Visualization of Ocean Currents and Eddies in a High-Resolution Global Ocean-Climate Model

Francesca Samsel, Mark Petersen, Gregory Abram, Terece L. Turton, David Rogers and James Ahrens

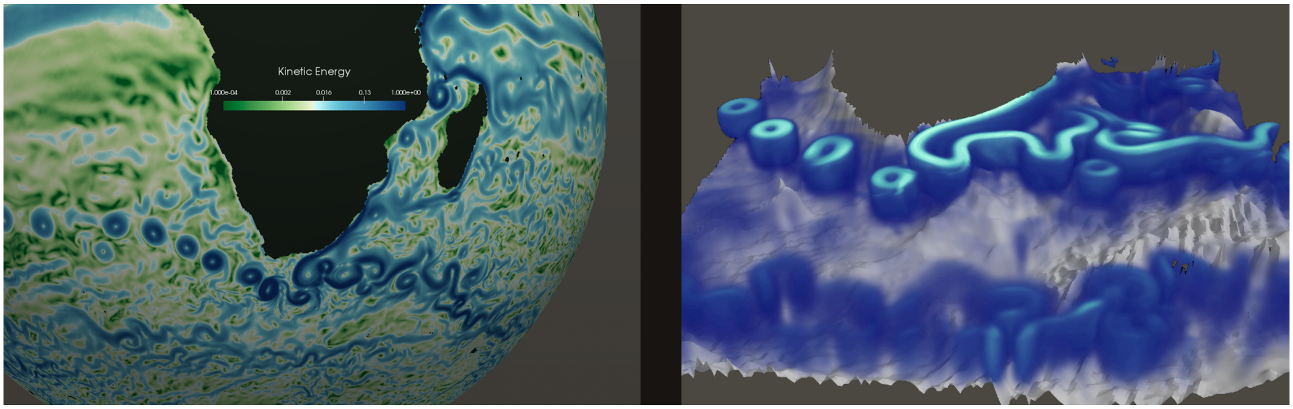

Fig. 1. Left: The Agulhas current and retroflection, shown in kinetic energy, m^2s^{-2}. Right: A three-dimensional image of the Agulhas current and retroflection, shown in kinetic energy in the Southern Ocean just south of Africa, where aqua is 1 m^2s^{-2}.

Abstract— Climate change research relies on models to better understand and predict the complex, interdependent processes that affect the atmosphere, ocean, and land. These models are computationally intensive and produce terabytes to petabytes of data. Visualization and analysis is increasingly difficult, yet is critical to gain scientific insights from large simulations. The recently-developed Model for Prediction Across Scales-Ocean (MPAS-Ocean) is designed to investigate climate change at global high-resolution (5 to 10 km grid cells) on high performance computing platforms. In the accompanying video, we use state-of-the-art visualization techniques to explore the physical processes in the ocean relevant to climate change. These include heat transport, turbulence and eddies, weakening of the meridional overturning circulation, and interaction between a warming ocean and Antarctic ice shelves. The project exemplifies the benefits of tight collaboration among scientists, artists, computer scientists, and visualization specialists.

1 Introduction

Predicting the risks of climate change is one of the great scientific challenges of our time. From severe weather events to loss of species to encroaching sea levels, understanding the impacts of climate change is a critical scientific endeavor. Computational climate models are an important facet of climate change research. The Accelerated Climate Model for Energy (ACME) is a new initiative by the Department of Energy (DOE) to develop the most complete, leading-edge climate model that will efficiently utilize DOE leadership computing resources. The ocean component of ACME is MPAS-Ocean, a new variable-resolution mesh model developed at Los Alamos National Laboratory. The mesh is based on Voronoi tessellations, which allows users to place high-resolution grid cells where they are most needed, in order to study particular regions of the earth, or to better resolve important physical processes.

Visualization plays a key role in developing scientific insight into the data produced by climate models, including MPAS-Ocean. Innovative visualization techniques allow the researcher to more clearly see and explore structures in the data, leading to a more intuitive understanding of the data, which in turn may lead to improved models and more robust predictions and understanding of climate change. A new suite of colormaps provide more perceptual depth into the MPAS-Ocean data, allowing researchers clearer visualizations of ocean currents. An innovative 3D ray casting tool is providing a new way of visualizing the structural depth of ocean currents and eddies.

