OUTLINE

• INTRODUCTION: Approaches to ocean studies

• MOTIVATION: Why model the ocean?

• THE MODELING PROCESS

• SIMPLE EXAMPLES

• CHALLENGES
Introduction: Approaches to oceanic studies

Drew, Emily, Stephan, Christian

Observational oceanography
Introduction: Approaches to oceanic studies

Observational oceanography

Drew, Emily, Stephan, Christian

Drew, Emily, Stephan, Christian
Introduction: Approaches to oceanic studies

Satellite oceanography

Ebenezer, Christian, et. al.
Introduction: Approaches to oceanic studies
Introduction: Approaches to oceanic studies

Chemical oceanography

Winn, Madelyn, Julia, et al.
Introduction: Approaches to oceanic studies

Chemical oceanography

Winn

Madelyn

Julia
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Hydrography/Coastal morphology

Stephan/Kwasi
Introduction: Approaches to oceanic studies

Hydrography/Coastal morphology
Introduction: Approaches to oceanic studies

Angela (Talk on Friday)
Introduction: Approaches to oceanic studies
Introduction: Approaches to oceanic studies

Laboratory tank experiments-

Ansong & Sutherland, 2010, JFM, vol 648
Introduction: Approaches to oceanic studies

Laboratory tank Experiments- Aline, Emily

Emily

Aline

Maddie
Introduction: Approaches to oceanic studies

Ansong & Sutherland (2010), JFM, vol 648
Introduction: Approaches to oceanic studies

Ocean modeling
Dimitris/Brian/Christian/Joseph et. al.
Introduction: Approaches to oceanic studies

Dimitris

Paige

Christian

Brian
What is an ocean model?
What is an ocean model?

It is a representation, in the form of equations/computer code, describing physical processes of our understanding of how the ocean works.

-Dr. Stephenie Waterman
What is an ocean model?

Physical processes:

a) Ocean movement/dynamics, including horizontal and vertical advection

b) Exchange of energy between the ocean and external sources (radiation, precipitation, evaporation, river-runoff, wind, etc)

c) 3D mixing and dissipation processes
Why is ocean modeling necessary, when we have alternative means?
Motivation: Why model the ocean?
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Motivation: Why model the ocean?

• Comparatively less expensive

• Higher spatial/temporal resolution compared to other methods:
  – Satellites provide only surface data, and
  – In-situ measurement are limited in spatial coverage

• Ability to forecast (e.g. SST, SSH, and positions of major fronts and eddies)
Motivation: Why model the ocean?

www.hycom.org
Motivation: Why model the ocean?

www.hycom.org
Motivation: Why model the ocean?
Motivation: Why model the ocean?
Motivation: Why model the ocean?
Understanding the 3D dynamics of the ocean on a GLOBAL scale.

MacKinnon et al, 2017
Motivation: not a competition
Motivation: *Team Work!*
Motivation: *Team Work!*
Motivation: global ocean currents
Internal gravity waves

Generation of Internal gravity waves by sinusoidal hills
(Prof. Bruce Sutherland)
Motivation: internal waves

Courtesy: Max-Planck institute of Ocean modeling
Motivation: internal waves

QUESTION?
How accurate are the Internal tides in global models compared to observations (altimeter-derived Internal tides)?

Building upon previous Paper…
Ansong et. al. (2015)

Ansong et. al., 2019, in prep
Where/how do I start learning ocean modeling?
Definition: ocean model

It is a **representation**, in the form of **equations/computer code**, describing **physical processes** of our understanding of how the ocean works.

-Dr. Stephenie Waterman
Equations of motion

• Start ocean modeling by understanding the equations of fluid flow (Navier-Stokes equations).

• Learn how to discretize the equations

• Understand some numerical analysis
• Know some Python, Matlab, etc
Equations of motion

\[
\frac{D\vec{u}}{Dt} + \text{?} = -\frac{1}{\rho_o} \nabla p + \frac{\rho}{\rho_o} \vec{g} + \vec{F}
\]

acceleration (local + advective)

Pressure gradient

buoyancy

Others (frictional, Tides, Winds, etc)

\(u=[u,v,w]\) are velocity components, \(p\) is the pressure, \(\rho\) the density, and \(g\) gravity.
Equations of motion:

\[
\frac{D\vec{u}}{Dt} + 2\vec{\Omega} \times \vec{u} = -\frac{1}{\rho_o} \nabla p + \frac{\rho}{\rho_o} \vec{g} + \vec{F}
\]

where \((\vec{u}=[u,v,w])\) are velocity components, \(\vec{\Omega}\) is the earth's rotation rate, \(p\) is the pressure, \(\rho\) the density, and \(\vec{g}\) gravity.
Continuity equation
(Conservation of volume)

