

Collapse of the Atlantic Ocean circulation: Can it? Has it? Will it?

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Abstract

In early June, 2026, a workshop was convened to address the topic of climatic changes in the Atlantic Ocean circulation – specifically, a weakening or collapse of the large-scale circulation in response to anthropogenic global warming. The gathering brought together 61 experts from across the fields of physical oceanography, climate dynamics, paleoceanography, and dynamical systems, and involved participation from 11 countries. This document reports on the workshop's aims, structure, and themes, and provides a summary of key discussions. The information comes from notes and recordings made during the workshop itself, as well as a summary survey conducted immediately following the event. The above listed authors constituted the workshop's organising committee. All participants were invited to contribute to and comment on this report. It should thus be considered a shared effort from that wider group. A full list of workshop participants can be found in the acknowledgements.

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Summary and highlights

At a workshop convened to gather interdisciplinary expertise on the Atlantic Ocean circulation, its weakening, and possible collapse, the following core messages emerged.

Participants broadly **agreed** on the following points:

- Atlantic Meridional Overturning Circulation (AMOC) will weaken under anthropogenic forcing. The anticipated sign of the future response is one of the strongest areas of consensus, though significant questions remain about rates, consequences, and mechanistic understanding.
- The current instrumental record (~20 years) is too short to isolate a signal of anthropogenically-forced weakening of the large-scale circulation. While long-term trends in the directly observed AMOC streamfunction can be discerned in some locations, they cannot yet be confidently distinguished from internal variability — more (and longer) observations are needed.
- Evidence for the total collapse of the AMOC in the past, e.g. during Heinrich stadial 1 and the Younger-Dryas, is less robust than it was once thought to be. At the same time,

changes in the strength and structure of the circulation almost certainly occurred during these periods.

- Statistical early warning signals (EWS) such as critical slowing down are not yet fit for purpose in real-world application. The dynamical systems / EWS approaches are not reliable for detecting an approaching AMOC tipping point in the real world, partly because the framework is insufficiently informative on its own (i.e. without deeper physical system understanding) and because false positives are a significant concern.

Participants broadly **disagreed** on the following points:

- The AMOC has already weakened during the observational/industrial period (~1850–present). This was the most contentious point, with disagreement centering on the applicability of fingerprints, significance of trends, and the inferences that can be made under large uncertainty.
- The North Atlantic warming hole is a reliable AMOC fingerprint. There's recognition that SST anomalies are related to AMOC, but deep disagreement on the nature and stationarity of that relationship, as well as the confounding impacts of atmospheric circulation changes, aerosols, clouds, and internal variability.
- The AMOC can/will “tip” under realistic anthropogenic forcing, where to “tip” here is to enter a state in which amplifying feedbacks become dominant and the AMOC progresses nonlinearly towards a collapsed/significantly weakened state. The existence of multiple equilibria in the circulation state is considered plausible, but the likelihood of transitioning between states under anthropogenic forcing is contested.

Reflecting on the wide-ranging discussions during the workshop, several areas of ongoing and renewed focus for the community are highlighted below. These suggested focal points reflect many salient discussions during the workshop, but the list remains *preliminary and non-exhaustive*. It was initially compiled by the workshop organising committee and shared with participants for comment. The points listed here will be elaborated on and expanded in an upcoming opinion piece.

- **Ongoing, cross-disciplinary, robust discussions** on areas of scientific agreement and disagreement, such as were pursued at the workshop, are a priority for resolving critical questions of Atlantic Ocean circulation change. A lack of discourse within and across disciplinary boundaries has invited misunderstandings, engendered disagreement, and ultimately impeded progress on otherwise tractable and answerable questions. Further workshops, webinars, and other arenas for engaged discussion should be prioritised.
- Attention should be paid to the **consistency and precision of our mathematical and linguistic definitions of circulation features and their transient evolution**. The wide variety of definitions and linguistic choices adopted in the field prevents easy intercomparison of results and understanding across different studies, research groups, and sub-disciplines. At the same time, it is debated whether adopting stringent definitions (for example, a specific AMOC metric, or a specific threshold for “collapse”) is appropriate for a problem that remains dynamically under-constrained. Consequently, the community should currently favour consistency and precision in definitions, while

moving towards improved system understanding that would facilitate consensus on the “correct” approach.

