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

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Introduction

- Complex ocean systems such as the **Antarctic Circumpolar Current (ACC)**, which play key roles in the Earth's climate through heat transport, carbon drawdown, and nutrient availability, are known to change in strength and location under climate change
- These shifts are not well constrained and their physical drivers are not well understood
- We use the machine learning-driven method **Tracking Heating with global Ocean Regimes (THOR)** to both identify and track regions of the ocean characterized by similar physics, revealing drivers of ocean dynamical shifts under climate change

Tracking Heating with global Ocean Regimes (THOR)

We extend THOR, originally developed by Sonnewald and Lguensat (2021), to a 0.25°, mesoscale, eddy-permitting ocean model, the **Modular Ocean Model version 6 (MOM6)**, a component of the Coupled Model version 4 (CM4). THOR consists of two components.

Step 1: Unsupervised clustering of ocean grid cells

- **Native Emergent Manifold Interrogation (NEMI)** (Sonnewald, 2023) is used to cluster ocean grid cells into **dynamical regimes** based on their physics during a pre-industrial control (piControl) run

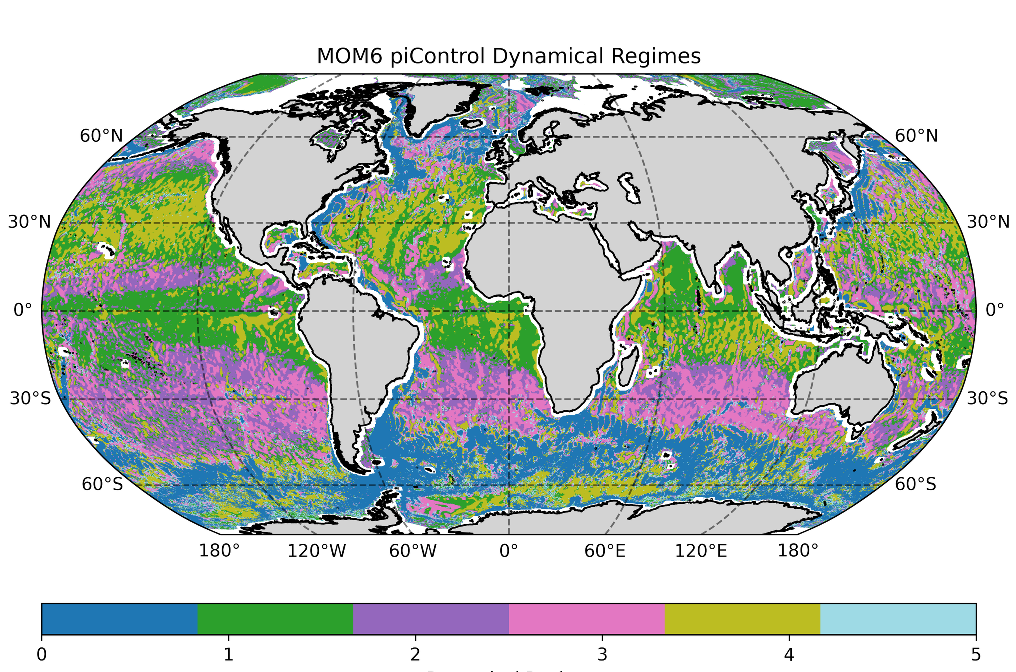

Figure 1: Six dynamical regimes discovered by NEMI on the piControl run of MOM6.

Step 2: Supervised learning of dynamical regimes

- An ensemble of **neural networks (NNs)** is trained to predict dynamical regimes from more accessible input fields for seamless application to other scenario experiments or entirely different ocean models
- **Core inputs**: sea surface height above the geoid (ZOS), depth relative to sea level (bathymetry), curl of surface wind stress torque ($\nabla \times \tau_s$), Coriolis parameter (f), depth-summed zonal and meridional mass transport (umo_2d and vmo_2d)
- **Entropy** quantifies the NN ensemble's uncertainty in its predictions

Application to the Southern Ocean

We apply THOR's NN to the **Historical** and **SSP585** runs of MOM6 to track regimes in the Southern Ocean under climate change.

