Ryan Abernathey: Research Statement

The overall goal of my research is to understand the factors which govern the large-scale ocean circulation, and resulting transport of heat and tracers, on timescales relevant for Earth's climate. The ocean components of global climate models are still relatively coarse and crude compared to their atmospheric counterparts, limiting our ability to make long term forecasts or study past climates. My driving principle is that the best way to improve this situation is through careful, focused studies of unresolved and poorly understood ocean processes.

Spatial and Temporal Variability in Mesoscale Turbulence

The ocean mesoscale (roughly 10-300 km), characterized by a turbulent tangle of eddies, jets, fronts, and filaments, is the most energetic scale in the ocean. Mixing by mesoscale turbulence represents an important mechanism for transporting ocean tracers such as heat, carbon, and oxygen. But due to the small spatial scales involved, much remains unknown about how mesoscale turbulence varies in space and time through the global ocean. Shedding light on this variability has been a central focus of my research.

My Ph.D. work *[Abernathey et al., 2010; Abernathey and Marshall, 2013]*, using a novel method for analyzing satellite observations of sea-surface height (SSH), showed that mesoscale diffusivity varies regionally over several orders of magnitude. Subsequently, we have developed a deeper physical explanation for this global variability using mixing length theory *[Klocker and Abernathey, 2014]* and cross spectral analysis of SSH and Sea Surface Temperature (SST) *[Abernathey and Wortham, 2015]*. This work led to two research grants from NASA and membership in NASA's Surface Water and Ocean Topography Science Team SWOT. Our ongoing work (collaborative with Shafer Smith of NYU) is helping to guide the science goals of this new satellite, due to launch in 2021.

A fundamental yet largely unexplored problem in physical oceanography is the question of how the large-scale characteristics of mesoscale turbulence (such as kinetic energy, eddy size, and mixing rates) vary on interannual and decadal timescales, and in response to climate change. This question is the topic of my NSF CAREER Award, entitled *Evolution of Ocean Mesoscale Turbulence in a Changing Climate*. Work on this topic has largely been led by students. In *Sinha and Abernathey (2016)*, we developed a theoretical model for the eddy kinetic energy response to time-varying wind forcing. *Uchida et al. (2017)* tackled the seasonal cycle in upper-ocean turbulence, showing that a high-resolution global climate model partially resolved a previously hypothesized mixed-layer instability mechanism. *Busecke et al. (2017)* found strong interannual variability in mesoscale mixing rates in the subtropical salinity maxima regions, and *Busecke and Abernathey (2017)* expanded this approach to reveal large correlations between mixing rates across the Pacific and ENSO. These studies show that mesoscale processes are a dynamic part of the climate system, rather than simply a passive source of diffusion. Many new future research directions emerge from this insight.

Mesoscale Lagrangian Coherent Structures

A new direction for my research is the application of Lagrangian Coherent Structures methods to satellite and model data. These methods, developed mostly by applied mathematicians working in dynamics systems theory, have the potential to resolve long-standing debates about the relative importance of "trapping" versus "stirring" mechanisms in mesoscale transport. Our group, with our emphasis on software and big data tools, is uniquely poised to exploit these powerful but computationally demanding techniques. A paper now in revision *[Abernathey and Haller, 2017]* uses one such technique applied to satellite data to quantify the trapped material transport due to coherent vortices across the Pacific basin. The results, which show that trapping makes a negligible contribution, directly challenge several recent high profile papers. Other work in progress on this topic includes a sensitivity analysis of the numerical method *[Zhang et al, 2017]*, an application to climate model simulations *[Tarshish et al, 2017]*, and an investigation into the role of submesoscales and internal waves in modulating Lagrangian transport barriers *[Sinha and Abernathey, 2017]*.

Southern Ocean Overturning Circulation

In addition to mesoscale dynamics, I maintain a strong regional interest in the Southern Ocean, which has emerged in recent decades as the central node of the global ocean overturning system. An NSF-funded collaboration with colleagues at Scripps Institution of Oceanography (and affiliated with the large SOCCOM Project) involves the study of the thermodynamic processes involved in the upwelling of deep water in the Southern Ocean. This work has revealed the relative importance of isopycnal mixing versus overturning in the response of subduction to changing westerly winds *[Abernathey and Ferreira, 2015]*. We have also explored the response of the Southern Ocean to changing climate in groundbreaking high-resolution coupled climate model simulations *[Bishop et al., 2016; Newsom et al., 2016]* A particular highlight was the discovery of a crucial role for Antarctic sea ice in maintaining the upper branch of the Southern Ocean overturning circulation *[Abernathey et al., 2016]*. We have also recently provided a new description of the three-dimensional pathways of upwelling using a hybrid Lagrangian / water-mass-transformation method *[Tasmitt et al., 2017]*.

Mesoscale Impacts on Climate and Ecosystems

I strive to connect my more technical work on the topics above to broader questions in oceanography and climate. A particular emphasis in this area has been to understand the implications of spatially variable mesoscale diffusivities for climate simulations. In a series of recent papers (collaboration with A. Gnanadesikan of Johns Hopkins), we have implemented my satellite-derived estimates of mesoscale diffusivity in the GFDL climate model. We showed that spatially variable diffusivities have a strong impact on helium distributions *[Gnanadesikan et al., 2014]*, and can modify the ocean uptake of anthropogenic $CO2$ by up to 25% *[Gnanadesikan et al., 2015]*. We also examined the impact of mesoscale mixing on ENSO variability, showing, somewhat counterintuitively, that stronger mixing rates near the equator cause the amplitude of ENSE to increase *[Gnanadesikan et al., 2017]*. Together, these results show that mesoscale mixing has a range of under-appreciated impacts on large-scale climate, opening the door to many future research questions.

We are also beginning to explore the role of small-scale transport processes on ocean ecosystems. In particular, via our NASA-sponsored work on the SWOT mission, we are developing a new series of simulations to model the vertical transport of heat, carbon, nutrients, and oxygen in two important regions: the Southern Ocean and the Arabian Sea. My Ph.D. student Takaya Uchida has just begun a new project investigating how mesoscale and submesoscale motions contribute to the supply of iron from the enriched waters of the deep Southern Ocean to the surface euphotic zone, where iron concentration is a limiting factor for primary productivity. Although still early, I am very excited about the potential for this work to make new connections between the physics and biology of the Southern Ocean.

Open Source Software for Big Data Oceanography

A unique aspect of my research group is our strong emphasis on the development of open source software tools for handling the increasing flood of "big data" in oceanography and climate science in general. New observing technologies (satellites, autonomous platforms, etc.) are high resolution numerical simulations are now capable of producing petabytes (a million gigabytes) of data. There is enormous scientific potential in such datasets, especially for investigating the multiscale phenomena central to my research. However, the sheer volume of data makes it extremely difficult to do exploratory analysis on such datasets.

Building on my strong track record within the scientific python community, I recently led a collaborative proposal between Lamont, NCAR, and Anaconda (a private software company) to further develop our emerging solution to the big data challenge. (The proposal was funded by the NSF Earthcube program.) This group, called Pangeo, is developing a suite of tools that will allow researchers to use cloud computing (and other high-performance computing platforms) to work with extremely large datasets using familiar python-based tools. I strongly believe that these efforts will pay off in the long term by enabling our group to tackle some of the most challenging problems in oceanography,

By the Numbers

citations

- 21 publications, plus 4 under review
- 475 citations,
- X grants funded ($total)
- 2 Ph.D. students supervised
- One postdoc (another on the way)