Ocean Surface Mixed Layer

Physical Phenomena and Challenges for Oil Spill Response

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Scope

- Describe physical processes involved in upper ocean fluid dynamics and implications for oil spills.
- Discuss observational methods, mathematical description, and numerical simulation.
- Outline challenges and opportunities for integrated oil-spill response modeling.

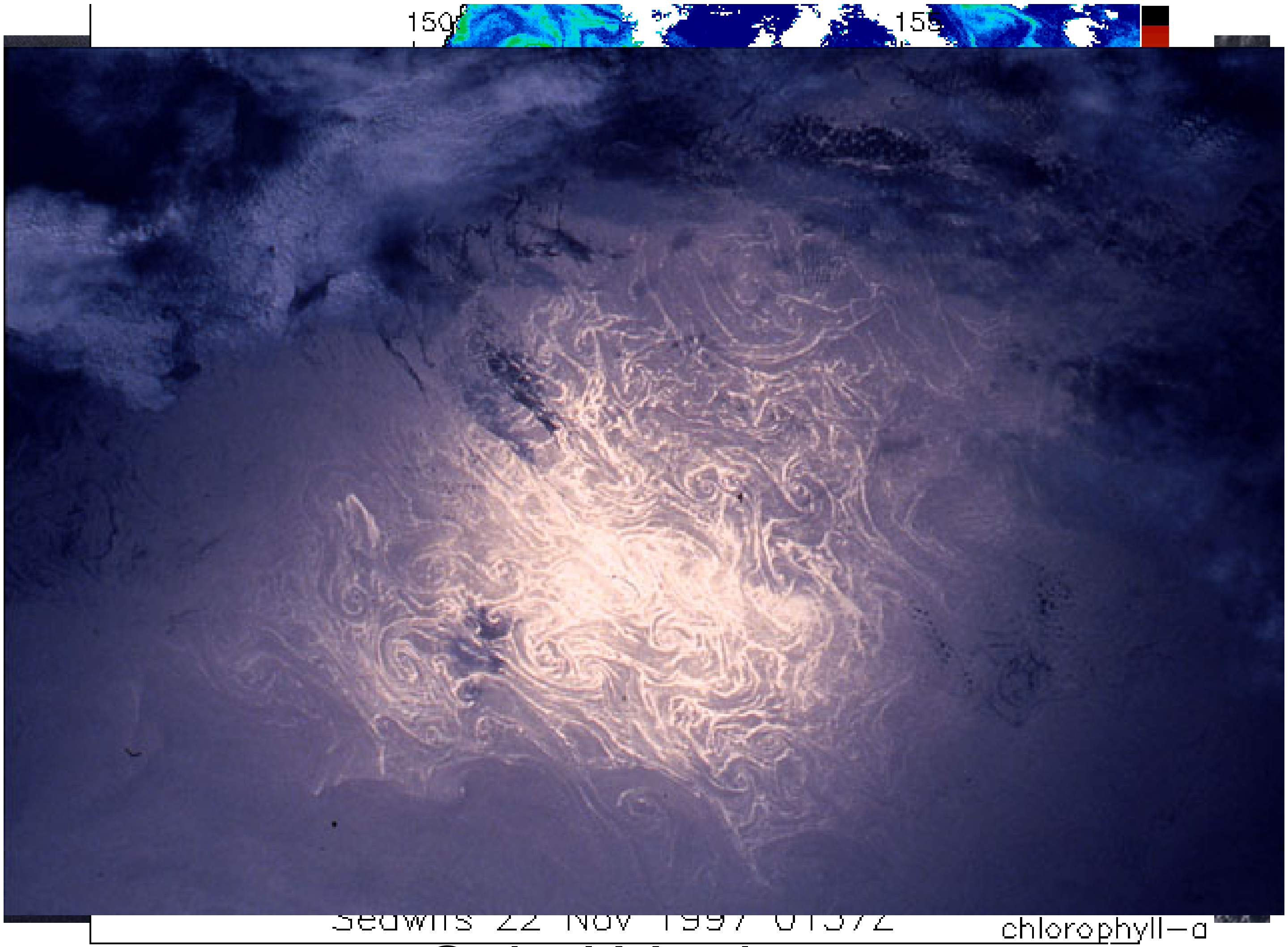
Oceanic Mixed Layer

Physical Phenomena

Upper Ocean Fluid Dynamics

- Very complex environment
  - Motions occurring over a wide range of space and time scales.
- Juxtaposition of order and disorder
  - Nonlinear superposition of coherent features (vortices, currents, waves) and turbulence.

