Southern Ocean Dynamics Under Climate Change: New Knowledge Through Physics-Guided Machine Learning

NeurIPS 2023 Workshop: Tackling Climate Change with Machine Learning

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The ocean and climate change

- The ocean, covering over 70% of the globe, has absorbed **more than 90%** of recent warming.
- Models predict changes in complex ocean systems.
- Example: shifts in location/strength of the Antarctic Circumpolar Current (ACC)
- However, the **physical drivers behind these changes are not well understood**.

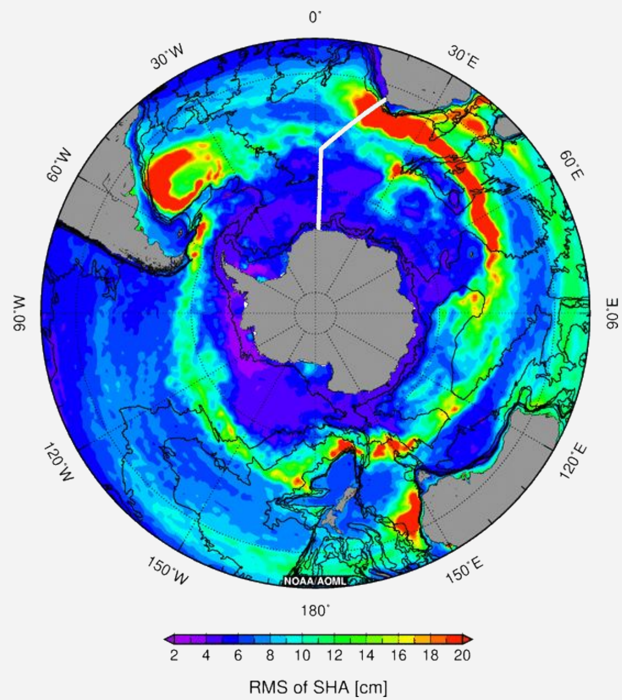


Image: NOAA/Atlantic Oceanographic & Meteorological Laboratory

Böning, C. W., Dispert, A., Visbeck, M., Rintoul, S. R., & Schwarzkopf, F. U. (2008). The response of the Antarctic Circumpolar Current to recent climate change. *Nature Geoscience*, 1(12), 864-869.

Global climate modeling

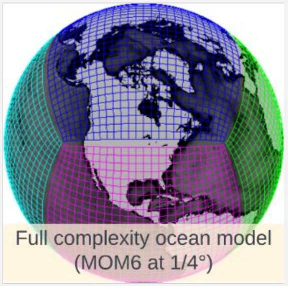
- Coupled Model Intercomparison Project Phase 6 (CMIP6)
  - Standardized experimental design and distribution protocol
  - Massive amounts of data (23.4 PBs shared, still sparse)
- Hard to disseminate
  - Understanding how the **underlying physics** of the ocean is changing is difficult

Image: Lawrence Livermore National Laboratory

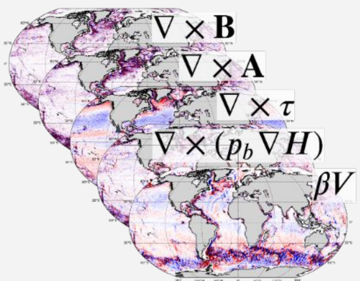
O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., ... & Sanderson, B. M. (2016). The scenario model intercomparison project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, 9(9), 3461-3482.

