Tipping points in ESMs

A brief overview of tipping points and their representation in Earth System Models

With contributions from: Catalyst, InteRFACE, E3SM, HiLAT, SciDAC ImPACTs, SciDAC FANNSIE, DOE ECR – Regional SLR

InteRFACE

FANSSIE
Framework for Antarctic System Science in E3SM

HiLAT RASM

ImPACTS

E3SM
Energy Exascale Earth System Model

catalyst
Cooperative agreement to analyze variability, Change and predictability in the earth system

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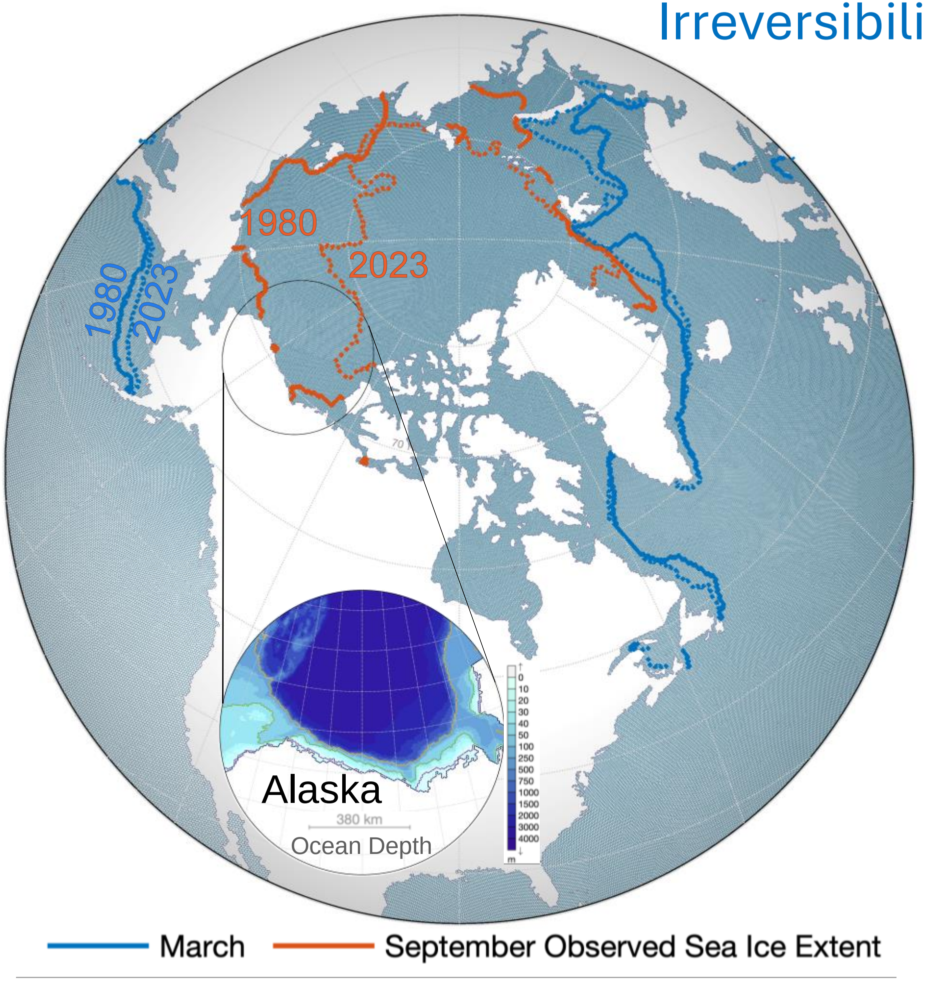
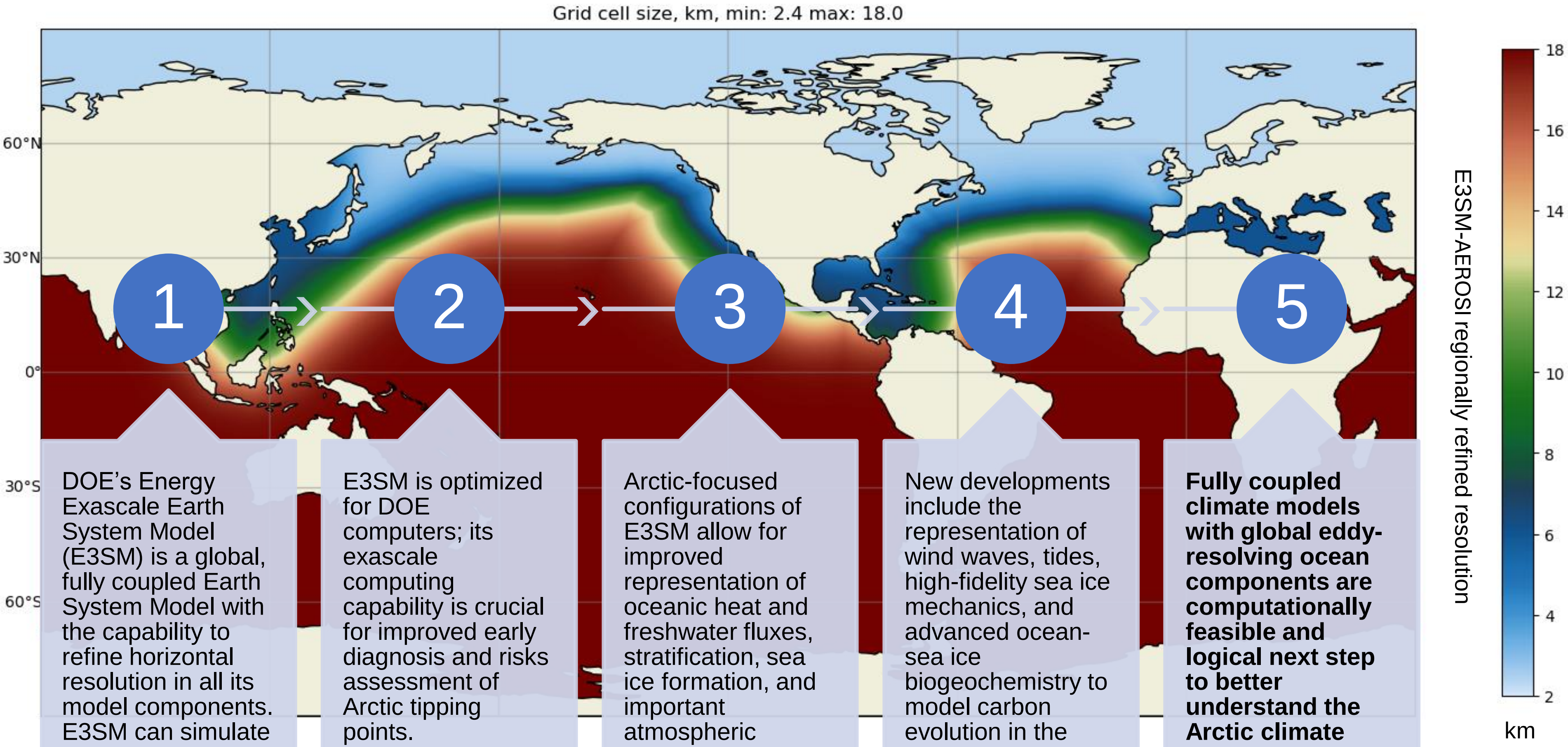
Irreversibility and thresholds in Arctic Sea Ice Loss