Multi-Scale Ocean Processes



Wake of an Oil Spill

Spiral Vortices

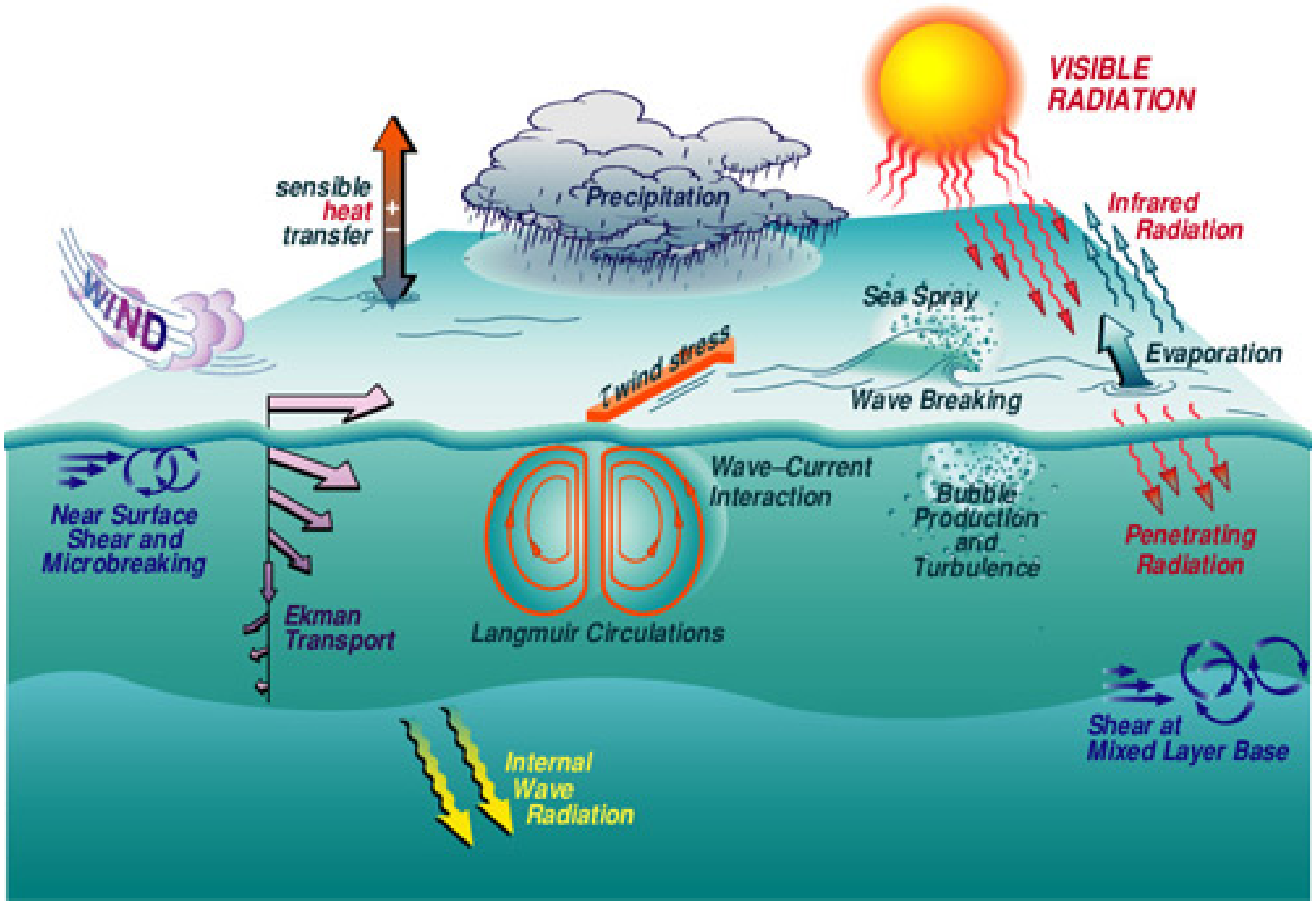
Mesoscale Eddies

NASA Image

P. Rhines, UW

O. M. Griffin

Mixed Layer Processes

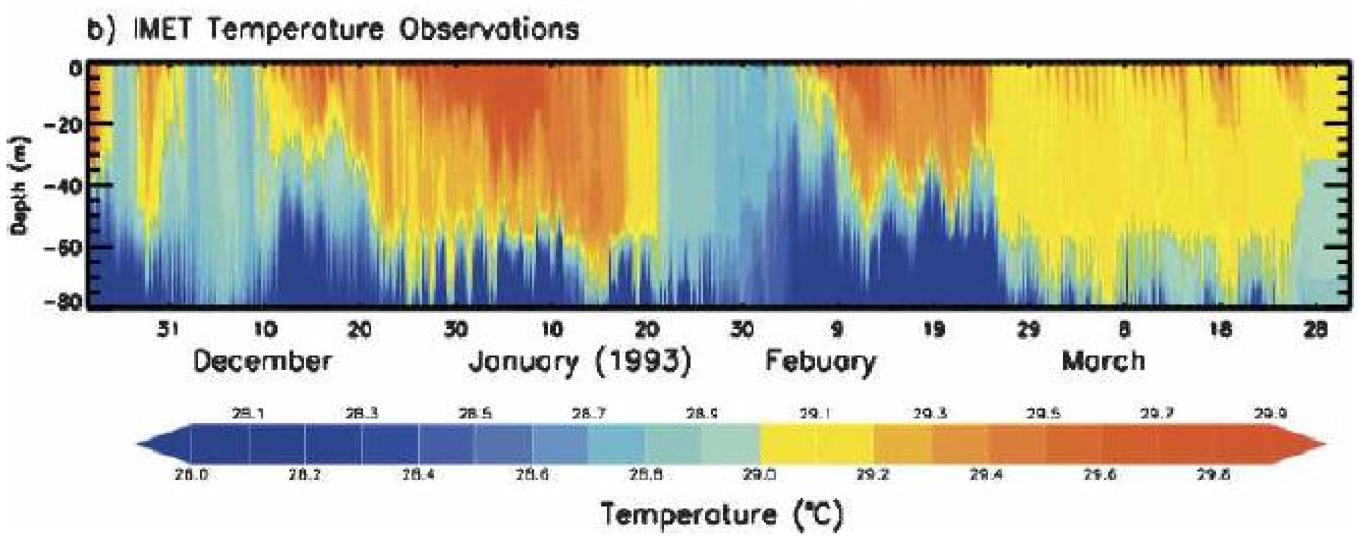


R. Weller, WHOI

Typical Scales

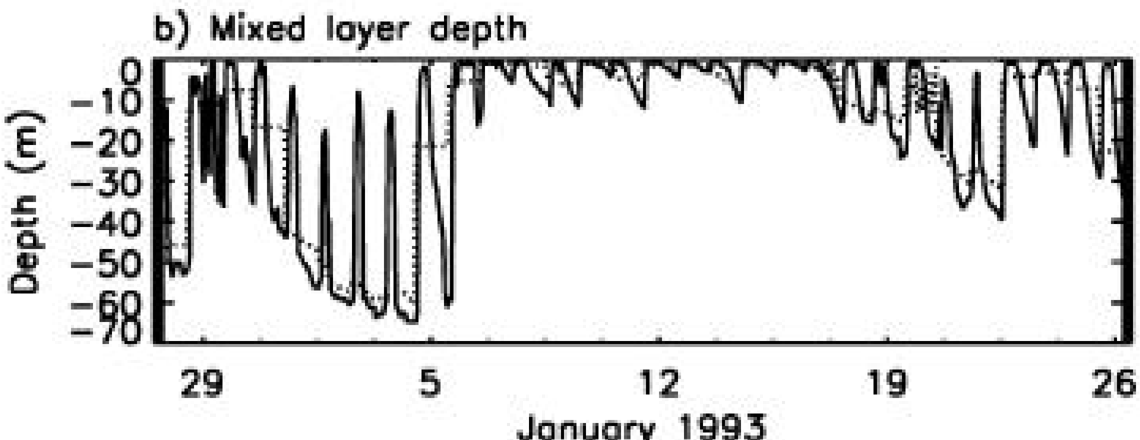
Processes	**Length**	**Time**	**Velocity**
Surface Waves	50m	10s	1m/s