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \]
Equation for tracers (Temperature, Salinity, and others),

Advection-diffusion equation:

\[
\frac{\partial T^c}{\partial t} + \vec{u} \cdot \nabla T^c = \kappa_T \nabla^2 T^c
\]

\(T^c = \text{Tracers}\)
Equation of state (Linear)

\[ \rho = \rho_0 [1 - \alpha (T - T_0) + \beta (S - S_0)] \]

\[ \rho_0 = 1028 \text{ kg/m}^3 \]  
coefficients of thermal, \( \alpha \),

\[ T_0 = 10^\circ C = 283 K \]  
and saline contraction, \( \beta \)

\[ S_0 = 35 \text{ psu} \]

Where \( T \) is temperature and \( S \) is salinity.
Equations of motions

7 equations in 7 unknowns:

- \{u,v,w\} – 3 velocity components
- T – Temperature
- S – Salinity
- Density
- P – Pressure
Now that I understand the equations, what next?
Now that I understand the equations, what next?

A. Discretize equations
B. Consider the horizontal grid
C. Consider the vertical grid
D. Boundary conditions
Discretize equations

- Continuous equations
  \[ \Downarrow \]
  algebraic equations (discrete set of operations)

- Discretization methods:
  - Finite difference methods
  - Finite element methods
  - Finite volume methods

Example early model grid by Lewis Fry Richardson (1928)
Model grid: horizontal

- Regular grids: regularly spaced lines
- Possible in a small domain
Model grid: horizontal

- Regular grids: regularly spaced lines
- On a spherical earth can’t have both uniform grid spacing and straight lines
- Regular lat/lon grids have a problem at the poles where grid lines converge
Clever solution: tripolar grid
-circular grid laid over Arctic region with poles on land
Model grid: vertical

- **z-coordinate** system based on a series of depth levels. Easy to setup. Difficult to locally increase resolution.
- **terrain-following** coordinate system. Mimics bathymetry and allows higher resolution near ocean floor.
Model grid: vertical

- density (isopycnal)-coordinate system based on density layers. Great in the deep ocean where there’s less diapycnal mixing. Poor in regions with high vertical mixing.
Model grid: vertical

- hybrid-coordinate applies the best suited coordinate system in different regions. Gives improved results but at a high computational cost.
Boundary conditions

• Free surface
  – Flux exchanges at surface: momentum and tracer (winds, solar radiation, rainfall, precipitation, etc).

• Ocean bottom
  – Topography/bathymetry
  – Velocity normal to bottom is zero
  – Lateral boundaries (open/closed)

• Flow normal to solid boundary is zero
Modeling: summary

- Complex differential equations
- Set of algebraic equations
- Step-by-step method of solution (model time stepping) at selected points in space (model spatial grid)

It takes years to develop a good ocean model!
Ocean models

- MOM (The Modular Ocean Model: http://mom-ocean.org/web)
- POM (The Princeton Ocean Model: http://www.ccpo.odu.edu/POMWEB)
- POP (The Parallel Ocean Program: http://www.cesm.ucar.edu/models/cesm1.0/pop2)
Ocean models

- MITgcm (MIT general circulation model: http://mitgcm.org/)
- HYCOM (The Hybrid Coordinate Ocean Model: https://hycom.org/)
- ROMS (Regional Ocean Modeling System: www.myroms.org)
Simple Examples
Test Case 1: Upwelling

- East-West periodic channel
- Spatially-uniform winds blowing from east to west
- Wind stress = 0.1 Pascals

Contributed by Anthony Macks and Jason Middleton (Macks, 1993)
Upwelling

Initial temperature distribution
Upwelling
Regional Modeling
Regional Modeling

Operational Guidelines:

1. Choose a domain and resolution.
2. Build a bathymetry.
3. Interpolate atmospheric forcing to the domain.
4. Choose vertical structure
5. Interpolate T/S climatology to the model domain
6. Run the simulation.
7. Plot and analyze results.
Regional Modeling

Etopo5: http://www.ngdc.noaa.gov/mgg/global/etopo5.HTML

1/4th degree, ~ 28 km
32 vertical layers
Results: Tides
Results: tidal time series

Challenge: compare to tide-gauge data (Takoradi/Tema)
Challenges to ocean modeling

What are some challenges?
Challenges to ocean modeling

1. Variable spatial/temporal scales
Challenges to ocean modeling

2. Coupling the Atmosphere to the Ocean

Antonio Navarra
Challenges to ocean modeling

3. Complex topography and lateral boundaries

4. Few observational measurements for validation
   -most available data are confined to upper ocean

5. Availability of computational power
QUESTIONS?
• For a windows laptop/computer
  – download a VirtualBox
  – Install Ubuntu
• Install MITgcm (www.mitgcm.org)
  – Try some of the examples