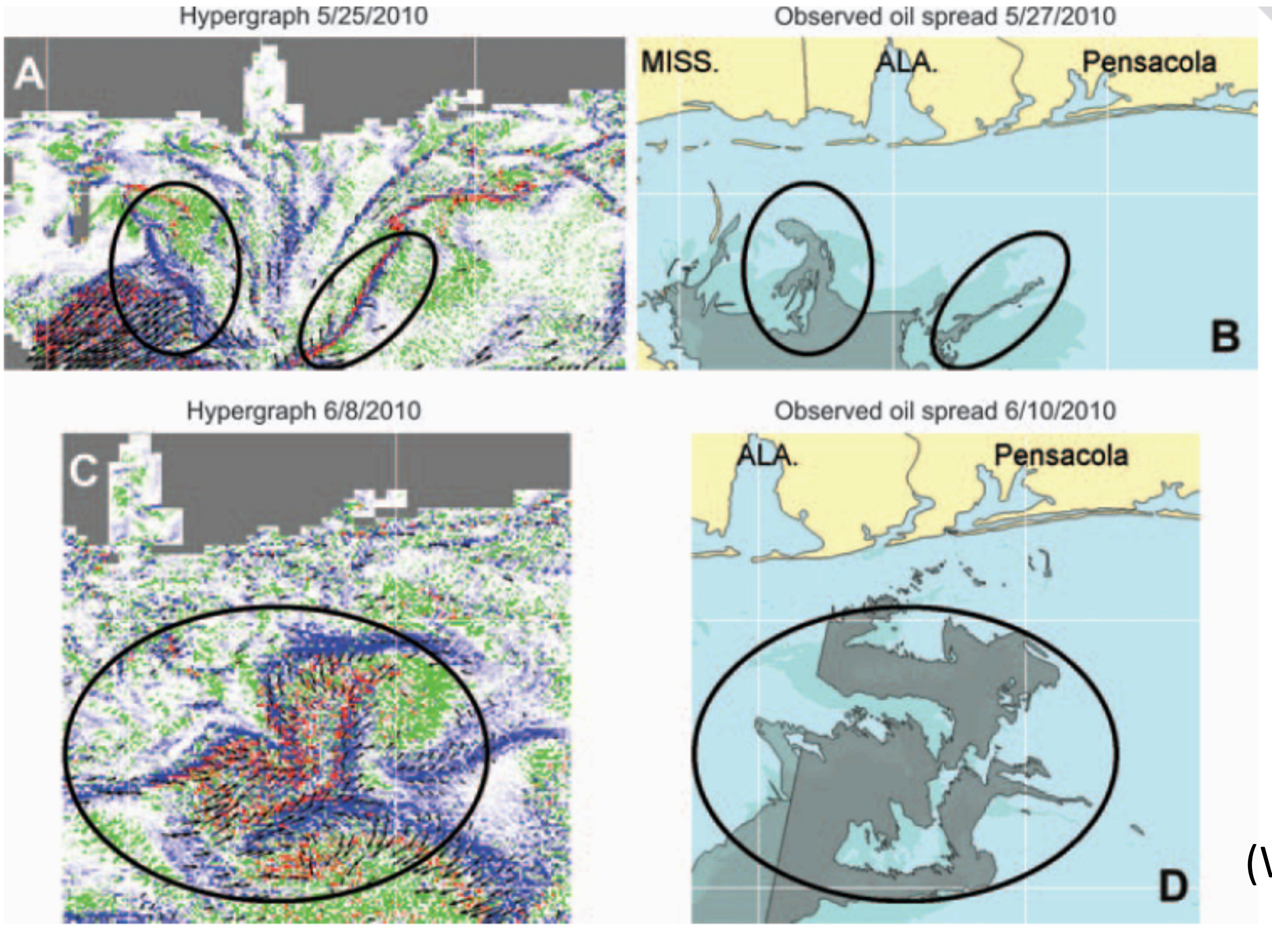
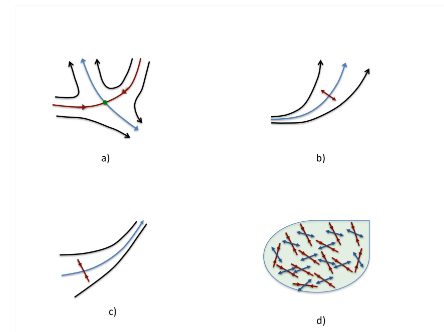