Ekman Currents	50m	3hrs	1-5cm/s
Wave-breaking turbulence	1cm-1m	0.01s-10s	1cm/s-1m/s
Thermal Convection	2-100m	20min	5-20cm/s
Langmuir Circulation	5-200m	20min	5-10cm/s
Density Stratification	10-100m	hrs-days	-----
Internal Waves	50m-10km	⅓hr-hrs	5-100cm/s

Mixed Layer Diurnal Cycling



1. S… is s…

2. W… ence t… yer.



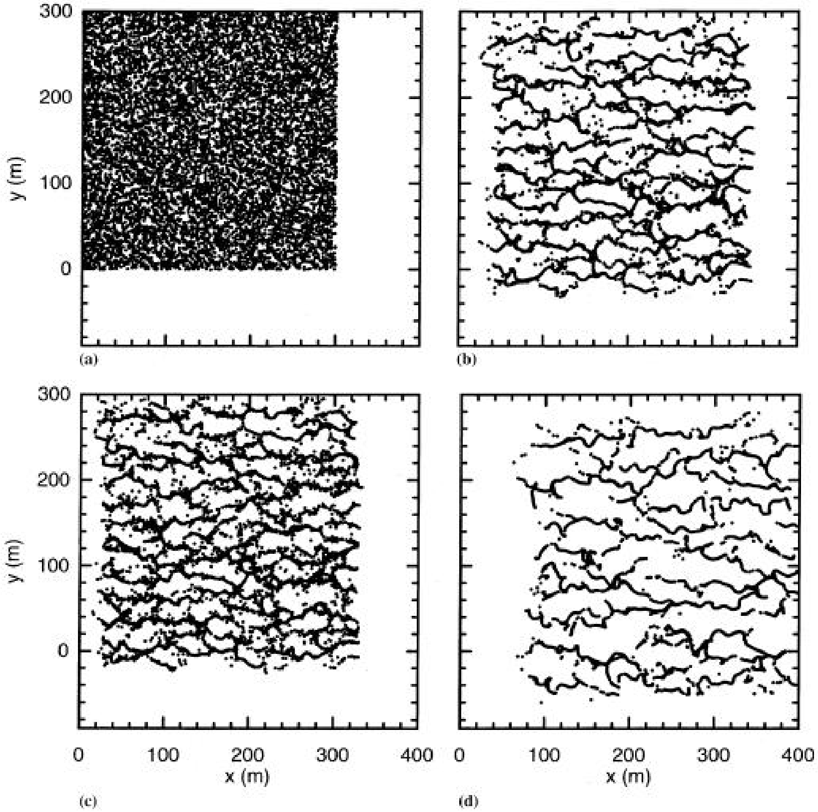
3. Nig… con… yer.

