Modeling Langmuir Turbulence in the Ocean Surface Boundary Layer with Dedalus

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Introduction: Climate Modeling

Climate vs Weather

Weather	specific events chaotic changes quickly difficult to predict
Climate	trends over time approximately in equilibrium changes slowly predicted with Earth System Models (ESMs)

Earth System Models

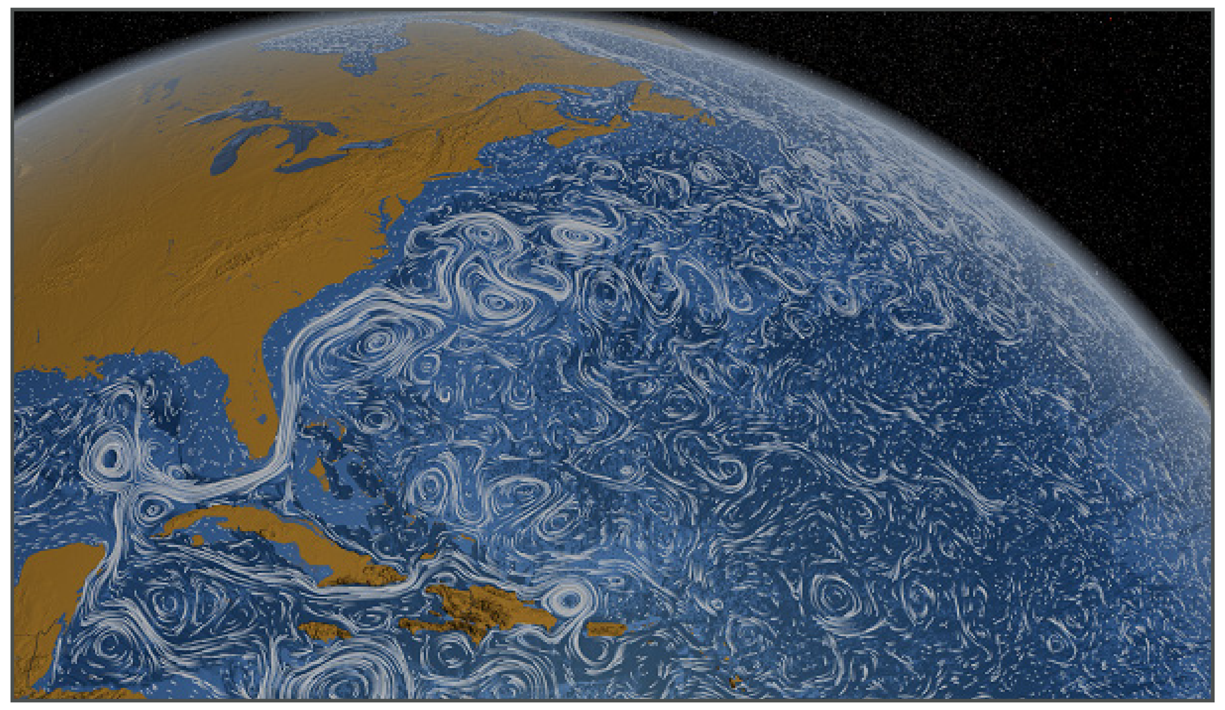


Figure 1: A visualization of ocean surface currents generated with data from MIT and JPL's joint project ECCO2. The project used MIT's global circulation model, MITgcm, a type of Earth Systems Model. [1]

1. **Describe** the Earth as fully as possible within a computer - the Earth model
   - at grid points in space, define: air temperature, ocean density, wind speed, solar radiation, etc.
2. Use known physical laws to advance the Earth model through time
   - let air and water flow, allow heating and cooling, evaporation, etc.
3. Climate statistics = trends over long periods of time
   - typical statistics = average seasonal temperature, ocean currents (see Figure 1), storm tracks, extreme event frequency, correlations between variables

Improving Climate Models

Sources of Error in ESMs:

- numerical solutions are approximate
- our understanding of how climate features interact
- ommission of some features
  - o poor spatial resolution (~100 km) -> sub-grid scales are not resolved

Turbulence is a sub-grid mechanism that is frequently neglected in climate models. In the ocean, turbulence is responsible for exchanging heat, moisture, and trace gases between the deep ocean, surface ocean, and atmosphere. As a result, including turbulence in ESMs is expected to improve uncertainties in values such as the ocean surface temperature [2, 3].