- Continuation of the **direct observation of the Atlantic Ocean circulation** is essential to understand its evolution under a changing climate. At the same time, further work to constrain the expected “time-of-emergence” of an anthropogenic signal in the circulation should be pursued. Aligned with this, a novel observational framework that is technologically and financially sustainable on the relevant detectability timescale should be designed, developed and deployed alongside existing observations.
- Overall understanding of the response of the AMOC to anthropogenic global warming would be considerably improved if **the sign of AMOC changes since the beginning of the industrial era could be better constrained**. For this to be achieved it will require one or several of the following: robust quantification of uncertainty in AMOC fingerprints (and associated historical/paleo measurements); assimilation of historical/paleo proxy data into a dynamically-informed modelling framework, including the application of novel machine-learning and data-driven approaches; a Bayesian inference framework to quantitatively combine independent lines of evidence.
- The **applicability of statistical early warning systems in a real-world context** needs further investigation and scrutiny. The nuance and limitations of these approaches could be more consistently communicated to those outside the immediate field (as indeed was achieved during the workshop). The capacity for these approaches to provide reliable quantitative insight on tipping risk – in light of the many other deep unknowns about the system dynamics – is currently unknown.
- Efforts to **detect and understand multistability and “tipping points” in climate models** should preferentially investigate this under CO₂ forcing rather than classical freshwater hosing. It is increasingly recognised that freshwater hosing experiments invoke notably distinct dynamics for AMOC weakening and collapse relative to CO₂-driven global warming scenarios. This is both due to the limited realism of the freshwater forcing magnitude and spatial distribution in such experiments (relative to, for example, how rapidly the Greenland Ice Sheet can melt), as well as the increased recognition that atmospheric warming acting to suppress ocean heat release is perhaps a more likely mechanism instigating circulation change in a warming world (one that is quite distinct from freshwater-induced stratification). Consequently, findings from freshwater hosing experiments are likely insufficient to address questions of future circulation collapse. Ultimately, a combination of forcing (both warming and freshening) and feedbacks will dictate AMOC stability in a warming world, and modelling frameworks that can faithfully represent this entwined complexity should be favoured.
- **Improving our dynamical/mechanistic understanding of the circulation and its sensitivity to change** (e.g. via observations, theory, conceptual/toy models, paleo-observations, and process modelling) is essential to better understand and interpret observed changes and to constrain future projections. This improved mechanistic understanding should inform ongoing efforts to **reduce ocean and coupled model biases in the North Atlantic** (which project strongly onto AMOC biases). At the same time, efforts to-date suggest that although improvements can be made (e.g. with higher ocean resolution), there is not a silver bullet to remove these impactful biases,

and a consistent/converged representation of the North Atlantic circulation is unlikely to be achieved in the near future. Application of dynamically-informed constraints to reduce uncertainty in future projections will continue to be essential.

Background

In early June, 2026, a workshop was convened to address the topic of climatic changes in the Atlantic Ocean circulation – specifically, a weakening or collapse of the large-scale circulation in response to anthropogenic global warming. The gathering brought together 61 experts from across the fields of physical oceanography, climate dynamics, paleoceanography, and dynamical systems, and involved participation from 11 countries. This document reports on the workshop's aims, structure, and themes, and provides a summary of key discussions. The information comes from notes and recordings made during the workshop itself, as well as a summary survey conducted immediately following the event.

The workshop was supported by the Advanced Research + Innovation Agency (ARIA) Forecasting Tipping Points Programme, with additional support from the Fund for Science and Technology and endorsement from the international CLIVAR Scientific Steering Group.

Motivation and aims

The possibility of major shifts in the circulation and structure of the Atlantic Ocean is ringing alarm bells across society. However, the scientific literature reveals considerable disagreement and apparently contradictory evidence on some of the most crucial questions on this topic. The resulting divergent narratives have led to uncertainty and confusion that are ultimately hindering progress in both scientific understanding and societal action.

The primary aim of the workshop was to bring together leading experts from across the scientific spectrum to interrogate and communicate the current state of understanding of the dynamical mechanisms, existing records, and future likelihood of major shifts in the currents of the Atlantic Ocean. The goal was to identify, discuss, and investigate areas of agreement and disagreement, and thus to uncover, and collectively report on, where consensus has been reached and provide a roadmap for where further work is needed.