<u>Mixed layer depth varies in space and time</u>

Langmuir Circulation

J. Smith, SIO
A. Szeri, Berkeley

Implications: Banding

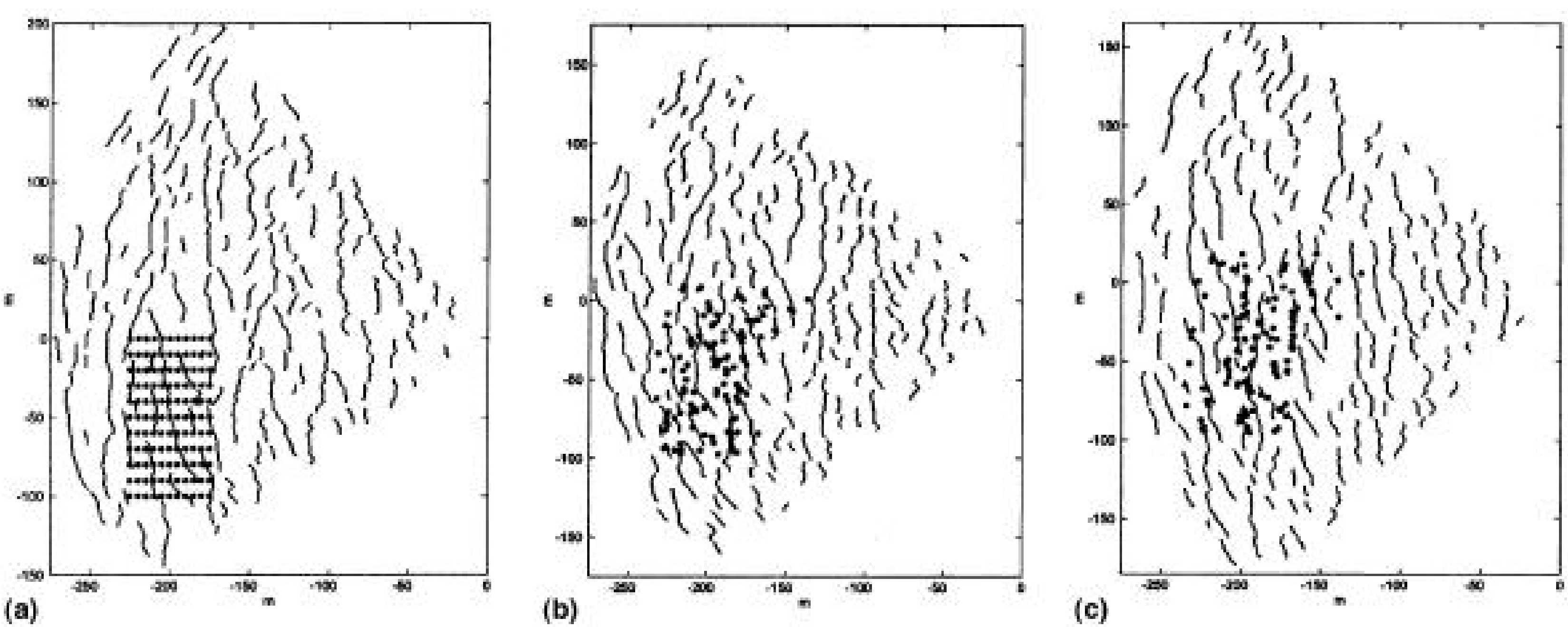


J. McWilliams et al.

NOAA Image

Time scale: 20-30 minutes.

Implications: Lateral Dispersion

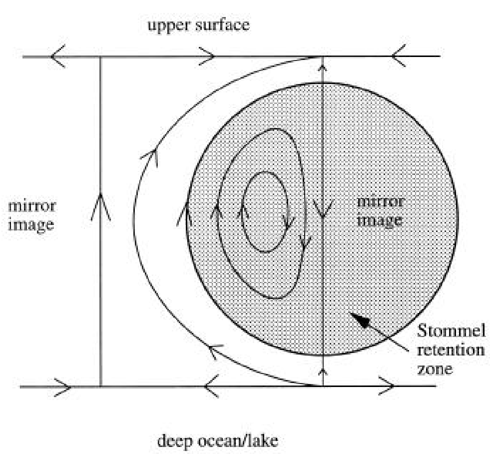


M. Li, U.Md

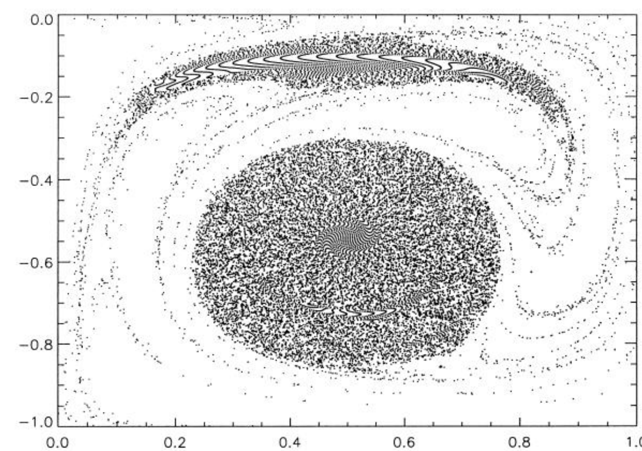
- Lateral dispersion of 50m over 30 minutes.
- Cell lifetimes: 2 - 30 minutes.