- *Francesca Samsel is with the Center for Agile Technology, University of Texas at Austin. E-mail: figs@cat.utexas.edu.*
- *Mark Petersen is with COSIM, Los Alamos National Laboratory. E-mail: mpetersen@lanl.gov.*
- *Gregory Abram is with the Texas Advanced Computing Center, University of Texas at Austin. E-mail: gda@tacc.utexas.edu.*
- *Terece L. Turton is with the Center for Agile Technology, University of Texas at Austin. E-mail: tlturton@cat.utexas.edu.*
- *David Rogers is with Data Science at Scale, Los Alamos National Laboratory. E-mail: dhr@lanl.gov.*
- *James Ahrens is with Data Science at Scale, Los Alamos National Laboratory. E-mail: jahrens@lanl.gov.*

2 The Ocean's Role in the Climate

There are many feedback paths between the ocean and atmosphere in a changing climate. The ocean absorbs carbon dioxide from the atmosphere, influencing the rate of atmospheric warming. The amount of carbon dioxide removed from the atmosphere depends on ocean dynamics, chemistry, and biology. Ocean currents, in turn, transport heat, nutrients and biological constituents, and are expected to change in the coming century, altering weather patterns in the atmosphere. For example, Northern Europe is warmer than Canada due to the heat flux of the Gulf Stream (Figure 2). In a changing climate, the Arctic will experience a large warming and more precipitation [1]. This makes the waters of the North Atlantic warmer and less salty, which will likely weaken the Gulf Stream and impact global weather patterns. The Gulf Stream is part of the Atlantic Meridional Overturning Circulation (AMOC), where warm waters move northward at the surface, sink near the Artic and return as cold water in the deep Atlantic (Figure 3). Based on the assessment of models, observations, and our understanding of physical mechanisms, it is very likely that the AMOC will weaken over the 21st century [1].

High-resolution simulations are needed to model these processes

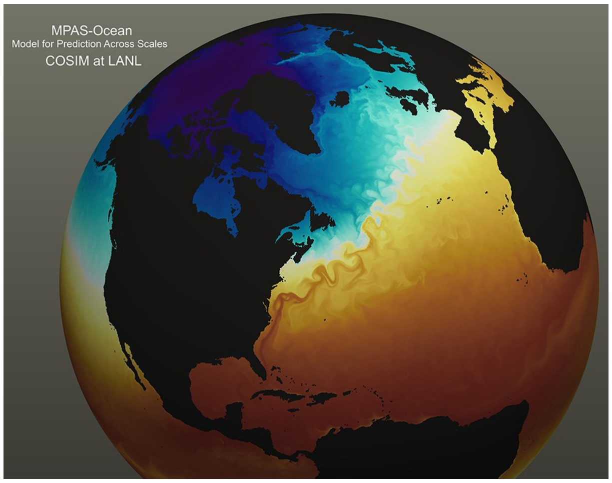

Fig. 2. The Gulf Stream transports heat from the tropics to Europe, as shown by surface temperatures in the MPAS-Ocean model. The divergent white point highlights the Gulf Stream at $20°C$.

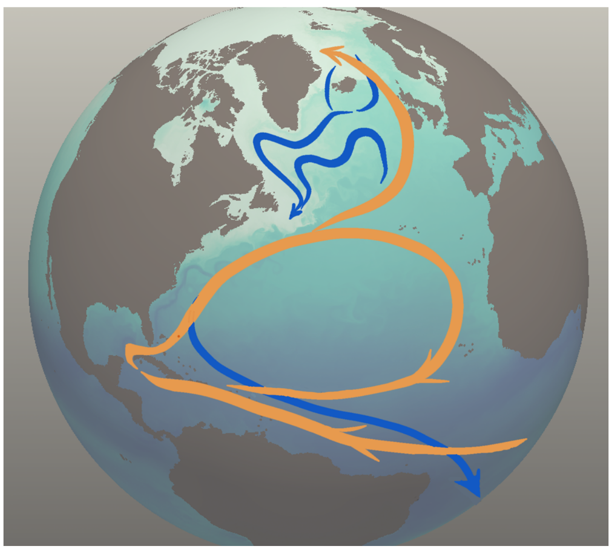

Fig. 3. The Atlantic Meridional Overturning Circulation in which the (orange) surface currents move northward to become the (blue) southward deep ocean currents. The surface currents move warm water towards the pole while the deep ocean currents move cold water southward in a global circulation pattern.

because the meso-scale variability, which occurs from 10 to 100 km, is an important part of the ocean's dynamics. The meso-scale includes the eddies that are visible throughout the ocean (Figures 5, 6). An ocean eddy is a turbulent feature of strongly rotating water. Eddies are created by shearing effects against coastlines, by pinching off of currents such as the Gulf Stream, and by baroclinic instabilities where the pressure and density gradients are misaligned.