The stated objectives of the workshop were threefold:

- To encourage productive engagement and discussion within and across disciplinary boundaries on the subject of Atlantic Ocean circulation change and possible collapse.
- To clearly and precisely identify areas of agreement, disagreement, and general confusion within the community.
- To discuss avenues for further research that will most effectively resolve disagreements and trend the community towards consensus on key outstanding questions.

Workshop format

Preparatory webinars

During the four weeks prior to the workshop, we hosted weekly 1.5-hour long webinars. These webinars were open to workshop participants and to the wider scientific community. Each webinar involved two plenary talks of approximately 20 minutes, with speakers selected from leading experts who would not be at the workshop in person.

The purpose of the webinars was two-fold. Firstly, they were intended to initiate thinking and conversation amongst workshop participants on some of the core topics and questions that would be addressed at the in-person event. Secondly, they were intended to facilitate inclusion from a broader spectrum of the community than could be accommodated at the in-person event. The webinars followed the broad themes of the workshop, with two speakers under each of the Can it? Has it? Is it? and Will it? Themes.

Recordings of the webinars are available here:

[Week 1: Andy Thompson and Janne Repschläger](#)

[Week 2: Niklas Boers and Feng He](#)

[Week 3: Henk Dijkstra and Susan Lozier](#)

[Week 4: Rym Msadek and Gavin Schmidt](#)

In-person workshop

The three days of the in-person workshop were divided into six science sessions, each addressing a set of core topics related to the topic of Atlantic Ocean circulation and its potential for change and collapse. Each session consisted of two plenary talks, each of which allowed extended time for discussion. The remainder of each session was dedicated to small group or plenary discussions. These discussions were conducted in a number of different formats, specifically designed to address the objectives of that session.

Session summaries

Session 1: Definitions and distinctions

Core questions: *What do we mean when we are talking about different features of the Atlantic Ocean circulation, their potential to change, and the timescales and nature of that change? Are the definitions and concepts that we use consistent?*

The first session of the workshop focused on developing collective understanding of the ways in which the Atlantic Ocean circulation and its potential change can be defined and described. The aim was to explore whether and how our use of different definitions or ambiguous language

contributes to collective confusion or misunderstanding within or across fields. Furthermore, we aimed to arrive at collective agreement with respect to what language and definitions would be adopted at the workshop itself. Plenary talks from **Léon Chafik** (*Definitions and indices for the Atlantic Ocean circulation*) and **Laura Jackson** (*Definitions of change and collapse in the Atlantic Ocean circulation*) were followed by small group discussion.

Discussions centered on both the challenges of robustly defining metrics for ocean circulation and the use of different terminologies and metaphors in the description of transient change. Concerns were raised about consistency in the use of circulation metrics across the scientific literature, such as the AMOC strength, which impeded intercomparison of different studies and results. Further concerns were raised about the common use of metaphors (e.g. “collapse”, “tipping”) within the scientific literature, which are recognised as helpful for communication in some contexts but at the same time can (and perhaps have) led to conceptual confusion and impeded progress. Some participants favoured settling on common definitions for “collapse”, such as a reduction of X% over Y years, while others felt this could be unhelpful in light of what is still poorly understood about the system dynamics and the impacts of circulation change. It was widely discussed that preciseness in definitions and language – both in the scientific literature and in verbal communication – should be viewed as a priority, particularly in aid of cross-disciplinary discussion.

Session 2: Can it?

Core questions: *Is it theoretically possible for the Atlantic Ocean circulation to move into a notably distinct configuration relative to its present state? Is this a unique steady state (i.e. oscillating around a different attractor), or is it a sustained, forced deviation from its equilibrium?*

This session aimed to establish a baseline understanding of the theoretical controls on ocean circulation strength and its variability and stability. This included discussion on both current theories for the transient evolution of the circulation under surface warming and recent advances in a dynamical systems framework of the circulation and its stability. For each of these broad topics, we had one plenary talk: **Helen Johnson** and **David Marshall** (*Physical theory for controls on the Atlantic Ocean circulation and its potential for change*) and **Reyk Borner** (*Dynamical systems perspectives on the Atlantic Ocean circulation*). These talks were followed by split discussions on several related topics, including: relevance of simple conceptual models, controls on the rate and extent of Greenland ice sheet melt, heat and freshwater budgets in the North Atlantic, timescales of ocean adjustment and feedbacks, and aligning physical theory with dynamical systems.