New approach: **Direct Statistical Simulation (DSS)**

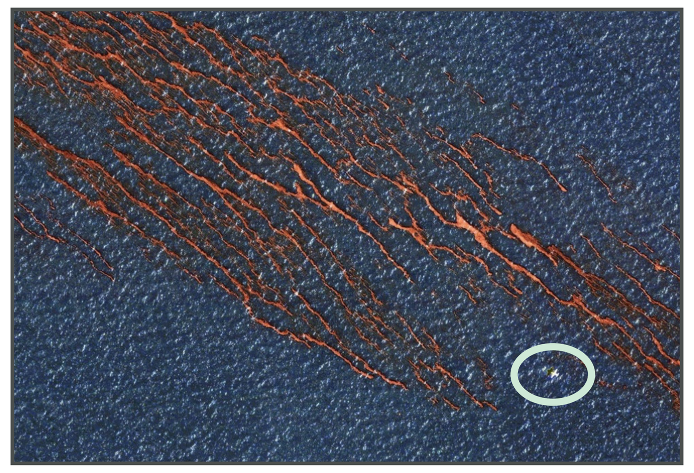
Use climate statistics themselves as variables rather than the Earth model's many physical states

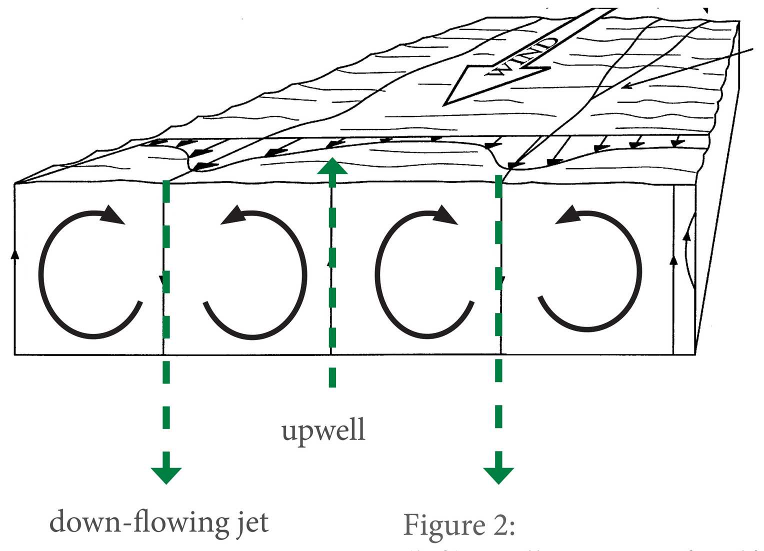
Mathematical Basis [Established] [4, 5] → Test specific features [in progress] → Apply to ESMs [TBD]

Langmuir Turbulence (sub-grid turbulence feature) — **Long-term project**

1. Write non-linear (nearly exact) Langmuir turbulence model in Dedalus — **This poster**
2. Apply DSS approximations to Dedalus model
3. Compare approximations to non-linear simulation
4. Determine whether DSS accurately models Langmuir turbulence

Langmuir Turbulence





Characteristics [7]**:**

rows of long "cells"

each cell: 2 m - 1 km wide

a few km long (Figure 2, left)

water within cell rotates (axis along ocean surface; Figure 2, right)

each cell rotates in opposite direction of its neighbors, like gears

in between cells, this pushes water up (upwell) or down (jet)