While ocean currents transport heat around the global oceans, a substantial portion of the ocean's heat transport is by the eddy, or time-varying, component. In the Southern Ocean, where eddies are ubiquitous and very energetic, eddies can transport as much heat as the mean currents and, in some locations, eddies can transport heat in the opposite direction of the mean flow.

In the Southern Ocean, around the Horn of Africa, the Agulhas Retroflection is a great mixing of the warm waters of the Indian Ocean and the perpetually cold waters of the circumpolar current around Antarctica (Figures 1, 5, 6). That mixing spawns large eddies that curl around the Horn of Africa into the South Atlantic, transferring heat and other constituents between the oceans.

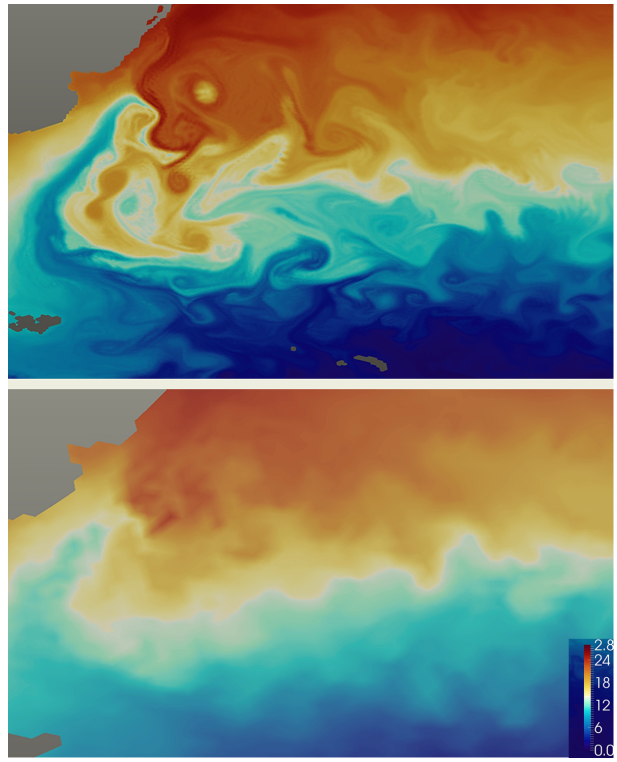

Fig. 4. A comparison of the Brazil-Malvinas Confluence near South America (temperature, $°C$), for (top) 10 km grid cells and (bottom) 60 km grid cells, demonstrating the need for high resolution models in order to resolve the eddy characteristics.

3 Simulation and Visualization

Computational models that accurately simulate ocean currents and eddy characteristics (Figure 4) are necessary to create models that will accurately predict climate change over long time periods. MPAS-Ocean is a high-resolution simulation using unstructured horizontal meshes based on Voronoi tessellations [4]. MPAS-Ocean has several next-generation features as a climate model. In addition to the multi-resolution capabilities, it includes conservation properties required for century-long climate simulations: conservation of volume and volume-weighted tracers; energetically neutral computation of the Coriolis force [8]; the exchange of kinetic and potential energy is conservative [5]; the algorithm includes a discrete analog of Kelvin's circulation theorem [5]. The vertical coordinate is Arbitrary Lagrangian-Eulerian (ALE) and provides freedom for the coordinate to move with the flow, reducing spurious mixing [2]. Analysis, which was historically a post-processing step, is now computed in-situ and at scale [11]. This is a significant improvement in the workflow, and the only feasible analysis method for ultra-high resolution simulations. The model also includes advanced parameterizations of sub-grid scale processes [6], and an in-situ Lagrangian particle-tracking model [10].