Discussions were wide-ranging, with the aim of both interrogating and communicating foundational understanding within and across disciplinary boundaries. There was particular focus on aspects of our mechanistic and dynamical understanding about the response of the circulation to global warming that remain poorly understood. This included the possible resilience of high latitude dense water formation, which may continue at a consistent rate even as its core location migrates northward. Discussions of AMOC multistability affirmed that its existence in the ocean is widely considered plausible in light of its consistent emergence across

a hierarchy of models, but how and on what timescale warming-derived AMOC weakening leads to a transition to a new equilibrium state (i.e. how amplifying feedbacks initiated by AMOC weakening, e.g. salt advection, come to dominate) remains broadly unknown and widely debated.

Session 3: Has it?

Core questions: *What is the current state of evidence for distinct regimes of circulation in the Atlantic Ocean in the geological past? How robust is this evidence, and how and where might it be challenged? What is known, or inferred, about the drivers of these changes?*

In the third workshop session, attention moved to the geological past and proxy records of historical circulation change and possible collapse. Plenary talks were delivered from **Tom Marchitto** and **Jean Lynch-Stieglitz** (*Geological evidence for change and collapse in the Atlantic Ocean circulation*) and **Camille Li** and **David Battisti** (*Interrogating the ocean's role in abrupt climate change*). The subsequent discussion was arranged to facilitate focused dialogue between the paleoclimate experts in attendance at the workshop, while other participants were invited to listen to these discussions and chime in with questions or requests for clarification at appropriate moments.

The most prominent topic of discussion centered on current expert perspectives on the paleo proxy record during the last glacial period and deglaciation. It was recognised – and broadly accepted by the paleo experts present – that prior claims about total collapse of the AMOC, specifically during Heinrich Stadial 1 based on Pa/Th data, are insufficiently supported when considering the entirety of existing data. At the same time, there is clear evidence that the strength and structure of the Atlantic circulation did change considerably during these freshwater forcing events, but in a manner that is not yet well constrained. It was noted that other Heinrich Stadial events that are presumed to be associated with higher levels of freshwater release (e.g. HS4) may be better candidates for total AMOC collapse, and require further investigation and scrutiny. Further, broad discussion encompassed the applicability of past climatic events as analogues for the current climate. In particular, it was widely discussed how the much-expanded sea ice extent during the most recent glaciation may fundamentally alter the dynamics and sensitivity of the circulation, rendering insight from these cold conditions insufficient for making claims about contemporary change.

Session 4: Is it? Evidence

Core questions: *What is the current state of evidence for industrial era changes in the circulation?*

In this session, the focus turned to the more recent period, including the instrumental record during which the strength of the circulation has been directly observed, and the longer industrial era, during which circulation and structure has been inferred through its effect on observed variables such as sea surface temperature. The plenary talks were delivered by **Isabela Le**

Bras (*The instrumental record of the Atlantic Ocean circulation*) and **Stefan Rahmstorf** (*Evidence for changes in the Atlantic Ocean circulation during the industrial period*).

To initiate the subsequent discussion, participants were asked to line up on a spectrum, with their position reflecting the extent to which they agreed or disagreed with the following statement: “The Atlantic Meridional Overturning circulation has weakened during the industrial era”. Once arranged, the spectrum was partitioned, forming small groups with similar levels of agreement on the given statement. Individuals were then encouraged to discuss their perspectives in the small group, interrogating why they were on that part of the spectrum, probing for areas of alignment, and considering what arguments or evidence would move them up or down the spectrum. When the small groups came back together for a plenary discussion, summaries were requested from each group, starting with those who most strongly disagreed and working towards those who most strongly agreed. The exercise revealed the distribution of perspectives on this key topic.