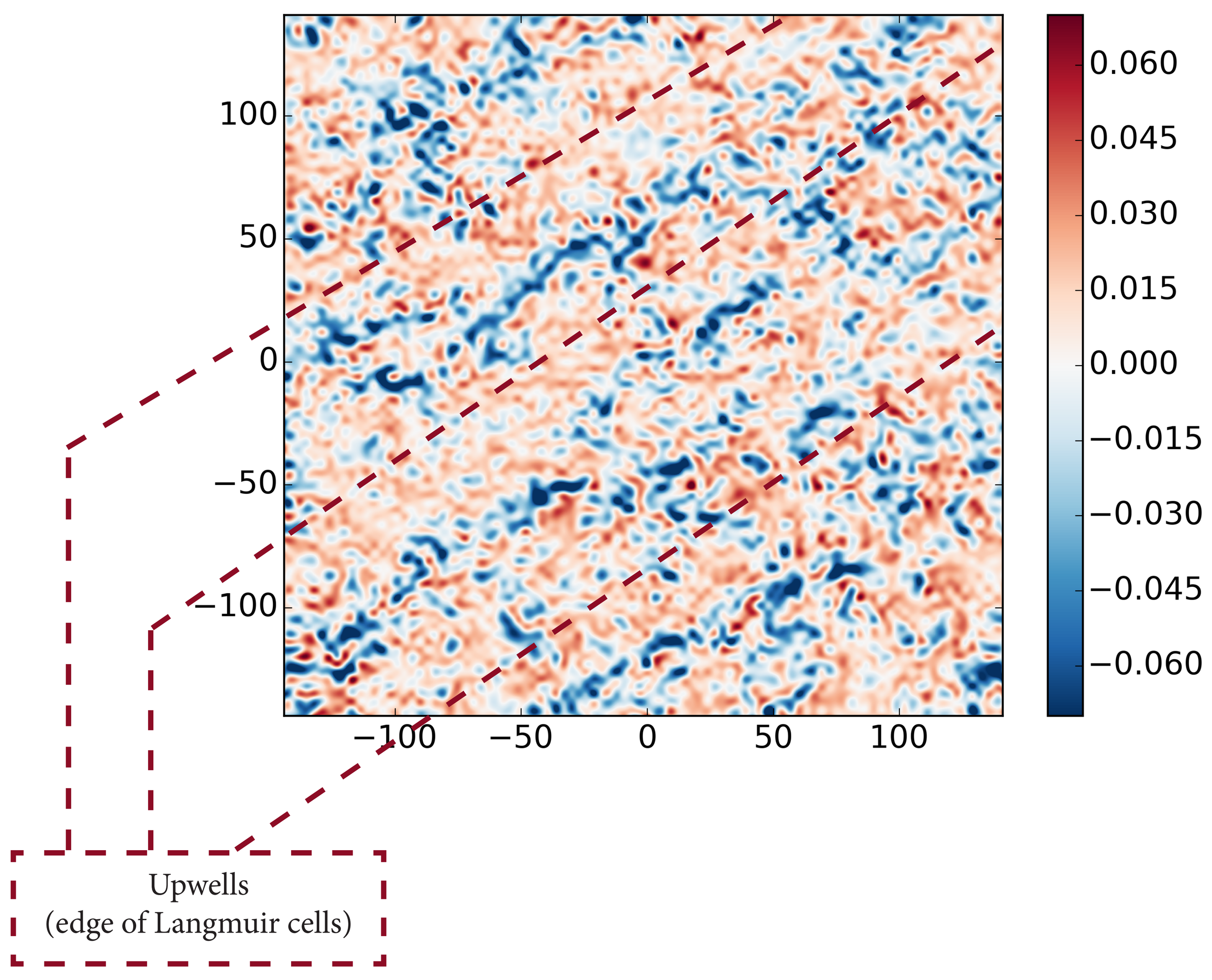
Figure 2:
(left) Satellite image of Gulf Oil spill showing Langmuir windrows. For scale: the white spot circled in the bottom-right is an airplane. [6]
(right) Diagram of four counter-rotating Langmuir cells. In between cells, water is pushed up (upwells) or down (jets). [adapted from 7]

Results: Non-linear Langmuir Turbulence

Modeled in Dedalus: open-source Python program that solves systems of non-linear differential equations. [8]

In the figure, Langmuir cells are visible as alternating strips of upwells (red) and down-flowing jets (blue).

Top-down view of vertical velocity from a depth of 7 m



Conclusions & Next Steps

Successfully constructed a Langmuir turbulence model in Dedalus

Moving forward in this project:
- Add calculations of energy and mean fields
- Incorporate quasi-linear approximation from DSS
- Compare approximation to non-linear results

DSS development:
- Reduce number of dimensions with proper orthogonal decomposition
  - DSS requires 5, current ESMs only need 4

References & Acknowledgments

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[1] "Perpetual Ocean", Scientific Visualization Studio, *NASA/Goddard Space Flight Center* (2011), located at http://svs.gsfc.nasa.gov/3827
[2] E. A. D'Asaro, J. Thomson, A. Y. Shcherbina, R. R. Harcourt, M. F. Cronin, M. A. Hemer, B. Fox-Kemper (2014), Quantifying upper ocean turbulence driven by surface waves, *Geophysical Research Letters*, 41, 1, 102-107.
[3] S. E. Belcher, A. L. M. Grant, K. E. Hanley, B. Fox-Kemper, L. Van Roekel, P. P. Sullivan, W. G. Large, A. Brown, A. Hines, D. Calvert, A. Rutgersson, H. Pettersson, J-R. Bidlot, P. A. E. M. Janssen, J. A. Polton (2012), A global perspective on Langmuir turbulence in the ocean surface boundary layer, *Geophysical Research Letters,* 39, 18.
[4] J. B. Marston, G. P Chini, S. M. Tobias (2016), The generalized quasi-linear approximation: application to zonal jets, *Phys. Rev. Lett.*, 116, 214501.
[5] F. Ait-Chaalal, T. Schneider, B. Meyer, B. Marston (2016), Cumulant expansions for atmospheric flows, New Journal of Physics, 18, 025019.
[6] Trumbull, Mark. (2010). Oil spill: Gulf of Mexico disaster holds big liabilities for BP, *The Christian Science Monitor.*
[7] S. A. Thorpe (2004), Langmuir circulation, *Annual Review of Fluid Mechanics,* 36, 55-79.
[8] K. J. Burns, G. M. Vasil, J. S. Oishi, D. Lecoanet, B. P. Brown, and E. Quataert (2016), Dedalus: A Flexible Framework for Spectrally Solving Differential Equations, *Astrophysics Source Code Library,* record ascl:1603.015