Tracking global Heating with Ocean Regimes (THOR)

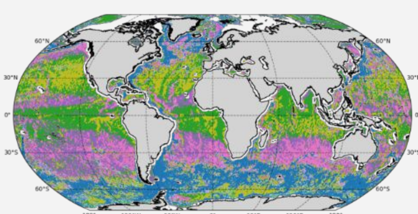
1) Cluster ocean dynamical regimes



Transform data to barotropic vorticity space

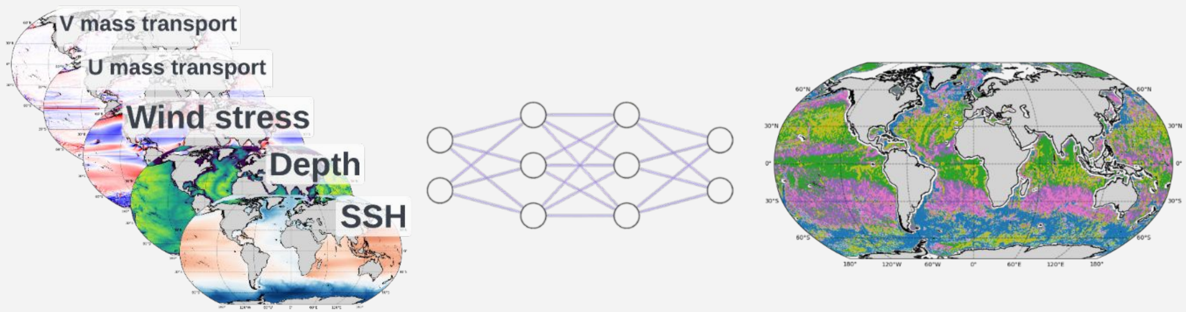


Native Emergent Manifold Interrogation (NEMI)



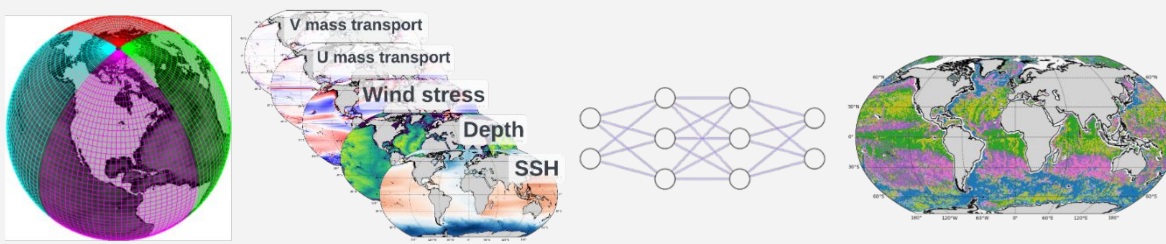
2) Supervised learning using labeled ocean dynamical regimes

With different inputs, train a neural network classifier using labels from Step 1



3) Tracking the effect of global Heating on Ocean Regimes (THOR)

Predict ocean regimes of models with no access to in-depth ocean data



New ocean model of interest

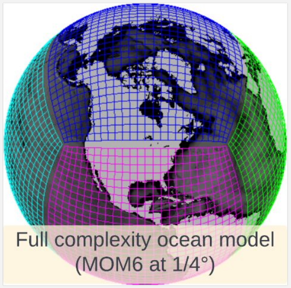
Extract input data needed for classification