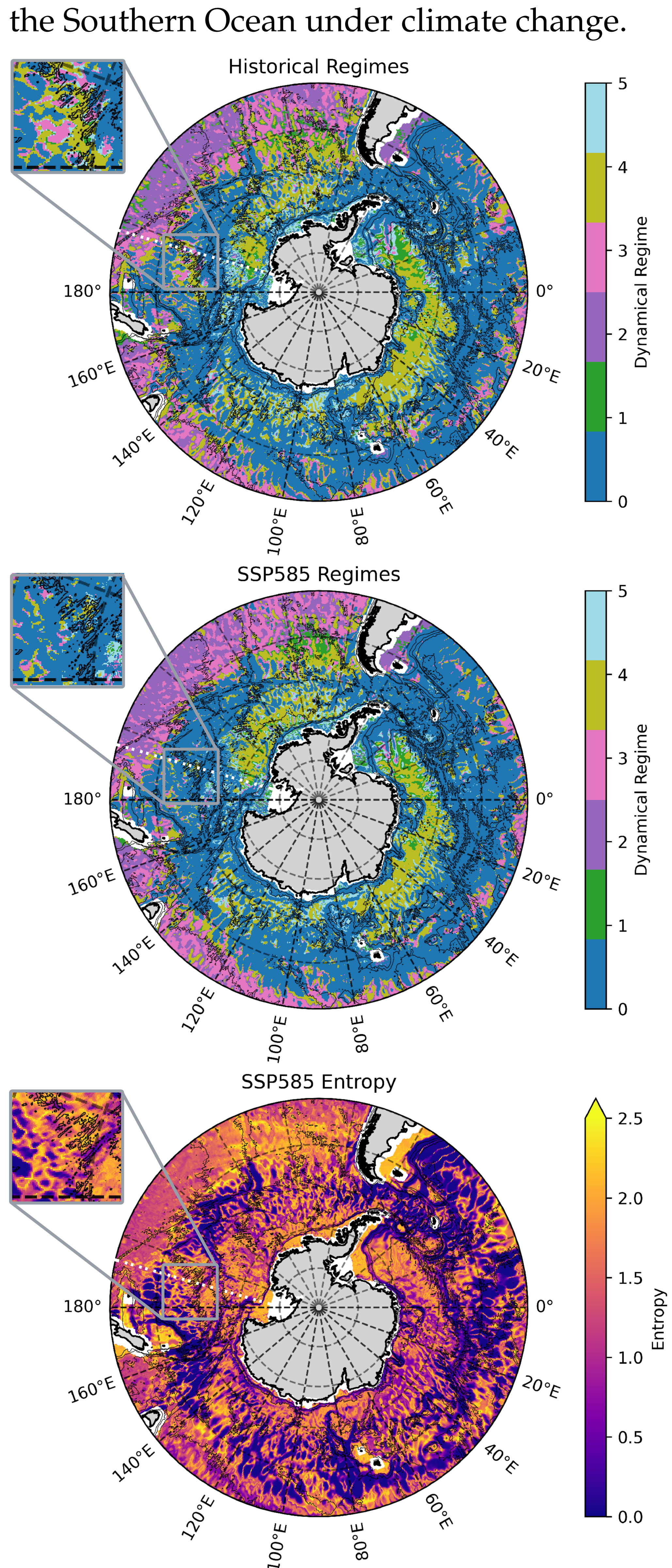

Figure 2: NN dynamical regime predictions for the Historical and SSP585 runs along with entropy for the SS585 predictions. The contours show bathymetry. The inset shows the area of interest where the ACC meets the PAR, and the dashed white line shows the meridian where the transects of Figure 3 are taken

- We focus on the region where the ACC meets the **Pacific-Antarctic Ridge (PAR)**, a divergent tectonic plate boundary characterized by rough bathymetry at around 60°S, 166°W
- Between the Historical and SSP585 runs we see a **shift in dynamical regime** from Regime 4 (light green), characterized by a large wind stress, to Regime 0 (blue), characterized by flow free of bathymetric influence

Guided by the new knowledge revealed by THOR, we find using two **eXplainable Artificial Intelligence (XAI) methods** that the **wind stress maximum shifts northward**, bringing the ACC with it and changing its interactions with the bathymetry of the PAR.

