Towards improving representation of the Atlantic Meridional Overturning Circulation in climate models

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Improving modelling of the AMOC

What: Approximately 50 researchers from modelling centers and academia attended a workshop organized by the CLIVAR Atlantic Regional Panel AMOC Task Team to discuss how to improve the modelling of the AMOC in climate models.

When: 23-25 September 2024

Where: Met Office, Exeter, UK

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The Atlantic Meridional Overturning Circulation (AMOC) provides a simplified, zonally-integrated representation of complex ocean currents in the Atlantic basin. It transports warm, salty waters from the tropics to the higher-latitude North Atlantic and Arctic, where the waters cool, sink, and flow back southward [Buckley and Marshall, 2016]. The AMOC helps regulate regional as well as global climate by redistributing heat, salt, carbon, and other tracers, and changes can significantly impact weather patterns, monsoon rainfall, sea levels, sea ice, and hurricane activity [e.g., Jackson et al. 2015, Zhang et al. 2019, Bellomo et al. 2021]. According to the latest International Panel for Climate Change (IPCC) assessment, the AMOC is very likely to weaken by 2100, however, model simulations show large differences in the rates of weakening [Fox-Kemper et al. 2021]. This uncertainty in the magnitude of response to anthropogenic warming, along with differing characteristics of internal variability, has profound implications for climate impact assessments.

Understanding and addressing these uncertainties is essential for improving the reliability of climate projections, since climate models with projections of a strong AMOC weakening have significantly different impacts compared to those with a weak AMOC weakening, for example in temperature change, precipitation patterns, and Atlantic storm tracks [e.g., Bellomo et al. 2021, Woollings et al. 2012]. Furthermore, differences in the mean climate state represented by the models have been shown to influence both the rate of AMOC weakening in projections and aspects of AMOC variability [e.g., Jackson et al. 2020, Lin et al. 2023, Reintges et al. 2024]. The source of these biases is unclear, with many processes affecting the mean state of the North Atlantic and the AMOC. Many key processes for the AMOC are often misrepresented in models: for example, the pathways of water masses, the separation latitude of the Gulf Stream, eddy mixing, and overflows [e.g., Fox-Kemper et al. 2019, Jackson et al. 2023]. Enhanced horizontal resolution can improve representation of some processes, though sufficient resolution is not practically achievable for long climate simulations [Hewitt et al. 2017]. Improved representation and understanding of these processes are active research areas.

The CLIVAR AMOC Task Team was established recently through the CLIVAR Atlantic Region Panel to promote international collaborations and to support research on the AMOC. The Task Team identified the significant uncertainties in climate models in their representation of present-day AMOC and future AMOC changes as a priority. To address these issues, a workshop was organized, bringing together researchers specializing in the

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AMOC and related North Atlantic processes, along with those focusing on model development. The workshop was held at the UK Met Office in Exeter, UK during 23-25 September 2024, with about 50 participants from all career stages. Presentations and discussion sessions covered a wide range of topics, including using observations and paleoclimate reconstructions to evaluate models; the impacts of model horizontal resolution; reanalysis products; the representation of critical processes such as overflows, transport pathways of light waters (Gulf Stream and North Atlantic current) as well as dense waters (deep western boundary current), eddy mixing; and the impact of biases on AMOC variability and projections. On the final day, three breakout groups organized by career stage were tasked with identifying one to three pressing topics for the community to pursue over the next two to three years. There were several common priorities across the groups, with the following being suggested by at least two of the three groups.

The first priority activity identified was defining a set of standard metrics that can be compared to observations for evaluating the AMOC in models. This would ensure not only validation of model performance, but would also highlight areas for improvement, and enable model inter-comparisons. It was recommended that metrics should represent a wide range of processes important in the North Atlantic, in addition to those connected to the sustained observational sites, e.g., at RAPID (McCarthy et al, 2020) or OSNAP (Lozier et al, 2019). Suggestions for metrics included: different components of the AMOC transport, overflow properties, subpolar heat content, Gulf Stream separation, North Atlantic current pathway, surface flux driven water mass transformations (Marsh, 2000) and heat and freshwater transports.

A second priority raised was to develop a framework for consistent budget analyses. Many studies show relationships in models between the AMOC and densities in specific regions, so understanding what controls the temperature and salinity through using budgets can indicate how and why the AMOC evolves. However, this analysis is challenging across models because of availability of relevant data and model idiosyncrasies. There is also an opportunity raised by the availability of longer time records of heat and freshwater transports from the RAPID and OSNAP arrays for more in-depth comparisons with observations. A standardized framework would allow experts with access to the data to calculate diagnostics for different models, facilitating inter-model and observation comparisons. This framework could potentially be implemented through the ESMValTool (Eyring et al, 2020), an open-

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source, community-developed tool designed to provide diagnostics and performance metrics for evaluating and analysing Earth System Models. Currently, ocean diagnostics are limited, highlighting the priority to enhance the capability for calculating diagnostics, especially for calculating budgets. Process-based analyses could also be a promising approach to evaluate the development of model biases during spin-up. A need was also identified for a platform to share outputs of budget analyses.

The third priority was the representation of the Nordic Seas overflows, where dense waters flow out of the Nordic Seas into the subpolar North Atlantic, forming part of the lower limb of the AMOC. Representing the water properties and mixing involved is very challenging in models, with many having spurious numerical mixing [e.g., Legg et al. 2009, Fox-Kemper et al. 2019]. The workshop recommended focusing on how better representation of overflows affects the AMOC and downstream biases. This could be done through coordinated experiments to relax properties downstream of the overflows. There are also opportunities to improve the numerical representation of overflows, for instance through terrain-following coordinates [Bruciaferri et al. 2023] or parameterizations [Danabasoglu et al. 2010]. Testing these approaches and assessing the improvements these might bring, and collaborating on the implementation of such schemes, could result in significant improvements in AMOC representation.

A final priority was the representation of freshwater input from melting ice sheets, and its impact on the AMOC. Most models participating in CMIP7 will not fully include freshwater input from melting ice sheets, which has shown to slightly weaken the AMOC in past experiments [Devilliers et al, 2021, Martin et al, 2022]. However, some argue many models are too stable, and that future freshwater input could have a larger impact on the AMOC [Liu et al, 2014, Valdes, 2011]. At the workshop a need was identified for a common protocol to represent freshwater input in future projections and historical reconstructions. Coordinated storyline experiments were also suggested to examine the sensitivity of the AMOC to Greenland ice sheet melt and to enhance understanding of impacts. These activities are now part of the Tipping Points Model Intercomparison Project (TIPMIP), with planned experiments in the ocean domain that include both realistic and idealized rates of Greenland ice sheet melt input.

While these priorities address long-standing issues, there were also discussions about emerging opportunities. One such opportunity is the potential of machine learning to improve

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parameterizations of unresolved processes as well as to identify sources of persistent biases. Progress in this area requires increased collaboration and communication between ocean modelling and machine learning communities with a particular focus on addressing AMOC-relevant biases. Also, the increase in the number, type, and lengths of observational records provide new opportunities for understanding how well the AMOC is represented in models. For example, longer observational time series allow for a comparison of trends and variability with model simulations (e.g., Danabasoglu et al. 2021; Roberts et al. 2014), and observations of AMOC in density space from OSNAP have prompted many model comparison studies (e.g., Yeager et al. 2021, Jackson and Petit 2022).

While it remains unclear which properties or processes we need to capture correctly to produce robust and reliable projections and predictions of AMOC and related fields in the Atlantic basin, the four priorities discussed above aim to address these challenges, advancing our knowledge and providing societally relevant information.

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