**Fig. 3.** (**A**) Ocean hypergraph map in front of the Biloxi-Pensacola shoreline on 25 May, forecasting strong oil incursion toward the coastline (circled) in the following 3 days. (**B**) NOAA's oil spread estimate in front of the Biloxi-Pensacola shoreline on 27 May. The major directions of oil spread were predicted by the hypergraph map 2 days earlier. The oil reached the shore several days later, on 2 June. (**C**) Ocean hypergraph map in front of Pensacola on 8 June, forecasting a strong oil mixing event in front of the shoreline and extension of the oil slick toward Panama City Beach in the following 3 days. (**D**) NOAA's oil spread estimate on 10 June in front of Pensacola. The oil developed a large slick forecasted by the hypergraph map 2 days earlier and continued to flow toward Panama City Beach.

Analysis based on

$$\det \nabla \mathbf{v}^*(\mathbf{x}_0)$$




Hyperbolic behavior

(With P. Hogan – ONR Stennis
V. Fonoberov – Aimdyn,
S. Loire - UCSB)

Science, 2010

# Deep Water Bacterial Population

- Model: the HYbrid Coordinate Ocean Model (HYCOM) hydrodynamic model

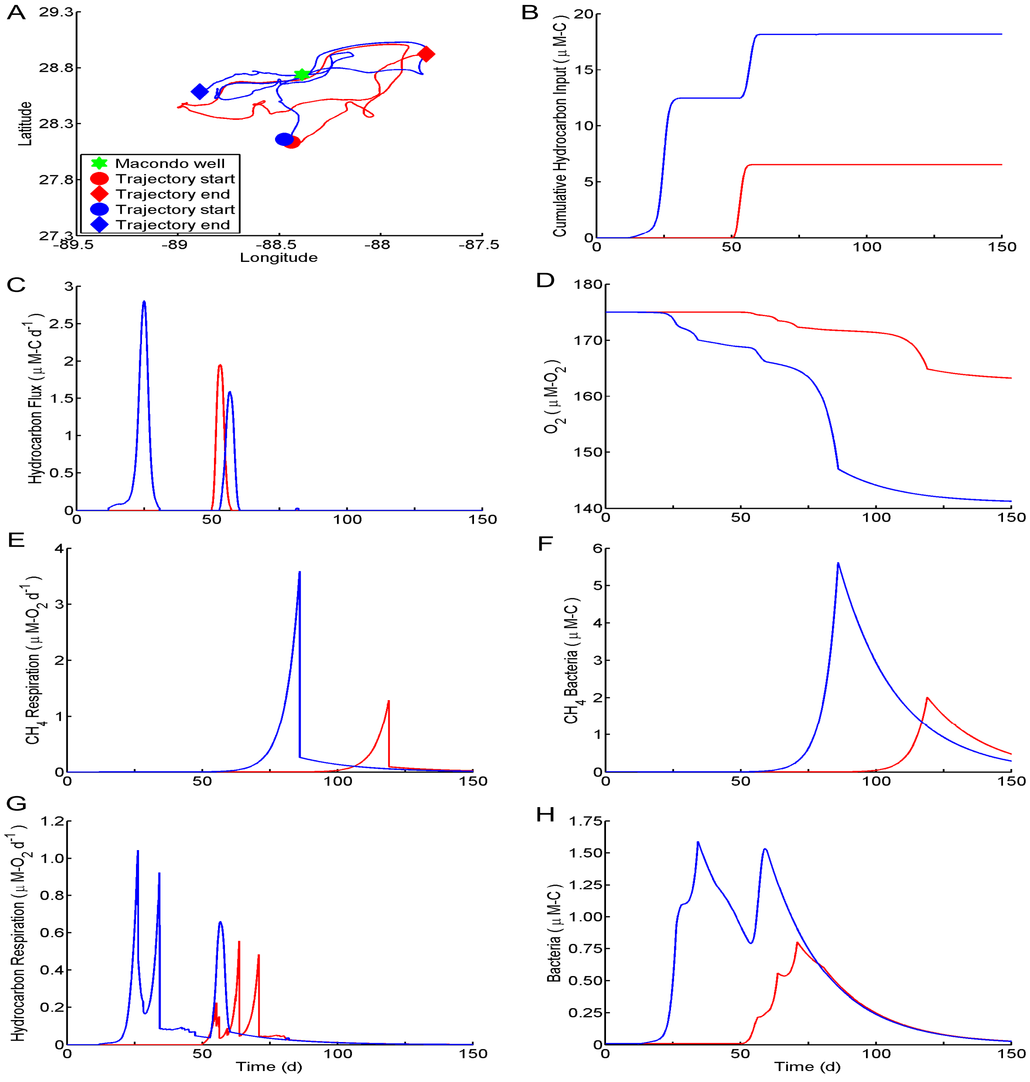
  +

  mass action chemical reaction model

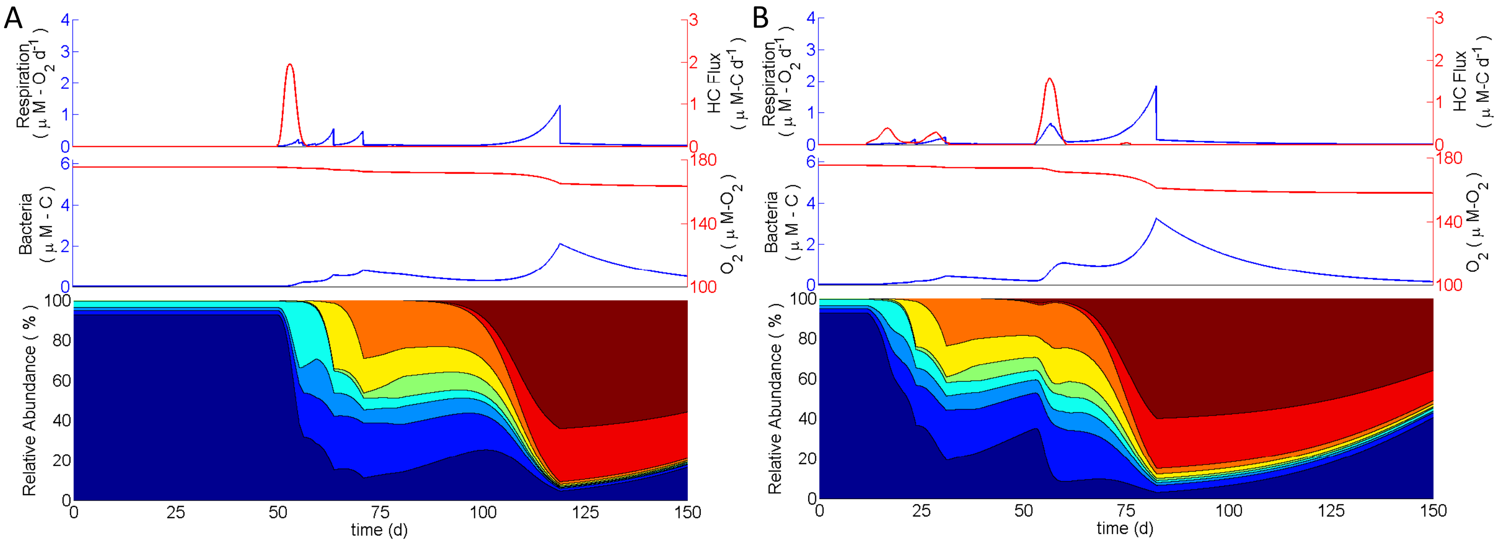
  +

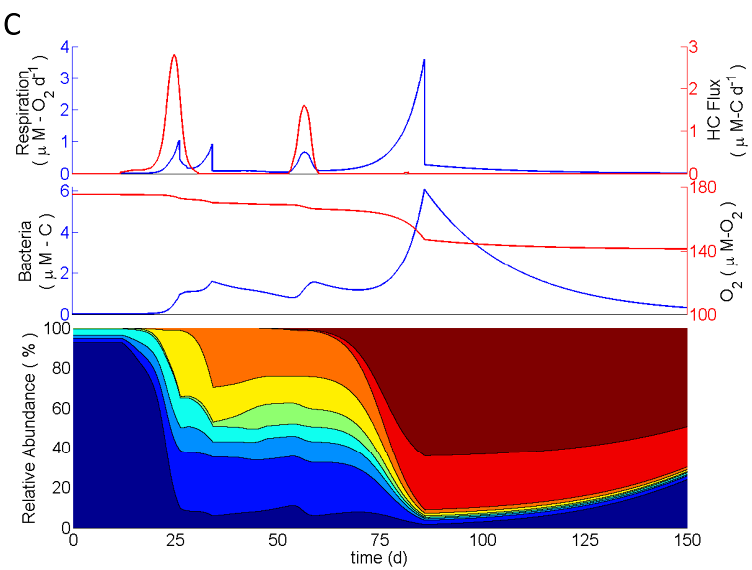
  backward-forward Lagrangian particle evolution.
- Primary and secondary hydrocarbon consumers
- Primary: 1/3 biomass+1/3 $CO_2$ + 1/3 secondary chemical compound
- Secondary: ½ biomass +1/2 $cO_2$

