

Revealing mechanisms of change in the Atlantic Meridional Overturning Circulation under global heating

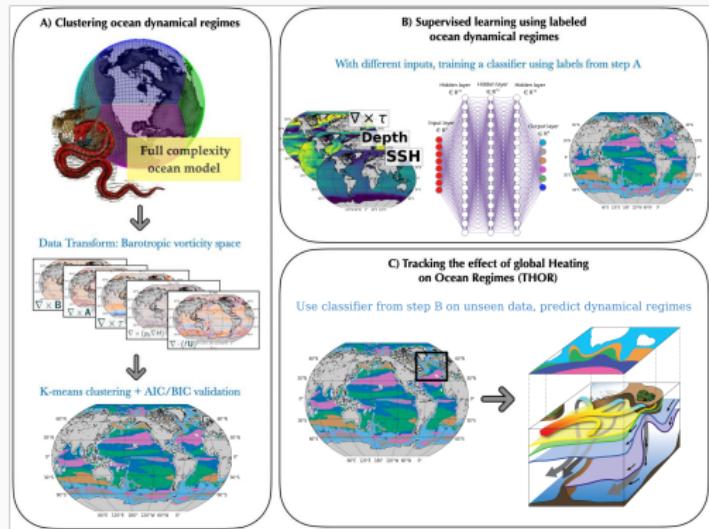
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Overview

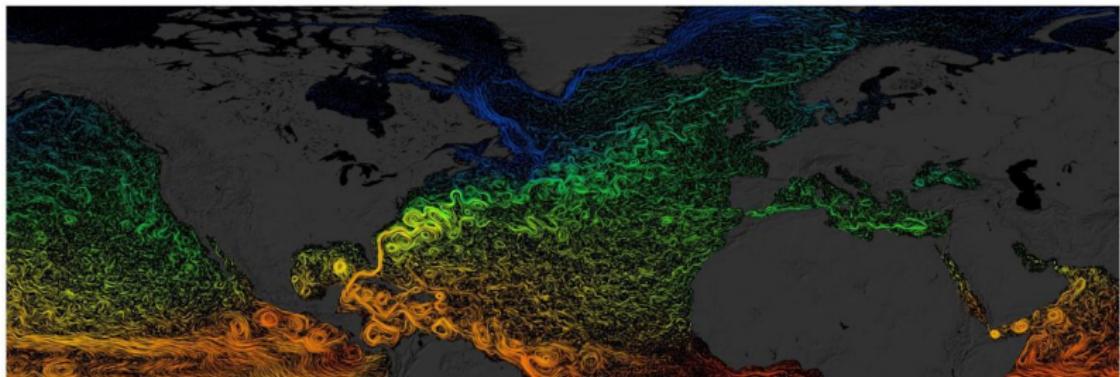
- Motivation:
 - AMOC
 - Machine learning
- Tracking global Heating with Ocean Regimes (THOR)
- AMOC under global heating in GFDL-ESM4.1
 - Historical
 - 1% CO₂
 - Abrupt 4× CO₂



THOR reveals changes in Trans Atlantic Current,
Gulf Stream and downwelling areas
Could accelerate model analysis



Motivation: North Atlantic circulation



Is every location unique?

