Visualizing Oceanic Eddy-mean Flows

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The Model for Prediction Across Scales (MPAS) is a collaborative project for developing atmosphere, ocean and other earth-system simulation components for use in climate, regional climate and weather studies.

MPAS-O (the Ocean core of the project) is designed for the simulation of the ocean system with temporal resolutions raging from months to millennia, and spatial resolution ranging from <1km to global circulations. MPAS-O facilitates the study of multi-scale phenomena within the ocean, as well as the study of anthropogenic (human-driven) climate change[1].

Ocean eddies -- circular currents in water -- contribute strongly to the general circulation of the ocean and to the transport process of the global climate system. Understanding how to model the behavior of ocean eddies, at multiple spatial and temporal scales, is critical to the study of climate systems and climate change. Visualization plays a key role in testing and improving such models, however existing methods are inadequate and fail to accurately capture important patterns and relationships within the data.

Visualization Problem Breakdown:

- Accurately modeling the behavior of ocean eddies is critical to modeling the global ocean and climate systems.

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[1] More information about MPAS and MPAS-O may be found at https://mpas-dev.github.io

- Visualization plays a key role in developing and improving these models.
- Current "best" 2D and 3D approaches visualize either a snapshot of the flow or the mean flow over time.
- The challenge is to combine these two approaches, visualizing both the eddy flow as a function of time, and the mean of the flow across time. And to do this in 3D

Data Breakdown:

- Netcdf file format (readable via MPAS reader in ParaView, or python-based netCDF4 or xarray)
- Two datasets:
  - Snapshot used for eddy flow: 1 time value
  - 20 years of averaged data for the mean: 1 time value
- All data includes zonal (x) and meridional (y) velocity, on unstructured grid array of size (1, nCells, nVertLevels)
- Scalar temperature data also included
- Total data size ~ 3 GB

Glossary of Key Terms:

Diffusivity: the rate of change of the variance of the mean pathline of a cluster of particles over one or multiple realizations.

Eddy flow: as apposed to the time-mean flow, eddy flow describes the properties of flow as a function of time. Static depictions of eddy flow offer snapshots of the flow in time.

Eulerian vs. **Lagrangian** reference frames: two frames of reference for characterizing flow. The **Eulerian** reference frame can be described as installing sensors at static locations within a fluid domain, and measuring various attributes of the fluid -- as it moves past the sensors – as a function of time. The **Lagrangian** reference frame, on the other hand, can be described as tossing sensors into the fluid and tracing the motion of the sensors as well as measuring attributes their surrounding fluid environments.

Realization: a (turbulent) realization describes the behavior of a cluster of Lagrangian particles over a given time period.

Space-mean flow and **time-mean flow:** in fluid dynamics (and especially around the study of turbulence) flow can be averaged as a function or time or space, **space-mean flow** averages flow as a function of space, **time-mean flow** averages flow (at each physical location) as a function of time.

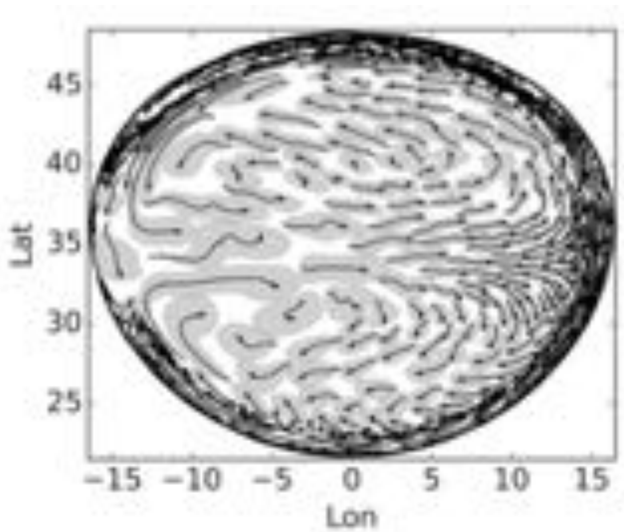
Isopycnal or potential density surfaces: surfaces of constant density. Flow is thought of as flowing between constant lines of density and particle tracking is typically performed on a constant density or "isopycnal" surface that is defined by a specific potential density surface.

Zonal: east-west direction in oceanography

Meridional: south-north direction in oceanography

Visualizing Eulerian and Lagrangian Data Simultaneously (an additional vis challenge):

MPAS-O models the ocean system in Eulerian space. The eddy-mean flow visualizations described earlier are also generated in Eulerian space. Studying ocean eddies additionally in Lagrangian space helps researchers better understand the behavior of eddies and how they enhance mixing. Approaches exist for visualizing the Lagrangian data in 2D. Such approaches show how eddies create mixing and how the mixing and mean flow are connected.



Wolfram, P.J., T.D. Ringler, M.E. Maltrud, D.W. Jacobsen, and M.R. Petersen. Diagnosing isopycnal diffusivity in an eddying, idealized mid-latitude ocean basin via Lagrangian In-situ, Global, High-performance particle Tracking (LIGHT). J. Phys. Oceanogr., 45(8):2114–2133, 2015.

Steps to create the above visualization:

- a fluid domain is selected and is separated into layers as a function of density (isopycnal layers)
- for each isopycnal layer, Lagrangian particles are distributed across the layer
- particles are then grouped spatially into clusters
- the behavior of each cluster is tracked over a period of time, resulting in a single realization
- this process is repeated to generate multiple realizations
- from the realizations, the mean position of each cluster over time is computed across realizations (represented by the black line, or mean pathline, where the arrowhead marks the end of the realization)
- the variance corresponding to the mean is calculated (represented by the grey regions surrounding each mean pathline)
- the diffusivity is then calculated as the rate of change of the variance over time (corresponding to the rate at which the width of the gray regions change along the length of the mean pathlines).

See:

Wolfram, P.J., T.D. Ringler, M.E. Maltrud, D.W. Jacobsen, and M.R. Petersen. Diagnosing isopycnal diffusivity in an eddying, idealized mid-latitude ocean basin via Lagrangian In-situ, Global, High-performance particle Tracking (LIGHT). J. Phys. Oceanogr., 45(8):2114–2133, 2015.

for mathematical detail.

Visualization challenges:

- This above visualization does as fairly good job of showing how eddies create mixing and how the mixing and mean flow are connected for a single isopynal layer. However, the reality is that this mixing is inherently occurring in 3D.
- How can we create this visualization in 3D, across isopycnal layers?
- How can we incorporate these Lagrangian-space visualizations (2D or 3D) into the Eulerian-space visualizations discussed in the first part of this document?