Implications: Vertical Mixing

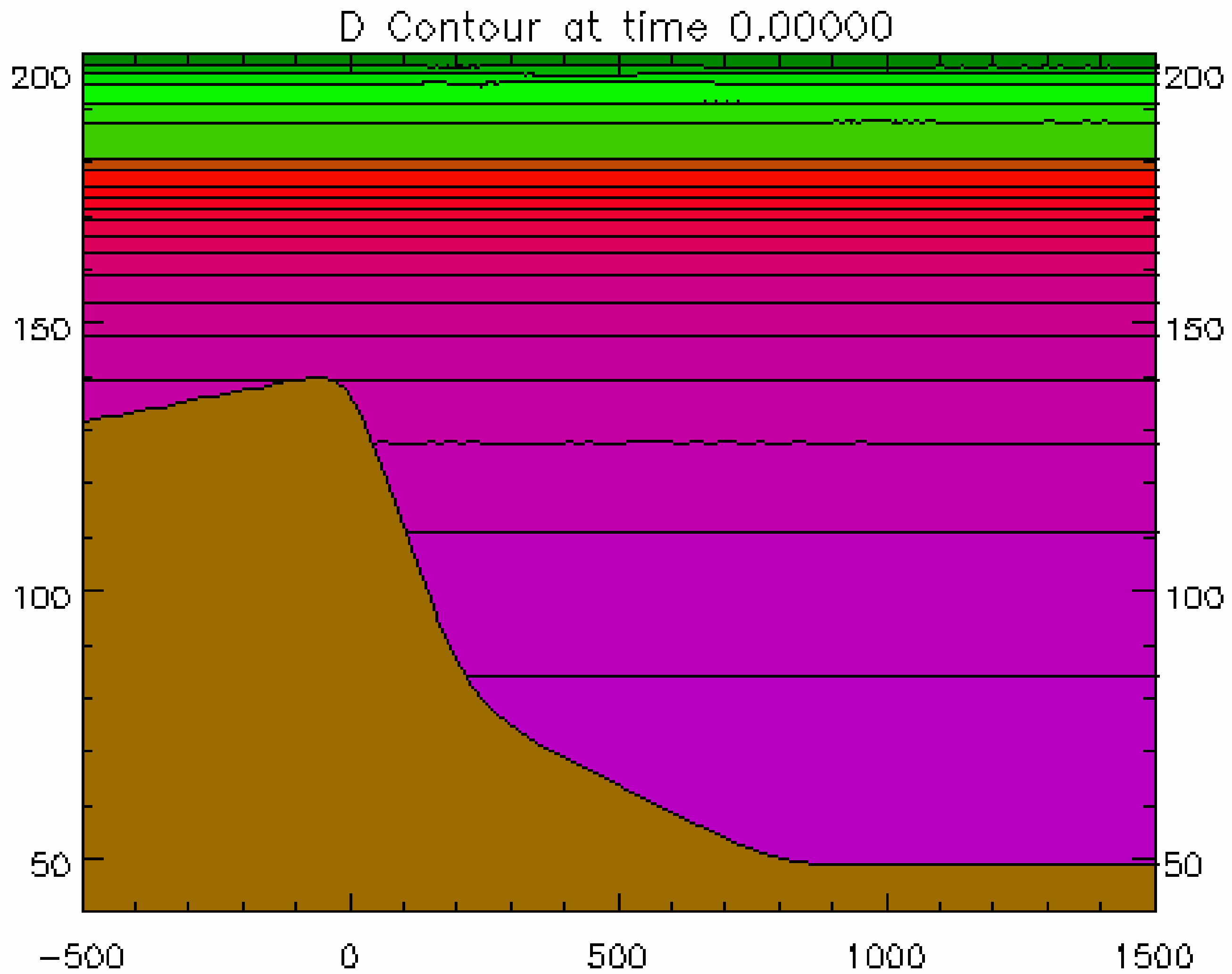
- Neutrally buoyant oil droplets follow mean LC streamlines and diffuse to uniform distribution?
- In practice, “mean unsteadiness” over 1-2 hour periods, causes non-uniform distribution.
- If buoyant, potential exists for droplets to get trapped in “Stommel Retention Zones”.