Run the trained classifier from **Step 2**

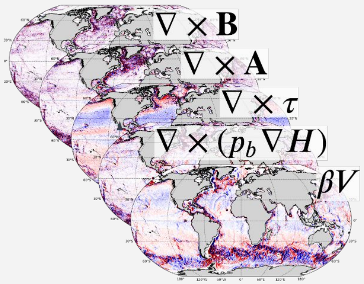
Interpret inferred dynamical regimes

Step 1: Mesoscale unsupervised clustering

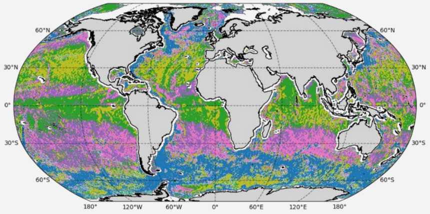
1) Cluster ocean dynamical regimes



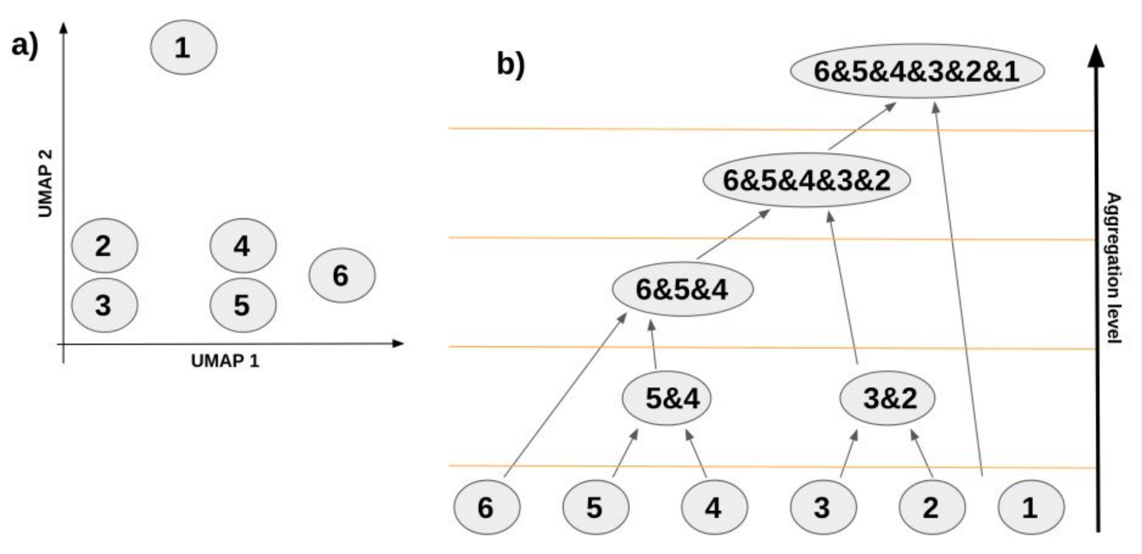
Transform data to barotropic vorticity space



Native Emergent Manifold Interrogation (NEMI)



- **Native Emergent Manifold Interrogation (NEMI)** utilizes Uniform Manifold Approximation and Projection (UMAP) paired with **agglomerative clustering**



- Partitions the ocean grid cells into clusters (**dynamical regimes**) based on their physics

McInnes, L., Healy, J., & Melville, J. (2018). Umap: Uniform manifold approximation and projection for dimension reduction. *arXiv preprint arXiv:1802.03426*.
Sonnewald, M. (In review). A hierarchical ensemble manifold methodology for new knowledge on spatial data: An application to ocean physics. *JAMES*.

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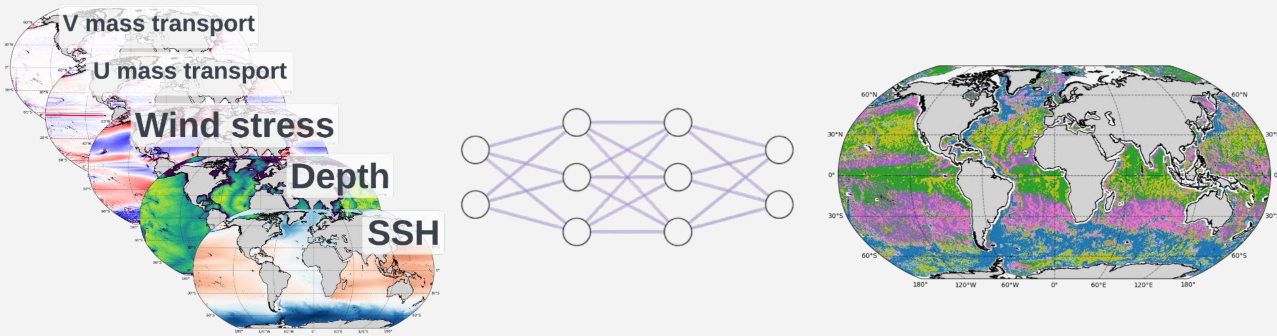
Step 2: Learning regimes from readily available fields