# Autoinnoculation



# Autoinnoculation

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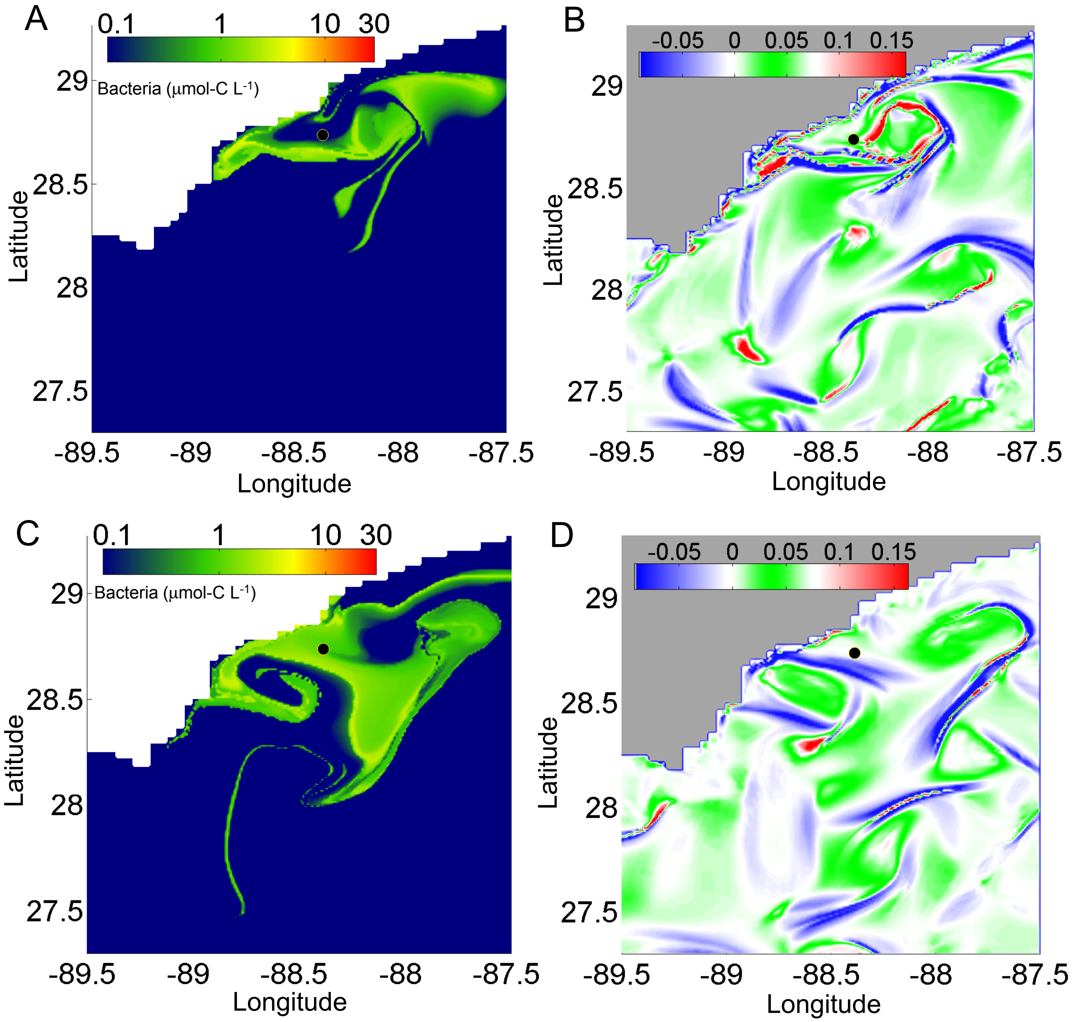
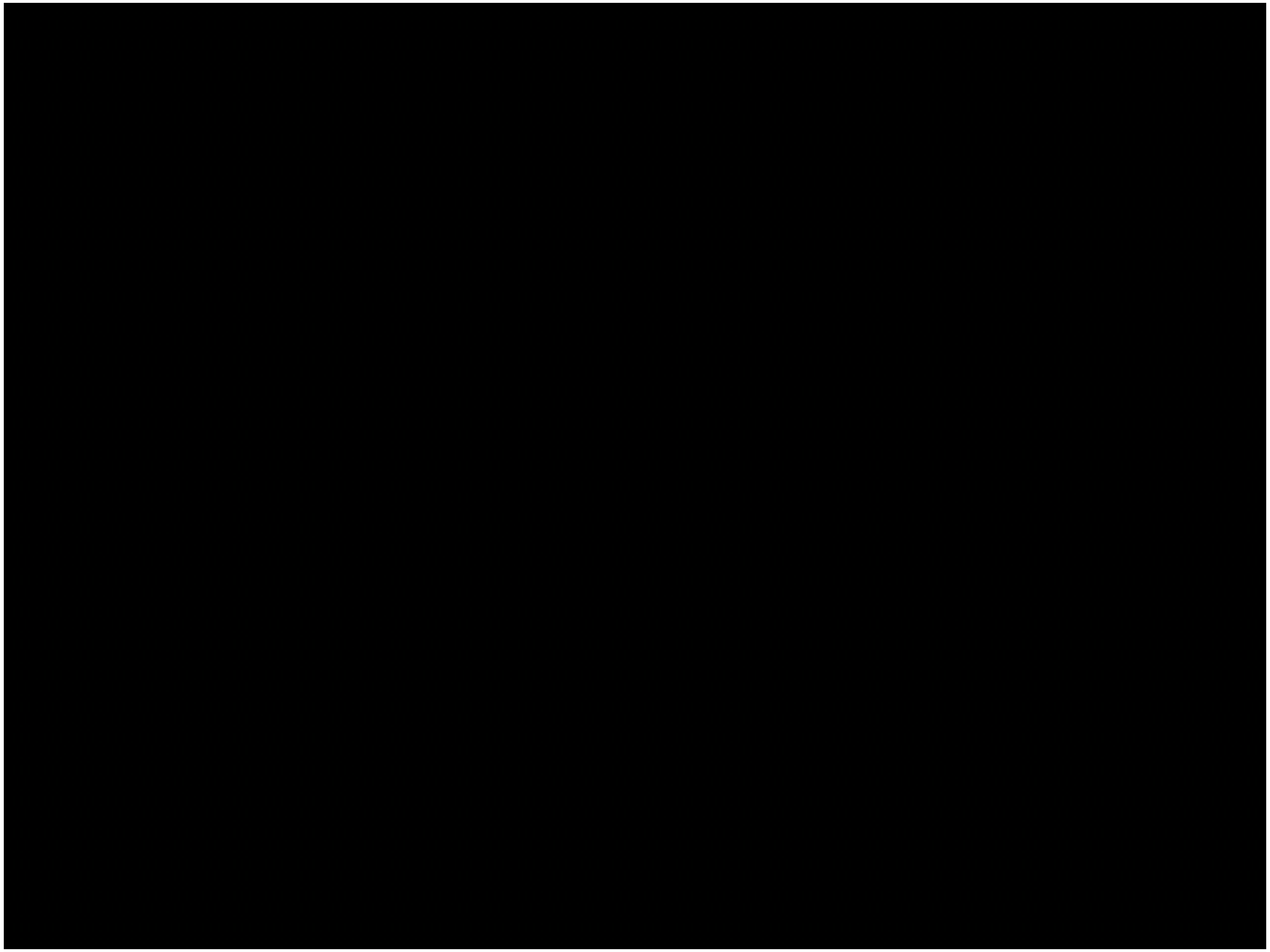
| OMTs | Affiliation | Function |
|---|---|---|
| -- | -- | Pre-spill background Community |
| Eth', Pro', Alk1' – 8', Oil1' – 4' | Colwellia, Oceanospirillales | Secondary degraders |
| Oil1 – Oil4 | Oceanospirillales | Oil degraders (droplets) |
| Alk1 – Alk8 | Oceanospirillales | Degraders of $C_4$+ dissolved alkanes |
| Btx1 – 5, Btx1' – 5', Aro1 – 6, Aro1' – 6' | Cycloclasticus | Aromatic HC degraders |
| Pro | Colwellia | Propanotrophs |
| Eth | Colwellia | Ethanotrophs |
| Met' | Methylophaga, Methylophilaceae | Methylotrophs |
| Met | Methylococcaceae | Methanotrophs |