- The accumulation of heat and freshwater in the Arctic Ocean has increased in both the surface and deeper ocean, reflected partly in thinning and shrinking sea ice.
- Irreversibility in sea ice loss displayed by Budyko-Sellers column models have seldom been reproduced in fully coupled Earth system models, which have so far displayed reversibility with atmospheric CO_2 concentration.
- There is a new theory of sea ice tipping points associated with the release of deeper ocean heat through wave-sea ice-ocean interactions, but this remains to be tested with fully coupled Earth system models.
- Arctic sea ice tipping points may also be dependent on coupled thresholds including in the Arctic halocline stability and Beaufort Gyre freshwater release, possibly linked to an AMOC stability tipping point.
- Arctic sea ice loss may also cause irreversibility in the Earth system due to differing recovery timescales of impacted phenomena but is yet to be proven.

DOE capabilities to advance science and inform risk of Arctic tipping points



1. DOE's Energy Exascale Earth System Model (E3SM) is a global, fully coupled Earth System Model with the capability to refine horizontal resolution in all its model components. E3SM can simulate global climate while regionally resolving important

2. E3SM is optimized for DOE computers; its exascale computing capability is crucial for improved early diagnosis and risks assessment of Arctic tipping points.

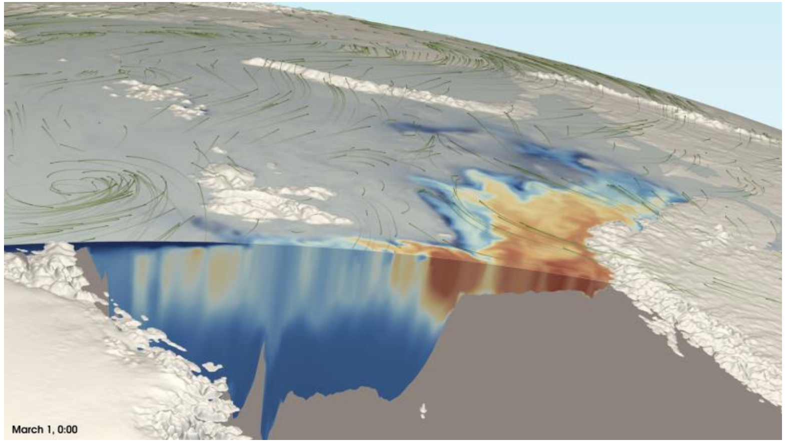
3. Arctic-focused configurations of E3SM allow for improved representation of oceanic heat and freshwater fluxes, stratification, sea ice formation, and important atmospheric processes like Arctic cyclones and Atmospheric

4. New developments include the representation of wind waves, tides, high-fidelity sea ice mechanics, and advanced ocean-sea ice biogeochemistry to model carbon evolution in the Earth system.

5. **Fully coupled climate models with global eddy-resolving ocean components are computationally feasible and logical next step to better understand the Arctic climate system, its related tipping points, and their global**

Grand Challenges

- Very high resolution required for very long simulations
- Need to include robust wave sea ice interactions.
- Interconnectedness of tipping points (e.g. AMOC)



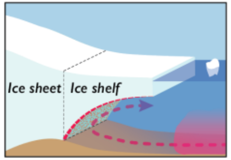
Ice sheets

Energy Exascale Earth System Model

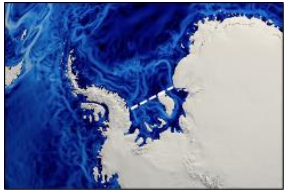
Framework for Antarctic System Science in E3SM

Ice-Sheet & Sea-Level Tipping Points

Ocean Melting Tipping Point

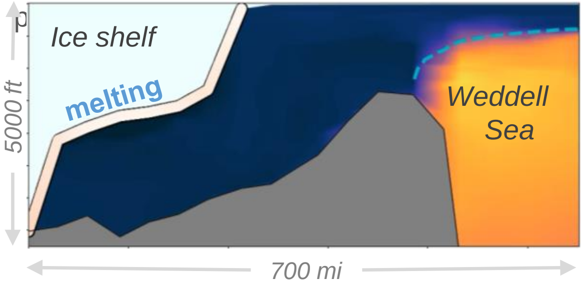


If increasing meltwater reaches a threshold, ocean density drops and deep warm water masses reach Antarctica.

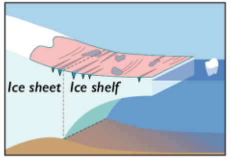


E3SM can simulate ocean circulation beneath ice shelves and the melting of the ice-shelf base.