M. Bees et al.



Internal Wave-Induced Mixing

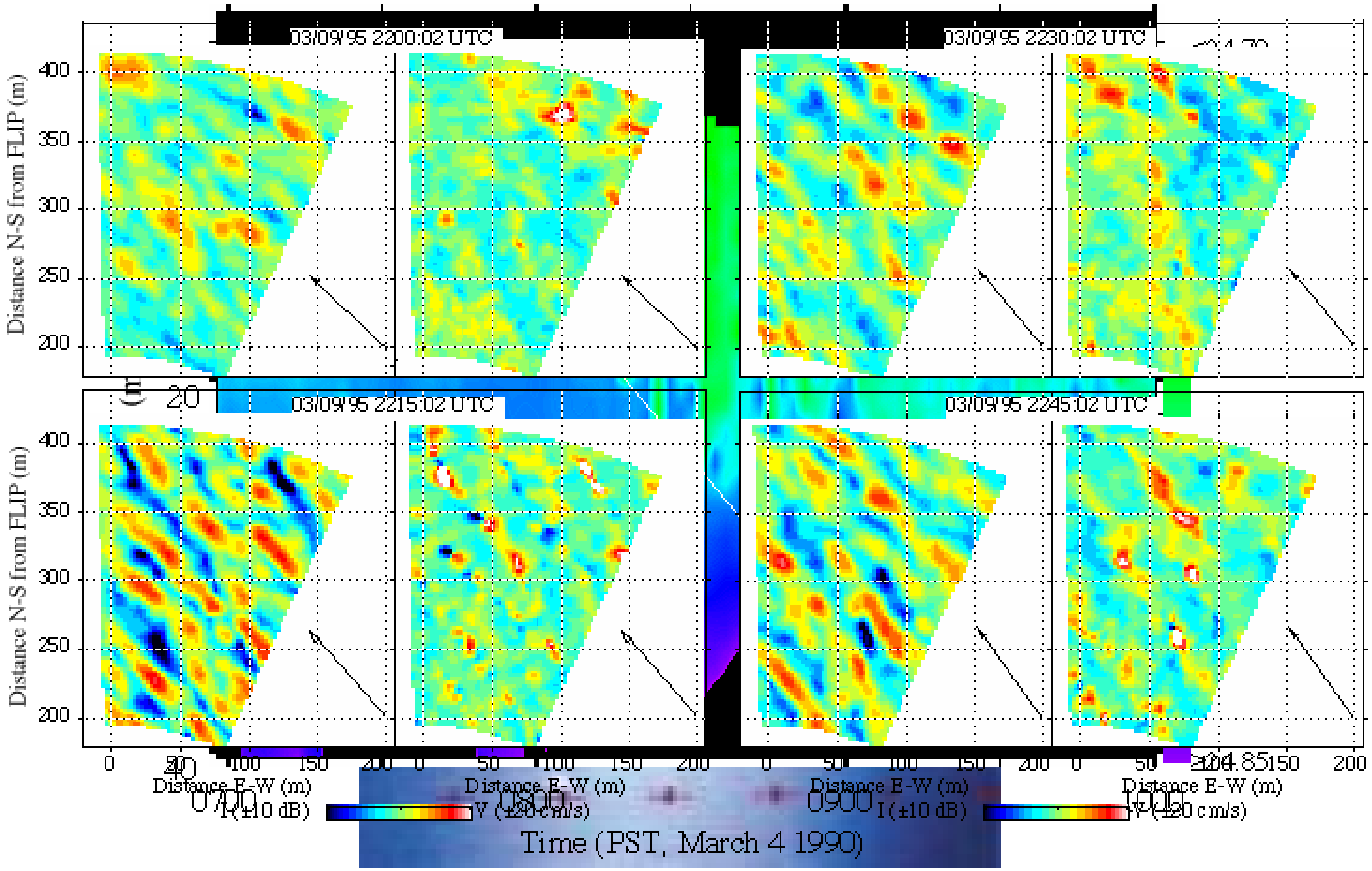


K. Lamb, U. Waterloo

Oceanic Mixed Layer

Observations, Mathematical Modeling, and Simulation

Observing the Mixed Layer



CTD Scanner

Infrared Camera

Sonar

J. Smith, SIO

J. Smith, SIO

H. Rye

Mathematical Description: Navier-Stokes Equations

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-2\Omega v=\frac{-1}{\rho_o}\frac{\partial p}{\partial x}+\upsilon\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+2\Omega u=\frac{-1}{\rho_o}\frac{\partial p}{\partial y}+\upsilon\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=\frac{-1}{\rho_o}\frac{\partial p}{\partial z}-\frac{\rho}{\rho_o}g+\upsilon\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0, \qquad \frac{\partial \rho}{\partial t}+u\frac{\partial \rho}{\partial x}+v\frac{\partial \rho}{\partial y}+w\frac{\partial \rho}{\partial z}=0$$

Required Inputs to NS Eqns

- Boundary conditions:
  - Air-sea interface.
  - Bottom topography.
  - Inflow and outflow for region of consideration.
- Initial conditions:
  - The state (instantaneous velocities) of the entire mixed layer at the start time.
- Material properties:
  - Viscosity, mean density, equation of state.

Numerical Simulation

- Rules (NS eqns) known, outcome not!
- Solutions chaotic, prone to instability, involve nonlinear scale interactions.
- Few exact analytical solutions known.
- Equations “solved” numerically by discretizing in space and time.
- To obtain accurate solution, must resolve all flow scales, from smallest to largest.

Computational Requirements

Large Eddies:	100m, 1min
Small Eddies:	0.01m, 0.01s
Grid size:	0.01m
# points:	10^{12} for 1 large eddy
Time step:	0.01s
# time steps:	10^{4} steps for 2 minutes
# unknowns:	4×10^{16}
# operations:	100/unknown $\rightarrow 4 \times 10^{18}$

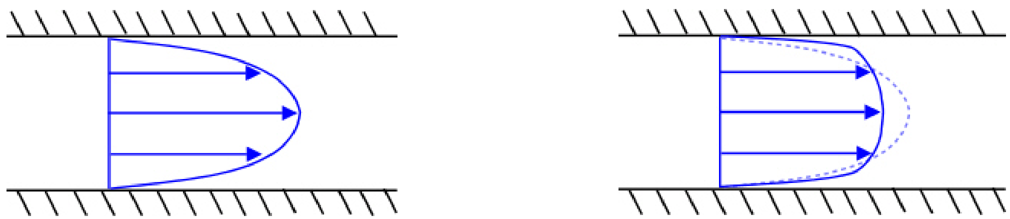
Total computer time on 10 Gflop computer = 1 year !!!!