# Mesohyperbolicity

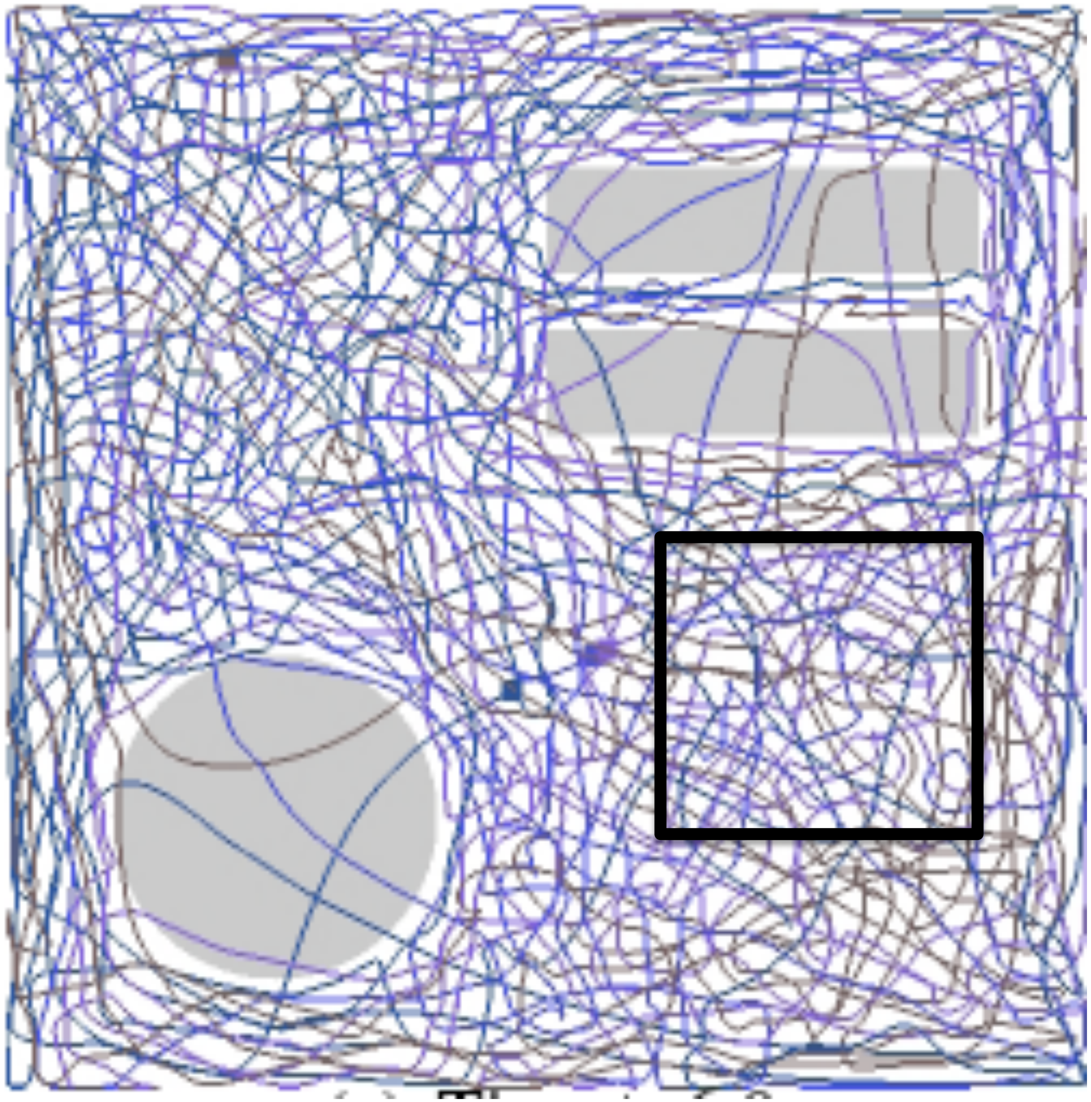


# Experiments vs. Model



Observations by Kessler et al, Camilli, et al, Diercks et al, Joye et al, Valentine et al, Hazen et al.

# Optimal Coverage (Clean-up)



# Control for Coverage