The participants at this workshop were widely spread from strongly agree to strongly disagree, but skewed slightly towards an agreement with the statement. The largest groupings were immediately either side of the center; that is, most people were in marginal agreement or marginal disagreement that the AMOC weakened in the industrial era. Notably, almost all participants – even those in strong disagreement with the statement – acknowledged that there is sound reasoning to expect that the AMOC will weaken in response to global warming. What caused the spread of perspectives, therefore, was (a) different ideas about the sufficiency of evidence making the claim that it already has weakened, and (b) different perspectives on whether an anthropogenic forced change would have emerged above internal variability over this period. It was evident that a “human” dimension dictates some spread in perspectives on this problem – specifically, degrees of comfort in making assertions under large or unknown uncertainty – which merits further investigation and reconciliation. Most disagreement (or hesitancy towards full agreement) emerged from a lack of robust, conclusive evidence for AMOC change. Those participants at the “strongly agree” end of the spectrum instead derived their confidence from the claim that although no single line of evidence is conclusive, an AMOC weakening is the most parsimonious explanation unifying numerous uncertain and inconclusive metrics of change in the system (i.e. fingerprints). Others challenged this line of reasoning on the grounds that structural uncertainty in fingerprint approaches, and an unconstrained role for feedbacks and internal variability, preclude AMOC weakening as the most likely explanation for the observed variability.

Session 5: Is it? Early warnings

Core questions: *Is there evidence for unprecedented changes in the circulation based on the application of dynamical systems theory? Can these approaches deliver viable early warning of future changes? Under what conditions should we expect those warnings to be robust and reliable?*

The penultimate workshop session addressed the question of whether there exists inherent predictability in the Atlantic Ocean circulation, and whether that predictability can be elucidated

through the application of dynamical systems theory. Two plenary talks were delivered by **Johannes Lohmann** (*Dynamical systems theory and early warnings of circulation change*) and **Till Wagner** (*Opportunities and challenges of early warning system frameworks*). These talks were followed by small group discussions in which participants were asked to broadly explore questions of predictability in the Atlantic Ocean circulation, including whether (and how) contemporary observations can be leveraged to make reliable forecasts of future nonlinear change and possible collapse.

The plenary talks effectively highlighted the many challenges of applying a dynamical systems framework to provide early warning of nonlinear change/tipping events in the real world. They noted in particular that while critical slowing down is a mathematically elegant and insightful tool, its reliable implementation for real world early warning poses significant challenges that do not yet have known, tractable solutions. Subsequent discussions fleshed out these challenges, and explored how our mechanistic understanding of the system could inform dynamical systems-based tools. This centered on deepening understanding of what observable components of the ocean circulation exhibit both low signal-to-noise with respect to forced change, as well as high memory or inertia such that they imbue the system with predictability. Many lines of evidence therein point to the importance of deep ocean observations.

Session 6: Will it?

Core questions: *Will the Atlantic Ocean circulation change (collapse, substantially weaken, or shift configuration) under future anthropogenic climate change? If so, under what forcing conditions, and on what timescale will this change take place? Will this be a linear response to the applied forcing, or will amplifying feedbacks initiate transition to a new state that will not be reversed with a reversal in the forcing?*

In the final session of the workshop, participants turned their attention to future projections, and the current evidence for circulation weakening and collapse in the immediate and far future. Plenary talks were delivered by **Elizabeth Maroon** (*Simulating the Atlantic Ocean circulation*) and **Alexey Fedorov** (*Projections of Atlantic Ocean circulation change and collapse*). The first talk highlighted the intrinsic challenges of simulating the Atlantic Ocean circulation in terms of unresolved processes and persistent model biases, while the latter talk highlighted what such models suggest about future change in spite of their challenges and biases.

For the subsequent discussion, a spectrum activity (as in Session 3) was carried out. On this occasion, the statement was “Our existing capabilities are sufficient to make reliable predictions of future Atlantic Ocean circulation change.” Participants again spread across the spectrum, with a slight skew toward “disagree”. Compared to the spectrum in Session 3, there was greater divergence in the interpretation of the question; that is, what was meant by “existing capabilities”, “sufficient”, or indeed “future”. This ambiguity was intentional, with a component of the exercise being to understand how people interpret these statements, but it also led to some challenges in focussing discussion and discerning sources of disagreement. Broadly, those in strong disagreement with the statement cited the many important but as yet poorly represented processes in coupled climate models, suggesting that model biases are simply too broad to

presume that we can project future change with sufficient fidelity. In contrast, those in agreement with the statement consider that model convergence on the sign of change (most showing weakening over the 21st century) is sufficient to derive confidence in our predictive capabilities, even if more precise quantification of likelihood requires further work. Less discussion was afforded to model representation of future AMOC collapse, with most participants paying attention to 21st century weakening.