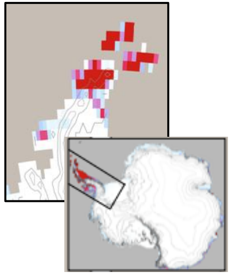
Ice-shelf bottom melting increases by 10x when density blockage (blue dashed line) erodes, allowing warm water to reach Antarctica. This occurs in some future p



Surface Melting Tipping Point



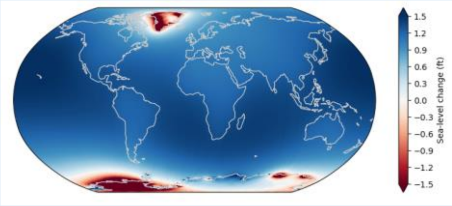
If surface melting reaches a threshold, ice shelves fracture and disintegrate.



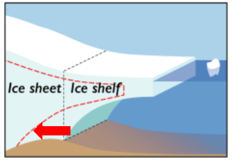
E3SM can simulate snow melt and water accumulation.

Future melt rates reach critical thresholds under current greenhouse gas trajectories beyond 2200.

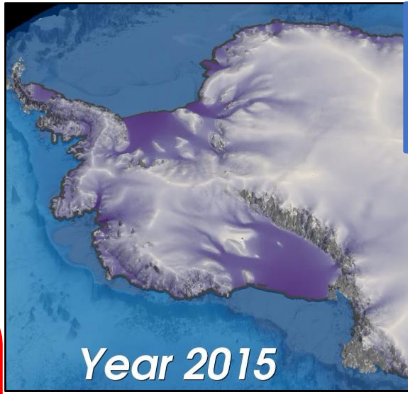
Sea-level change varies regionally due to deformation of the Earth's crust and changes in Earth's gravitational field as ice melts



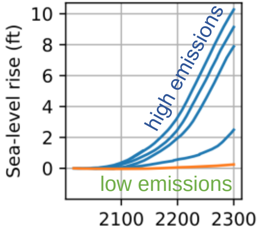
Marine Ice-Sheet Instability Tipping Point



If ice-shelf thinning reaches a threshold, the Antarctic Ice Sheet speeds up, causing



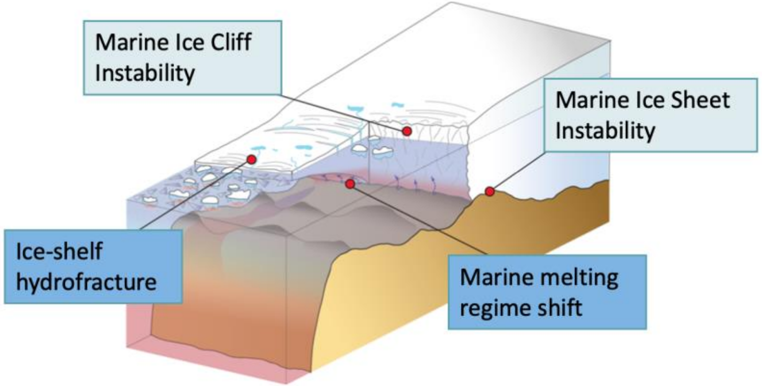
E3SM simulating ice-sheet response to ocean and surface melting



Multi-foot sea-level rise is unavoidable beyond 2200 under current greenhouse gas trajectories but timing is very uncertain.

Grand Challenges

- Much higher resolution required (sub km vs several kilometers)
- multicomponent interactions - process affected by 4 E3SM components (ATM, LND, ROF, GLC)
- model validation of rare events
- Nonlinear responses – small model biases can dramatically alter projections



Atlantic Meridional Overturning Circulation

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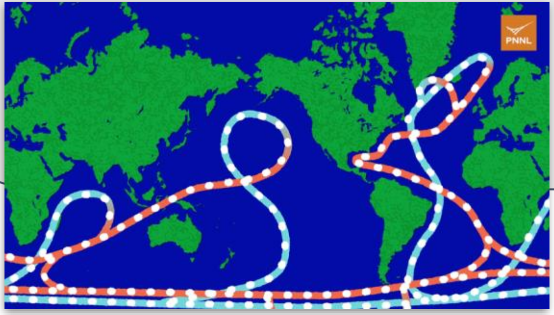
AMOC Slowdown and Global Consequences