The simulation in the accompanying video uses 1.4 million cells in the horizontal, which are mostly hexagons and vary in size from 30 km at the equator to 10 km near the poles. The vertical grid is structured, includes sub-surface bathymetry, and uses 60 levels varying from one meter near the surface to 200 m at depth. Simulations may be run on 1000 to 10,000 processors, and typical throughput is five simulated years per day on 4000 processors. For simulations this large, efficient and scalable I/O is a high priority: restart files are 5 GB, and output files are 20 GB per time slice. MPAS-Ocean uses parallel-netcdf and PIO libraries to write large files on a Lustre file system.

Visualization is an essential tool for scientists to gain an intuitive understanding of the physical system. These insights lead to specific

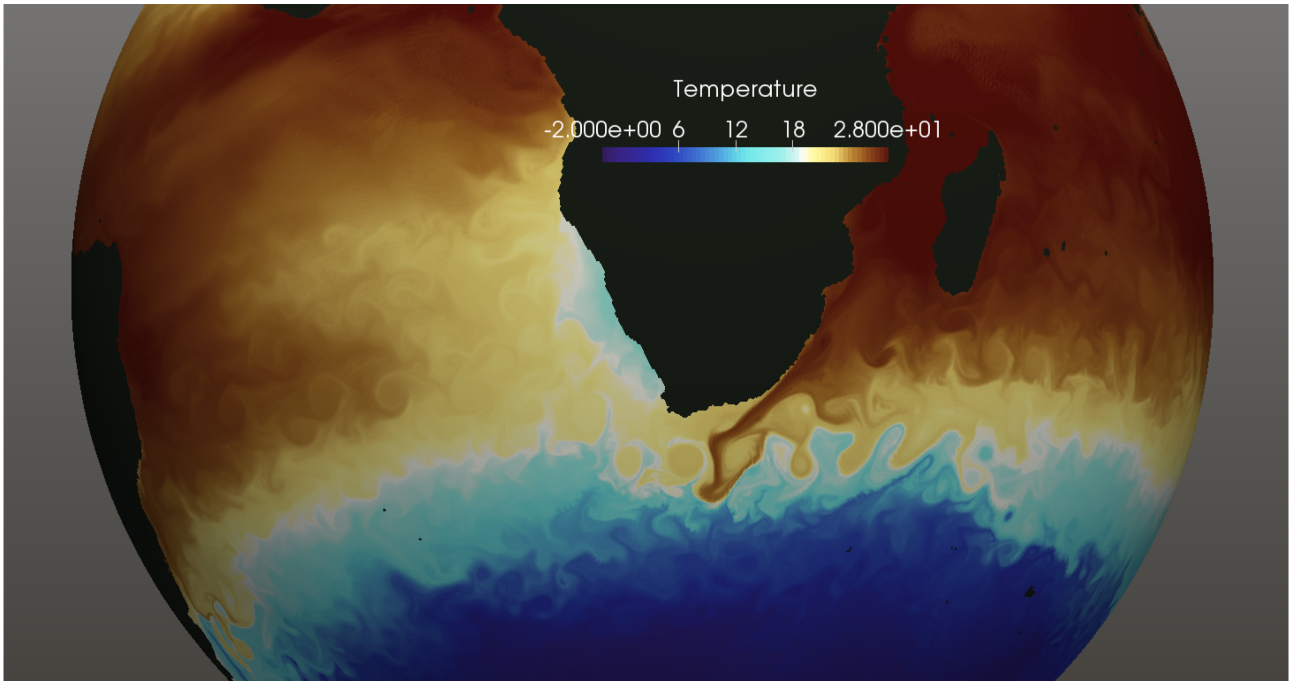

Fig. 5. The Agulhas current and retroflection, shown in temperature, $^{\circ}C$.

mathematical analyses and an improved ability to validate the model with respect to previous models and observational data. Typical output variables that are relevant to modeling of currents and eddies include temperature (Figure 5), salinity, kinetic energy (Figure 1), and relative vorticity. Secondary diagnostics include the Okubo-Weiss parameter (OW) [9], which shows the relative contribution of vorticity versus shear. OW images clearly show eddy cores, which are strongly rotating, surrounded by rings of strong shear (Figure 6). The boundary between rotation and shear defines the eddy surface in three dimensions, which is the first step in eddy detection algorithms. This leads to global analyses of eddy characteristics such as size, depth, and geographic distribution [3].