The Advanced Research + Innovation Agency Forecasting Tipping Points programme

The ARIA Forecasting Tipping Points programme aims to build an early warning system for critical climate thresholds. Backed by £81M, the initiative focuses on the North Atlantic Subpolar Gyre and the Greenland Ice Sheet. Explore the [programme thesis](#) and review [currently funded teams](#) for context. A second solicitation opens in mid-September and will seek expertise in sustained ocean observations, interannual-to-decadal forecasting, and tipping point impacts and response.

Participant list

The following individuals were in attendance at the in person workshop. Members of the organising committee are highlighted in bold.

<u>Surname</u>	<u>First name</u>	<u>Institution</u>
Asbjørnsen	Helene	University of Bergen
Battisti	David	University of Washington
Bellomo	Katinka	University of Padova
Bonan	Dave	University of Washington
Borner	Reyk	Utrecht University
Castruccio	Frederic	NSF National Center for Atmospheric Research
Chafik	Leon	Department of Meteorology, Stockholm University
Chapman	Ruth	Grantham Research Institute, London School of Economics
Czaja	Arnaud	Imperial College
De Boer	Agatha	Stockholm University
de Jong	Femke	Royal Netherlands Institute for Sea Research
Ditlevsen	Peter	University of Copenhagen
Elipot	Shane	University of Miami
Falkena	Swinda	Utrecht University
Fedorov	Alexey	Yale University
Foukal	Nick	University of Georgia Skidaway Institute of Oceanography
Frajka-Williams	Eleanor	University of Hamburg
Fraser	Neil	Scottish Association of Marine Sciences
Gebbie	Jake	Woods Hole Oceanographic Institution
Groeskamp	Sjoerd	Royal Netherlands Institute for Sea Research
Hankel	Camille	University of Washington
Hernández-Guerra	Alonso	Universidad de Las palmas de Gran Canaria
Hines	Sophie	Woods Hole Oceanographic Institution
Hu	Aixue	NSF National Center for Atmospheric Research
Hughes	Chris	University of Liverpool/NOC
Ivanovic	Ruza	University of Leeds
Jackson	Laura	Met Office Hadley Centre
Johnson	Helen	University of Oxford
Jones	Spencer	Texas A&M University
Kilbourne	Hali	University of Maryland

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Le Bras	Isabela	Woods Hole Oceanographic Institution
Li	Camille	University of Bergen & Bjerknes Centre for Climate Research
Lohmann	Johannes	University of Copenhagen
Lohmann	Gerrit	AWI, Helmholtz Centre for Polar and Marine Research
Lynch-Stieglitz	Jean	Georgia Institute of Technology
MacGilchrist	Graeme	University of St Andrews
Madan	Gaurav	University of Reading
Marchitto	Tom	University of Colorado Boulder
Marotzke	Jochem	Max-Planck-Institut für Meteorologie
Maroon	Elizabeth	University of Wisconsin-Madison
Marshall	David	University of Oxford
Martin	Torge	GEOMAR Helmholtz Centre for Ocean Research Kiel
Mehling	Oliver	Utrecht University
Moffa-Sanchez	Paola	Durham University
Osman	Matt	University of Cambridge
Petit	Tillys	National Oceanography Centre
Pöppelmeier	Frerk	University of Bern
Rae	James	University of St Andrews
Rahmstorf	Stefan	Potsdam Institute for Climate Impact Research
Ruiz-Angulo	Angel	University of Iceland
Romanou	Anastasia	NASA-Goddard Institute for Space Studies/Columbia University
Slater	Donald	University of Edinburgh
Smedsrud	Lars	University of Bergen
Stainforth	Dave	London School of Economics
Stocker	Thomas	University of Bern
Straneo	Fiamma	Harvard University
Terhaar	Jens	University of Bern
Thornalley	David	University College London
Wagner	Till	University of Wisconsin-Madison
White	Michael	Nature Publishing
Wood	Richard	Met Office Hadley Centre