Oceanic Mixed Layer

Challenges and Opportunities for Oil Spill Response

Challenge: Simulation of Multi-Scale Nonlinear Systems

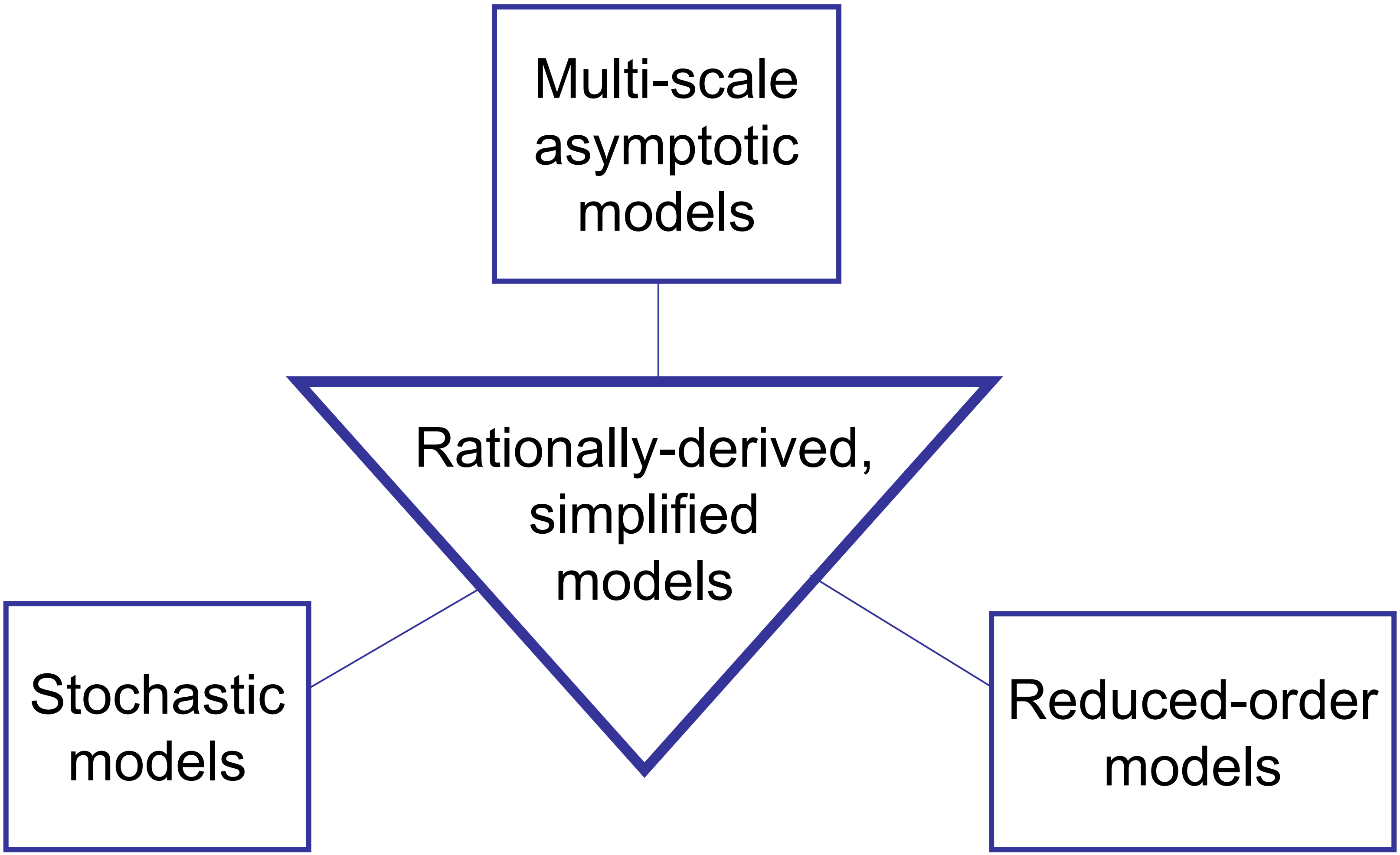
- Must “sweat the small stuff” - O(1) effect over long times due to nonlinearity.
- Examples
  - Pipe flow (turbulent fluctuations)



  - LC (surface waves)

BUT computationally prohibitive!

Multi-Scale Computation: Opportunities



Craik & Leibovich LC Model

- C-L idea: *prescribe* surface waves & then filter, exploiting time-scale separation.
- CL eqns = wave-filtered NS eqns (additional “vortex force” terms).
- Key input: wave Stokes drift velocity profile.
- Significant computational and analytical advantages.