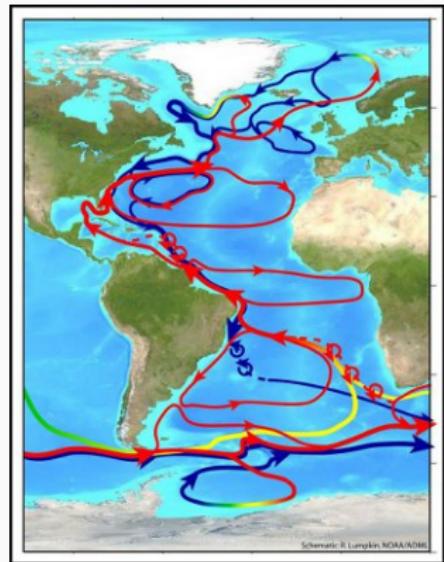
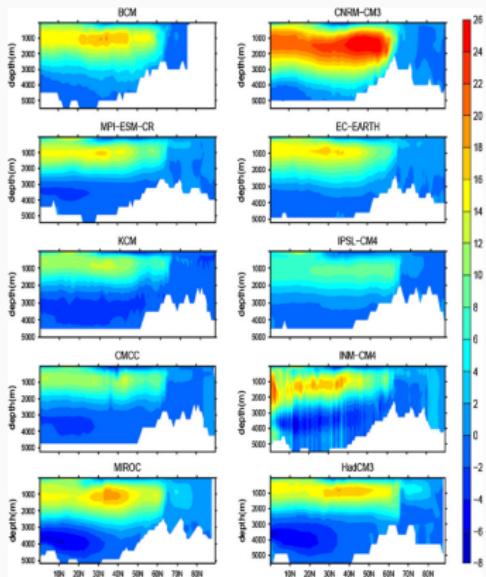
Can coherent dynamical regions be defined objectively?

ECCO group



Motivation: Why do we care about AMOC?

Warm waters brought northwards → become dense returning south
Major source of transport and storage of heat and carbon

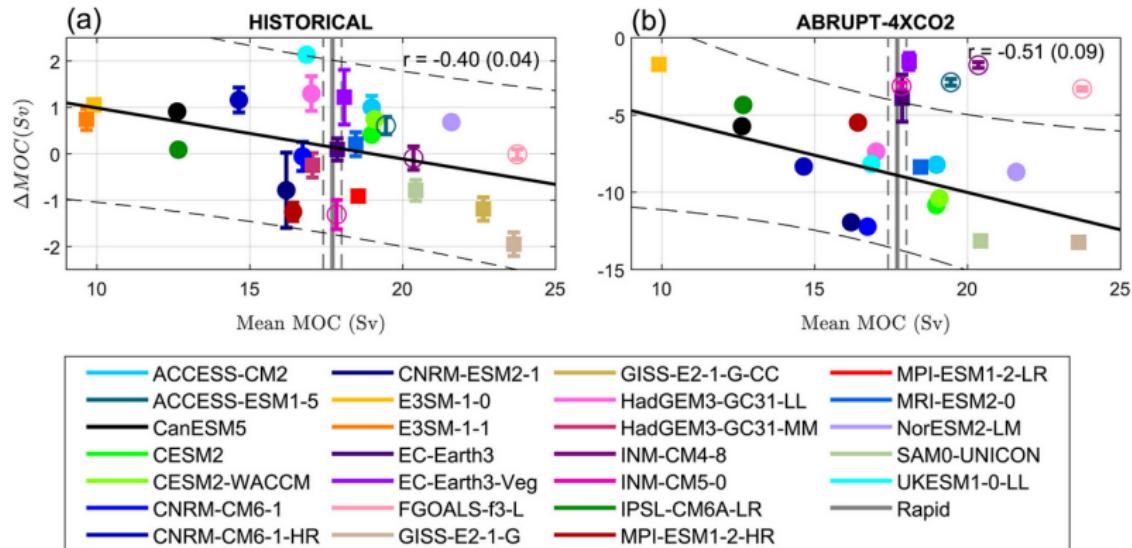


$$\Psi_{z\theta}(\theta, z) = - \int_{-H}^z \int_{\phi_2}^{\phi_1} v(\phi, \theta, z') d\phi dz',$$

H : depth, z : relative depth, v : meridional velocity, θ : lat, ϕ : lon



Motivation:



AMOC is a product of highly complex physics

Often presented as a bulk metric

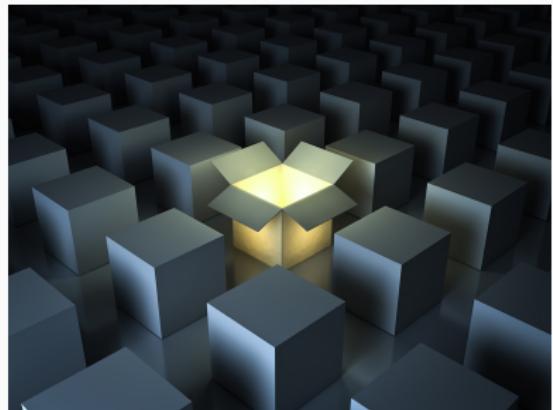
AMOC declines in many CMIP6 models, but why?