2) Supervised learning using labeled ocean dynamical regimes

With different inputs, train a neural network classifier using labels from Step 1

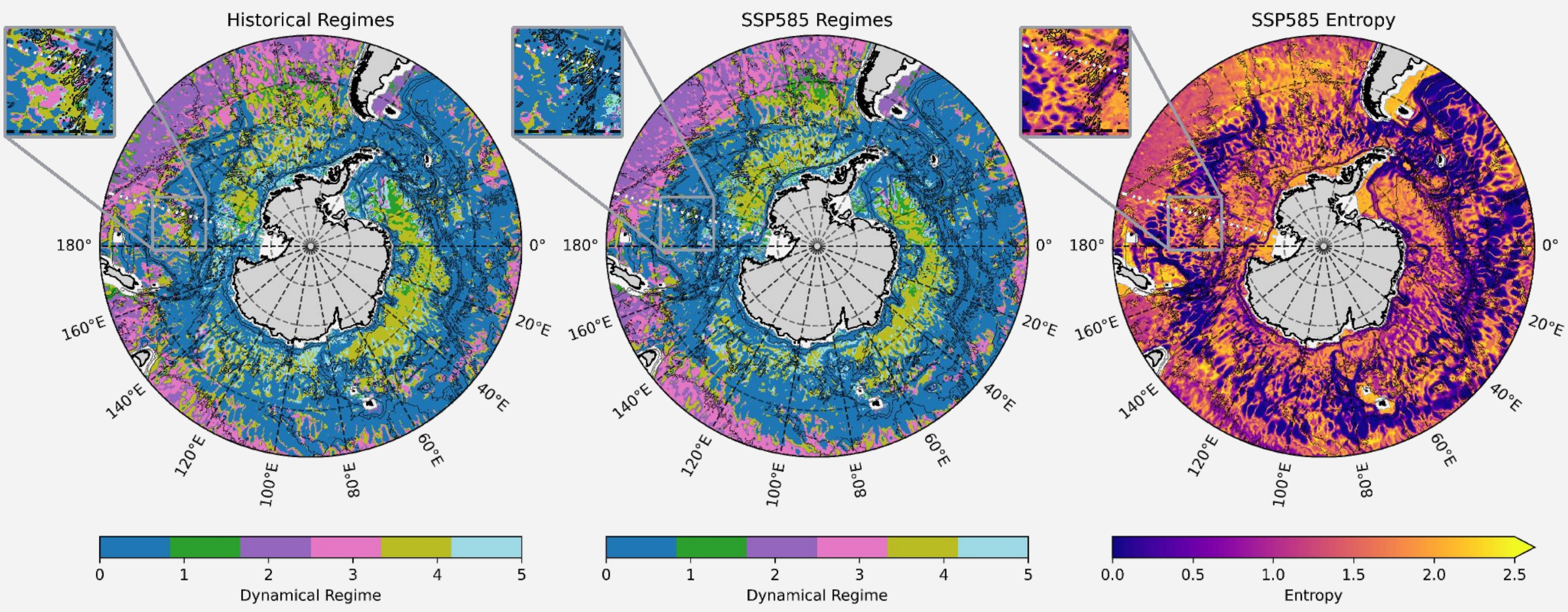


- Inputs
  - Sea surface height (ZOS) + x/y gradients
  - Depth (column height) + x/y gradients
  - Wind stress curl ($\nabla \times \tau$)
  - Depth summed monthly mass transport (umo_2d + vmo_2d)
  - Coriolis parameter (f)