The Atlantic Meridional Overturning Circulation

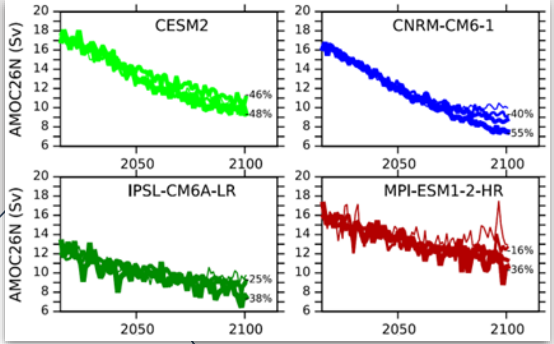
- The Atlantic Meridional Overturning Circulation (AMOC) is a global pattern of ocean circulation.
  - *Salty water cools and sinks to 2 km depth in the North Atlantic*
  - *This water flows southward and fills the rest of the ocean*
  - *Gradual warming and winds force the water back to the surface*
  - *The water flows back to the Atlantic to close the loop*
- The AMOC exerts a strong control on global climate from a large northward heat transport.
- Models agree that the AMOC will likely slow down in the 21st century.
- Models suggest that the AMOC could abruptly collapse, but there is no consensus as to how close we are to stability thresholds (tipping points).



Schematic of the AMOC, also known as the global conveyor belt circulation (credit Sara Levine, PNNL)

The AMOC in a Warming Climate

- In 2020 DOE scientists analyzed the AMOC in models that contributed to the Coupled Model Intercomparison Project Phase 6 (CMIP6), an activity of the WCRP.
- Models unanimously project a weakening of the AMOC in the 21st century (but no collapse!)..
- MOC weakening is not sensitive to future emission pathways suggesting that most of this weakening has been caused by 20th century CO_2 emissions.



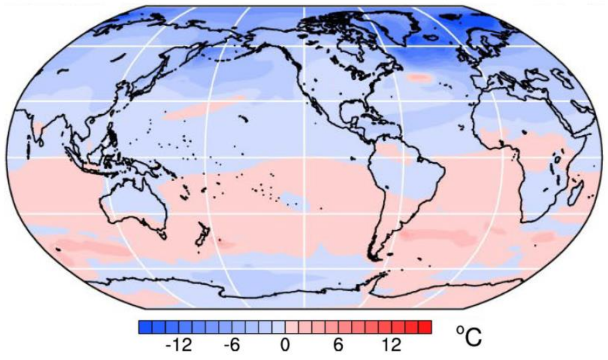
AMOC strength for 4 CMIP6 models, forced by 4 different scenarios of 21st century socio-economic development (SSPs). The lines hardly diverge for different scenarios suggesting that most of the AMOC decline has already been committed by historical emissions (Weijer et al. 2020)

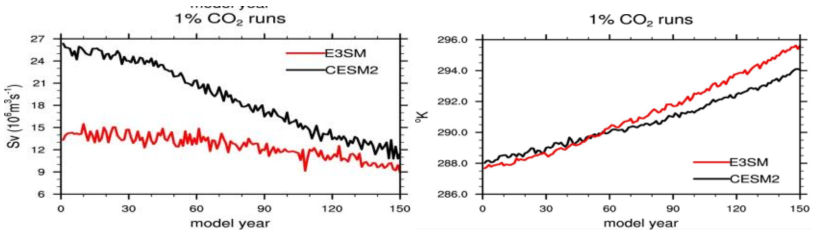
AMOC Stability and Thresholds

AMOC Stability

- Theory, models, and paleoclimate evidence suggest the possibility that the AMOC could abruptly *shut down*.
- Such a collapse could in principle be triggered by strong freshwater inputs into the North Atlantic Ocean, for instance due to a rapid disintegration of the Greenland Ice Sheet, possibly triggered by climate change.
- A 2019 review paper led by DOE scientists concludes that there is robust support for the *concept* that the AMOC *could* collapse.
- However, there is little confidence in the proximity to stability thresholds, so we have no idea how vulnerable the present-day or future AMOC is to collapse.
- Collapse of AMOC would have an immense impact on global climate within two decades.