Machines can be **misleading**: Black box magic?

Is a good prediction interesting if the source of skill is unknown?

- Interpretable ML
 - Experimental design
 - Unsupervised ML
- Explainable ML
 - Retrospective inference
 - Relevance maps

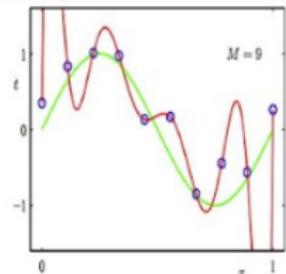
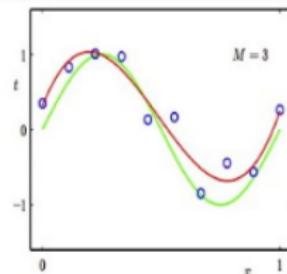
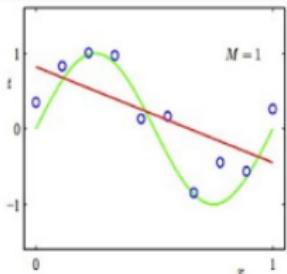


THOR is designed to be
interpretable (step A) and explainable (step B)



Choosing K: Information criteria

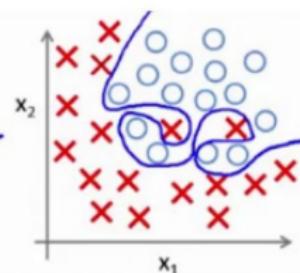
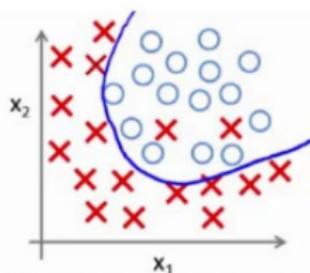
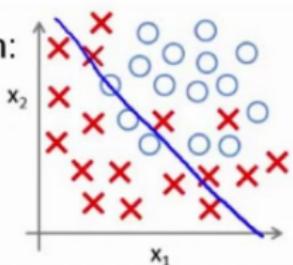
Regression:



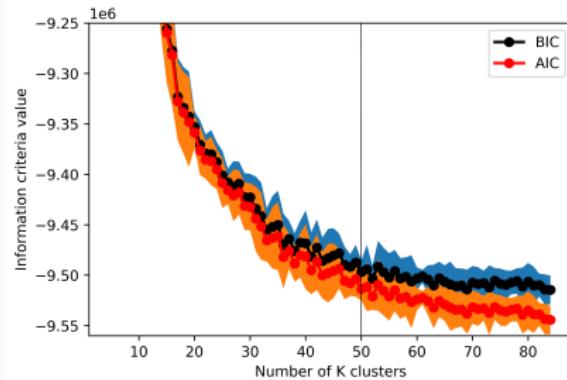
predictor too inflexible:
cannot capture pattern

predictor too flexible:
fits noise in the data

Classification:



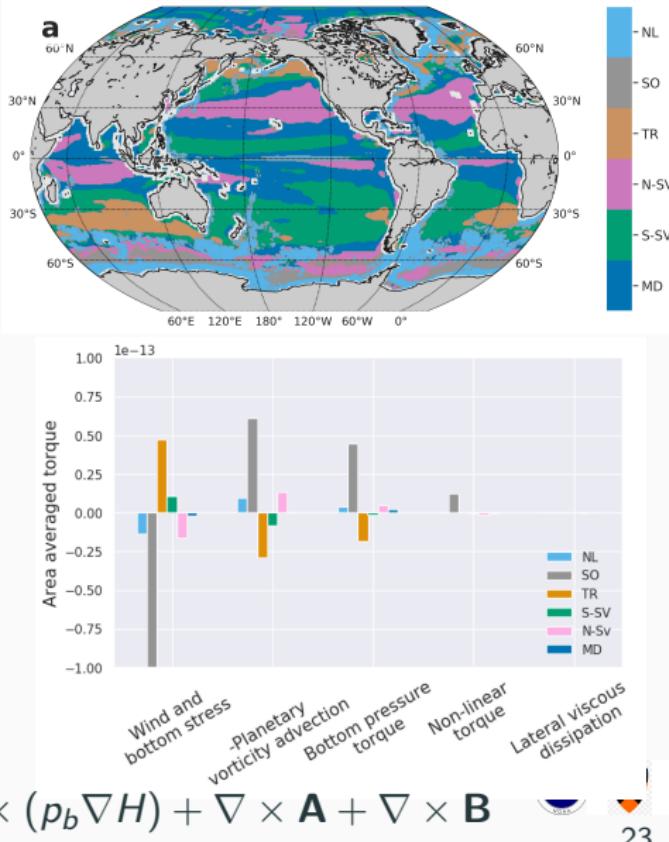
Robust results



- Test 1: Model fit is good.
 - Test 2: Dynamically significant regimes repeatedly emerge.
- Success: Rigorous method application + dynamically constructed test based criteria.

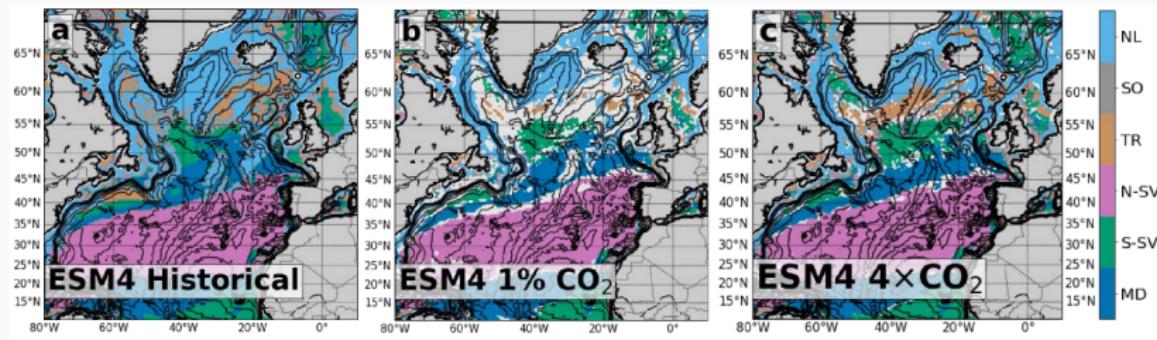
Global dynamical regimes

- Six global dynamical regimes
- Southward-SV and Northward-SV: Quasi-Sverdrupian
- Southern Ocean (SO) and Transitional (TR): Topographic Sverdrup balance
- MD: “Momentum Driven”
- Non-linear (NL): Composite



$$0 = \nabla \times \tau - \nabla \cdot (f\mathbf{U}) - \nabla \times (p_b \nabla H) + \nabla \times \mathbf{A} + \nabla \times \mathbf{B}$$

THOR dynamical regime prediction



1. Lighter dense water masses formed:
 - Location shifting to the Labrador sea
2. Trans Atlantic Current shifts east
3. Gulf Stream shifts north

White regions signify natural variability



Summary II

AMOC with Tracking global Heating with Ocean Regimes (THOR)

- C: AMOC in ESM4.1

- Historical run similar to ECCO
- Shifts seen concurrent with weakening AMOC in Gulf Stream, Trans Atlantic Current and dense water masses
- 4xAbruptCO₂ weaker than 1%CO₂
- Natural variability seen

- Significance

- THOR is scalable to large data volumes
- Can take any similar model e.g. CMIP6
- Predictive skill explained
- Part of a called for 'revolution' in analysis tools?