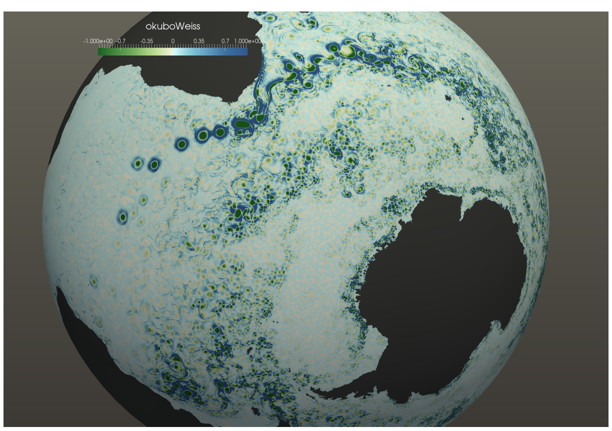

Fig. 6. The Okubo-Weiss parameter, where green colors show rotation-dominated regions, and blue shows strain-dominated regions. This diagnostic is used to detect and characterize eddies.

3.1 Model Validation

Validation is a critical task in order for climate model components to be trusted by the scientific community. The difficulty is that exact solutions are not available for the full climate or even ocean system, and comparisons with historical observations are expected to be close but not exact. Thus model components are run through an exhaustive suite of tests, from very simple idealized domains (Figure 7) that isolate a subset of the model physics [2], to full global simulations, driven by historical atmospheric forcing [4]. Real-world validation includes comparisons of the mean currents, averaged over decades, to historical climatology from satellite and shipboard observations. The eddy component, which varies in space and time, is important to climate dynamics and should also be compared against observations [3]. MPAS-Ocean simulations of currents and meso-scale eddies compare well against available observational data [4, 11] and other long-standing ocean models [2].

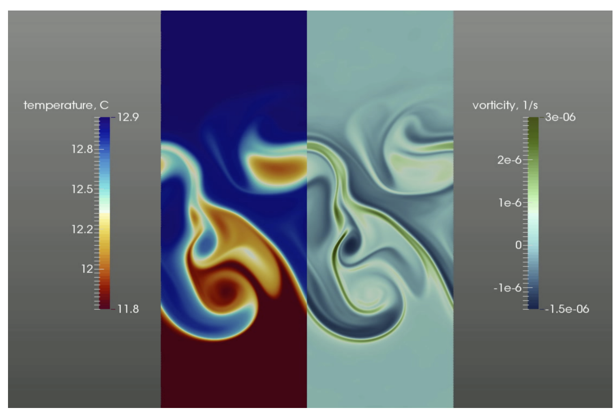

Fig. 7. A rectangular, periodic domain that tests eddy formation due to the baroclinic instability. Such idealized tests validate the ocean model's physical behavior and numerical algorithms.

3.2 The Importance of Color

The need for the scientist to see more detail in the data led to a collaboration between the lead author, a visual artist, and the MPAS-Ocean team. Standard colormaps easily available in commonly used visualization software were not always able to resolve or highlight the currents and eddies in these high-resolution data sets. With the development of design-based colormaps with provably more perceptual depth, the location and extent of important currents became more obvious [7]. Similarly, the ability to visually identify and follow eddies improved through the application of new colormaps. Visualizing the current and eddy variability over time and geographical range can give the scientist an intuitive feel for and insight into the data which in turn may lead to different analysis techniques and enhance communication of the data and the science.

3.3 3D Visualization via Raycasting

Characterizing ocean eddies three-dimensionally is necessary to understand their spatial structure and dynamics; however little observational data is available below the ocean surface [3]. Traditional methods of visualizing simulated data tend to be non-interactive even for the relatively small regions required to study the formation of eddies. These methods rely on the iterative processing of each cell of the computational grid to determine its contribution to the visualization. When the cell size is small relative to the final image, a great deal of work is done on cells that, after due consideration, do not affect the final visualization. Instead, we interpolate the unstructured computational grid onto a high-resolution Cartesian grid and use raycasting to do the visualization (Figure 1). While this nominally requires more elements to represent the data with equivalent fidelity, highly parallel vectorized algorithms can use the implicit structure of the Cartesian grid to quickly sample the data at arbitrary locations. By tracing rays from the viewpoint through pixel centers and into the data, a raycasting algorithm is able to reduce the number of samples to the minimum necessary for accurate integration. This approach has the further benefits of providing implicit surface evaluation, such as isosurfacing and slicing planes, without the need for time- and memory-consuming geometrical operations. In Figure 1 (right), the kinetic energy variable is used to visualize eddies around the Agulhas Retroflection.