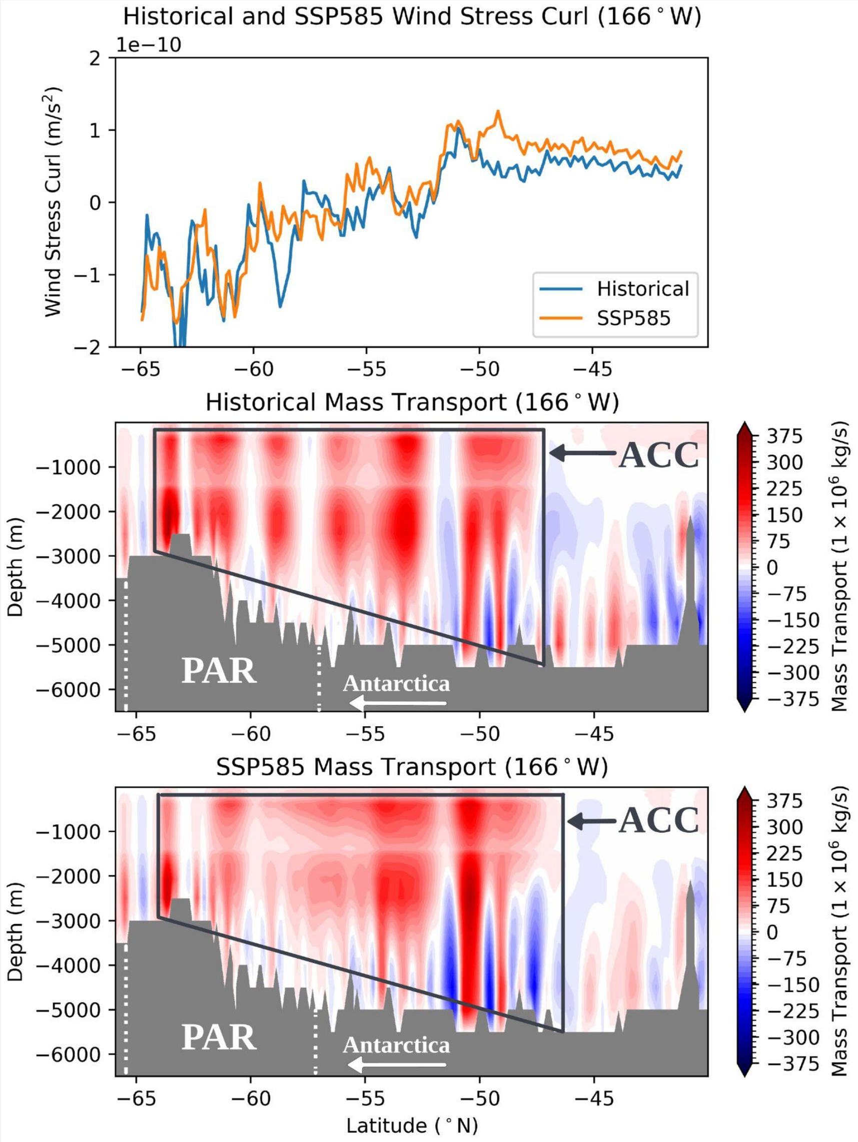
- Labels: 6 dynamical regimes identified by NEMI
- Ensemble of 50 feedforward MLPs for uncertainty quantification

Step 3: Predicting regimes under climate change

THOR reveals a shift in physics where the Antarctic Circumpolar Current (ACC) meets the Pacific Antarctic Ridge (PAR).



Key contributions



- **Mesoscale inference** of subsurface dynamical regimes
- **THOR guides further exploration** where the Antarctic Circumpolar Current (ACC) meets the Pacific-Antarctic Ridge (PAR)
- **THOR reveals a shift in dynamics**
- Due to increased wind stress, the ACC moves away from the rough surface of the PAR into a flatter region where it **flows more freely**

Future directions and conclusion

- Comparing CMIP models could give insight into how different representations of ocean physics affect predictions
- Predicting dynamical regimes with spatially aware neural networks, **without trading off with explainability**
- Questions? Contact **wyik@hmc.edu**

Read our paper! →

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