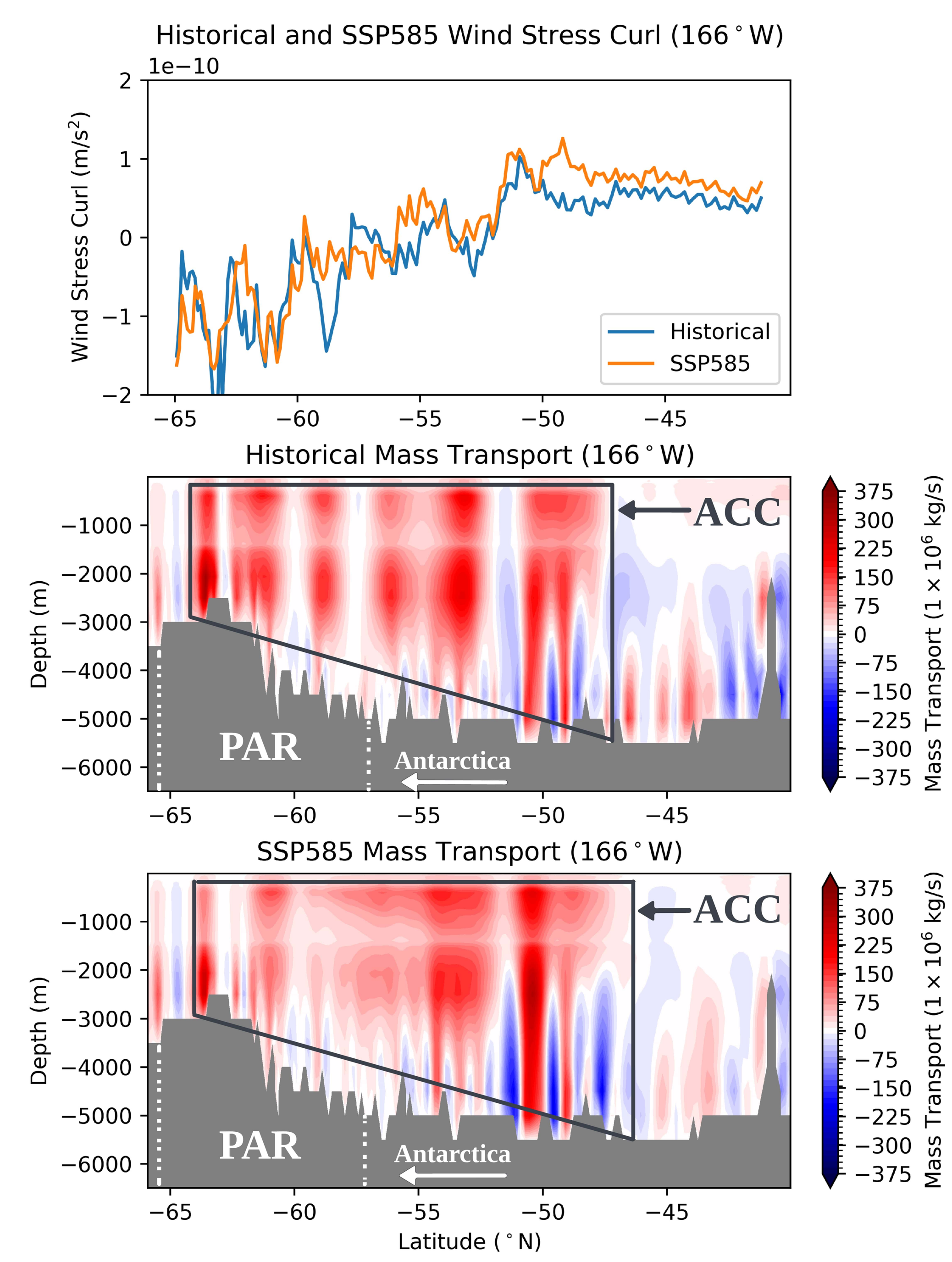

Figure 3: Wind stress curl and lateral (east-west) mass transport at 166°W for the Historical and SSP585 scenarios. The ACC (black) and PAR (white) are outlined. Red and blue indicate eastward and westward flow, respectively.

The northward ACC movement brings it away from the PAR into a new, less variable bathymetric region where its interactions with the sea floor are less strong, thus leading to **stronger baroclinic flow**.

Conclusion

- We extend THOR to a mesoscale, eddy-permitting climate model, allowing us to precisely identify and track ocean dynamical regimes under climate change
- Future work will include applying THOR to other climate models to understand differences in their ocean physics parameterizations

Read our paper!

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