4 Conclusions

Visualization plays an important role in climate change research, but is increasingly difficult as models push the limits of HPC systems. In ocean modeling, high resolution simulations are required to include the influence of meso-scale eddies in climate change simulations. We have presented detailed visualizations of ocean currents and eddies with colormaps chosen to improve perceptual depth. Three-dimensional raycasting techniques with highly parallel vectorized algorithms were specifically developed to visualize the eddy structure and depth with high fidelity. The ACME climate model and MPAS-Ocean model are powerful tools to predict the effects of climate change in the coming decades. Planned global ocean simulations at even higher resolution (5 km grid cells, 5.8 million grid cells and 100 vertical levels) will provide deeper scientific insights, but also greater challenges for HPC systems and visualization techniques. High quality visualization is critical to provide scientists, policy makers, and the public with insight from the huge amount of data produced by these simulations.

Acknowledgments

This material is based upon work supported by Dr. Lucy Nowell of the U.S. Department of Energy Office of Science, Advanced Scientific Computing Research under Award Numbers DE-SC-0012516 and LA-UR-15-20105. Mark Petersen, MPAS-Ocean, and ACME are supported by the U.S. Department of Energy Office of Science, Earth Modeling Program of the Office of Biological and Environmental Research. The authors would like to thank David Astrada for his videography expertise and the Bradbury Science Museum for their generous sharing of facilities and support.

References

[1] C. Field, editor. *IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A.*, Cambridge, United Kingdom and New York, NY, USA, 2014. Intergovernmental Panel on Climate Change, Cambridge University Press. Chapter 12.

[2] M. R. Petersen, D. W. Jacobsen, T. D. Ringler, M. W. Hecht, and M. E. Maltrud. Evaluation of the arbitrary lagrangian-eulerian vertical coordinate method in the mpas-ocean model. *Ocean Model.*, 86(0):93–113, 2015.

[3] M. R. Petersen, S. J. Williams, M. E. Maltrud, M. W. Hecht, and B. Hamann. A three-dimensional eddy census of a high-resolution global ocean simulation. *J. Geophy. Research: Oceans*, 118(4):1759–1774, 2013.

[4] T. Ringler, M. Petersen, R. L. Higdon, D. Jacobsen, P. W. Jones, and M. Maltrud. A multi-resolution approach to global ocean modeling. *Ocean Model.*, 69:211–232, 2013.

[5] T. D. Ringler, J. Thuburn, J. B. Klemp, and W. C. Skamarock. A unified approach to energy conservation and potential vorticity dynamics for arbitrarily-structured C-grids. *J. Comp. Phys.*, 229:3065–3090, 2010.

[6] J. Saenz, Q. Chen, and T. Ringler. Prognostic residual-mean flow in an ocean general circulation model and its relation to prognostic eulerian-mean flow. J. Phys. Oceanogr., in press, 2015.

[7] F. Samsel, M. Petersen, T. Geld, G. Abram, J. Wendelberger, and J. Ahrens. Colormaps that improve perception of high-resolution ocean data. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*, CHI EA '15, pages 703–710, 2015.

[8] J. Thuburn, T. D. Ringler, W. C. Skamarock, and J. B. Klemp. Numerical representation of geostrophic modes on arbitrarily structured C-grids. *J. Comp. Phys.*, 228:8321–8335, 2009.

[9] S. Williams, M. Hecht, M. Petersen, R. Strelitz, M. Maltrud, J. Ahrens, M. Hlawitschka, and B. Hamann. Visualization and analysis of eddies in a global ocean simulation. *Computer Graphics Forum*, 30(3):991–1000, 2011.

[10] P. J. Wolfram, T. D. Ringler, M. E. Maltrud, D. W. Jacobsen, and M. R. Petersen. Diagnosing isopycnal diffusivity in an eddying, idealized midlatitude ocean basin via lagrangian in-situ, global, high-performance particle tracking (light). J. Phys. Oceanography, 2015.

[11] J. Woodring, M. Petersen, A. Schmeißer, J. Patchett, J. Ahrens, and H. Hagen. In situ eddy analysis in a high-resolution ocean climate model. To appear in SciVis2015 and in IEEE Transactions on Visualization and Computer Graphics (Jan, 2016), 2015.