Response of annual mean surface temperature to an AMOC collapse (Hu et al. 2023)



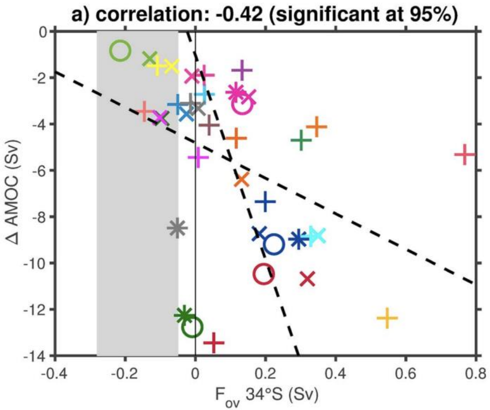


The climate response to increasing CO2 is sensitive to the AMOC strength and variability (Hu et al 2020)

AMOC Stability and Thresholds

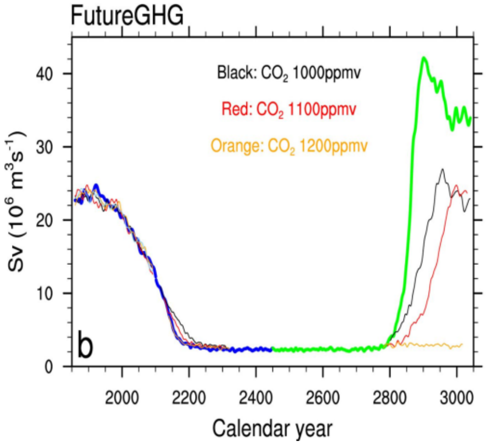
AMOC Thresholds and indicators

- The net freshwater import (Fov) into the Atlantic Basin is considered an indicator of AMOC stability, with negative values indicating potential of collapse.
- Most climate models have anomalously large Fov relative to observations suggesting they may be overly stable and we may be closer to AMOC collapse than models predict.
- Recent work by Hu et al (2023) has shown that as CO2 increases, the collapse of AMOC may be unavoidable.
- Coupled with additional freshwater input from melting glaciers and seaice could push this CO2 threshold lower.



Change in AMOC relative to the net freshwater export from the Atlantic. AMOC decline is not equivalent to AMOC collapse, and models with stronger AMOC may have had stronger initial AMOC (Weijer et al 2019

Large concentrations of CO2 result in collapse of AMOC for any concentration above a threshold value (Hu et al 2023)



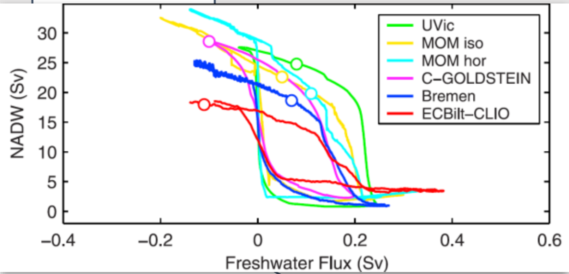
The Grand Challenge

DOE's Energy Exascale Earth System Model (E3SM) Meets AMOC Stability Grand Challenge

- Exploring the stability thresholds of the AMOC in climate models is an enormous computational challenge.
- To date, this has not been attempted for climate models that explicitly resolve critical transports by mesoscale (~10-50 km) eddies.
- The E3SM project is currently developing a new ocean model (OMEGA) that makes full use of the GPU capabilities of leadership class supercomputers at DOE facilities.
- OMEGA will allow us to perform the first-ever AMOC stability studies using a global climate model with eddy-resolving ocean component.

AMOC Tipping Point Model Intercomparison

- DOE scientists joined the leadership team of the AMOC-component of TipMIP.
- TipMIP-AMOC is developing an experimental protocol that would systematically explore the existence and location of AMOC tipping points in the current and future generations (CMIP6+/CMIP7) of Earth System Models.
- The goal is to provide an updated assessment of AMOC stability thresholds.



AMOC hysteresis curves with respect to North Atlantic freshwater input from several global climate models. Models disagree on the proximity of present-day climate (circles) to AMOC tipping points (Rahmstorf et al. 2005).