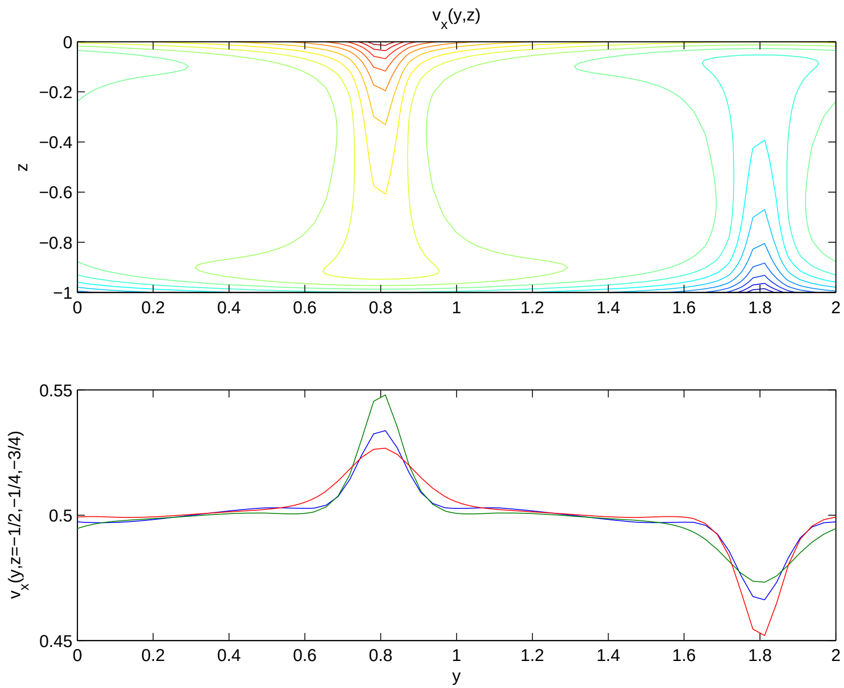
Current Multi-Scale LC Research

Systematically exploit scale disparity to reduce dimensionality and computational complexity.

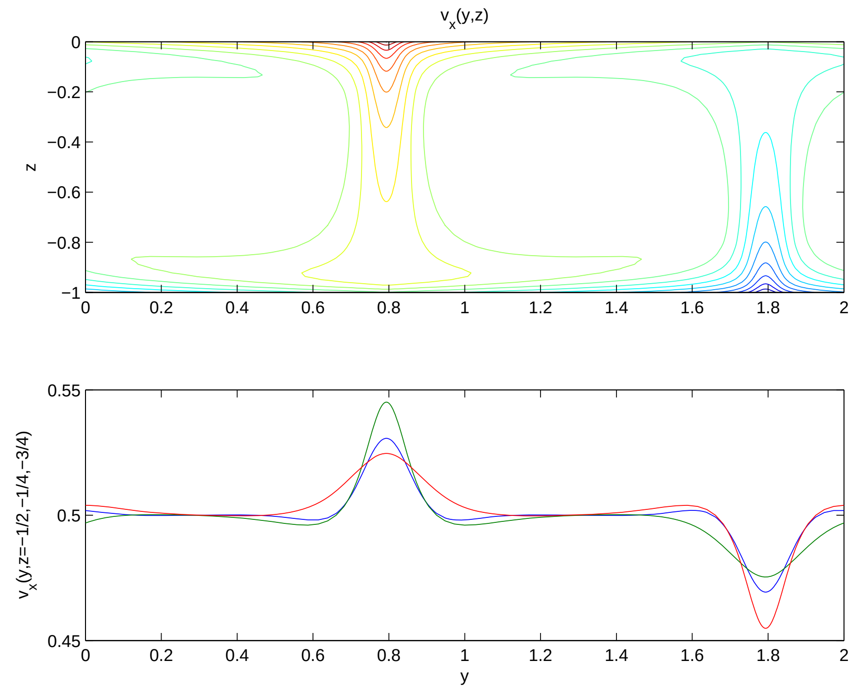
- Craik-Leibovich eqns for LC.
- Meso-scale flow / LC field.
- Elongated vortical structures.
- Narrow downwelling zones within 1 cell.

Single Cell Multi-Scale Model

Full Numerical Simulation



Semi-analytical calculation



Challenge: Transport and Mixing

- Given fluid dynamics, prediction of transport involves solving
  - Particle tracking models.
  - Two-fluid flows, interfacial phenomena.
- Coherent flow structures give rise to non-uniform mixing, “anomalous diffusion”.
  - e.g. convergences, stagnation points, recirculation zones.

Transport & Mixing: Opportunities

- Use dynamical systems and stochastic approaches.
  - Chaotic mixing, lobe dynamics, Lagrangian coherent structures, PDF methods.

- Use multi-scale methods to couple transport with ecology & toxicology.
  - LC downwelling jets = site of oil-accumulation and biomass.

Challenge: Unknown Boundary and Initial Conditions

- Simulations of mixed-layer dynamics and transport require knowledge of BCs, ICs.
- Measurements of ocean mixed layer notoriously difficult to make.
- Oil-spill environment – data starved!

BCs & ICs: Opportunities

- Modify computational models to operate in alternative “adjoint” mode.
  - Sensitivity analyses (quantify dependence of statistics on unknown inputs).
  - Data assimilation (keep forecasts on track).

- Develop reduced (multi-scale) models.
  - Operate in adjoint mode.
  - Use with remotely sensed data.
  - Require fewer inputs.

Summary

- Mixed layer incredibly complex multi-scale environment (3D, time-dependent).
- LC key mechanism for vertical transport, impacting dispersant usage and ecology.
- Interplay of coherent and disordered flow structures complicates transport prediction.
- Multi-scale numerical methods needed.