ADVANCING EARTH AND SPACE SCIENCE

JGR Oceans

COMMENTARY
10.1029/2020JC016745

Special Section:
Atlantic Meridional Overturning Circulation: Reviews of Observational and Modeling Advances

Key Points:

- UK RAPID and US AMOC Programs implemented an AMOC observing system and advanced understanding and modeling of AMOC variability and change
- Challenges remain to sustain observations, improve modeling and prediction on AMOC, and further knowledge of its climate impacts

Correspondence to:
M. Patterson,
mpatterson@usclivar.org

Citation:
Srokosz, M., Danabasoglu, G., & Patterson, M. (2021). Atlantic meridional overturning circulation: Reviews of observational and modeling advances—An introduction. *Journal of Geophysical Research: Oceans*, *126*, e2020JC016745. https://doi.org/10.1029/2020JC016745

Received 27 AUG 2020
Accepted 11 NOV 2020

Atlantic Meridional Overturning Circulation: Reviews of Observational and Modeling Advances—An Introduction

Meric Srokosz[1], Gokhan Danabasoglu[2], and Michael Patterson[3]

[1]National Oceanographic Centre, Southampton, UK, [2]National Center for Atmospheric Research, Boulder, CO, USA, [3]US Climate Variability and Predictability Project Office, Washington, DC, USA

Abstract This article provides a brief overview of AMOC science organized collaboratively between the UK RAPID and US AMOC Programs (with partners internationally) during the past 16 years as reflected in the set of synthesis and review articles in the AGU special issue entitled “Atlantic Meridional Overturning Circulation: Reviews of Observational and Modeling Advances.” The article highlights the programs' initial motivations and summarizes the successful implementation of the pan-Atlantic AMOC observing system, efforts to assess the state, variability, and changes in AMOC, advances in understanding AMOC variability mechanisms and predictability, and illumination of AMOC impacts on global and regional climate, sea level, and ecosystems.

Plain Language Summary The authors present a brief introduction of a collection of science summary articles that showcase research advances during the past decade and a half in observing, understanding, and predicting variations and changes in the large-scale circulation of the Atlantic Ocean and its impacts on climate variability and the potential for rapid climate change.

The 2001, Intergovernmental Panel on Climate Change (IPCC) Working Group I report on the scientific basis of climate change suggested that the Atlantic meridional overturning circulation (AMOC) could weaken over the 21st century (Houghton et al., 2001). In the following year, 2002, the US National Research Council's report *Abrupt Climate Change: Inevitable Surprises?* highlighted the North Atlantic circulation as at risk of abrupt change in a warming climate (NRC, 2002). In 2007, the Ocean Research Priorities Plan issued by the US Joint Subcommittee on Ocean Science and Technology (NSTC JSOST, 2007) identified improving understanding of AMOC as a key near-term priority. These reports noted the significant consequences for climate that are associated with AMOC, especially for those regions bordering the North Atlantic, but also further afield. Such reports provided the impetus for the deployment in 2004 of the AMOC observing system at 26.5°N in the Atlantic under the auspices of the joint UK-US Rapid Climate Change program (a.k.a., RAPID) and the formation in 2008 of the US AMOC Program and Science Team.

The aim of this AMOC virtual special issue in AGU journals is to review and synthesize what has been learned about the AMOC since the beginning of the RAPID and US AMOC Programs, in terms of both observations (modern and paleo) and modeling (theoretical and numerical). In addition, the special issue manuscripts identify many remaining gaps and challenges, providing guidance for future studies. The issue consists of nine papers across three journals: *Journal of Geophysical Research: Oceans* (Bower et al., 2019; Hirschi et al., 2020; Jackson et al., 2019; Johnson et al., 2019; Little et al., 2019; Weijer et al., 2019), *Reviews of Geophysics* (McCarthy et al., 2020; Zhang et al., 2019), and *Paleoceanography and Paleoclimatology* (Moffa-Sanchez et al., 2019). The research described in these papers has focused on implementing, evaluating, and sustaining a pan-Atlantic observing system; assessing the AMOC state, variability, and secular change, including the use of paleoclimate records; and advancing our knowledge of AMOC variability mechanisms and predictability, as well as its impact on global climate, sea level, and ecosystems.

Prior to 2004, observations of the AMOC near latitude 26°N had been obtained from single basin-wide ship-based measurements only intermittently (1957, 1981, 1992, and 1998), and these (together with a further hydrographic section in 2004) suggested that a possible slowdown of the AMOC had occurred (Bryden et al., 2005). However, five measurements over a period of almost 50 years could not be regarded as conclusive. In contrast, the RAPID 26.5°N observing system provided daily measurements of the AMOC's strength and vertical structure and continues to do so at the present time (McCarthy et al., 2020). The RAPID and US AMOC Programs, together with the 26.5°N AMOC observations, provided the foundation and impetus for a large number of studies covering observations (both modern and paleo) and ocean and climate modeling. For example, a recent OceanObs'19 paper details the many new AMOC observing systems that have been deployed in the North and South Atlantic over the last few years, stimulated by the success of the 26.5°N observing system (Frajka-Williams et al., 2019). The 26.5°N observations now provide a unique time series of the strength and vertical structure of the AMOC. These observations have enabled new research, provided new insights into the AMOC, and challenged the climate modeling community to improve the representation of the AMOC in coupled Earth system models that are used to predict future global climate change.

The role of the AMOC in the past abrupt climate changes was championed by Wally Broecker (e.g., Broecker, 1991, 1997; Broecker et al., 1985; see also Alley, 2007). Essentially, this is the idea that freshening of the surface waters of the North Atlantic could trigger a reorganization of the AMOC leading to climatic impacts on short time scales (orders of years to decades, rather than centuries or millennia). The relevance of this idea to current climate change is clear. Since Broecker's early work, significant effort has been expended to study past climate changes under this paradigm. However, much of this research relates to what happened under conditions that are very different to those of the present climate (see e.g., Alley, 2007). Perhaps more relevant to understanding the AMOC today is to set the recent modern AMOC observations in a longer term context but under similar climatic conditions. For this reason, research has focused on the behavior of the AMOC over the last 1–2 millennia (Moffa-Sanchez et al., 2019).

As with all paleoceanographic studies, examining the behavior of the AMOC over the last 2 millennia depends on using oceanographic proxies for changes in that behavior and its impacts. The proxies can provide information on a range of parameters (see Table 1 of Moffa-Sanchez et al., 2019). A continuing challenge is linking the various proxy data, each with a different temporal resolution and length of record, to provide a coherent picture. A further challenge is comparing the proxy results with climate model simulations (Moffa-Sanchez et al., 2019 describe such comparisons for the last millennium). Some recent results suggest a weakening of the AMOC over the last 150 years (Caesar et al., 2018; Thornalley et al., 2018), but further back in time the behavior of the AMOC based on proxy data becomes less clear. However, the last 2 decades have seen the collection of far more proxy data than previously available, thereby allowing progress (Moffa-Sanchez et al., 2019).

Related to the question of abrupt change is that of the stability of the AMOC. As originally noted by Stommel (1961), based on a simple box model of the circulation, the overturning could be in a monostable or bistable regime. If the latter is the case then, in principle, the AMOC could abruptly flip into an off state, with serious consequences to climate, sea level, and ecosystems. Weijer et al. (2019) note that, despite progress in observations and modeling, the possibility of multiple equilibrium states for the existing or future AMOC cannot be ruled out, and that determining whether the AMOC is near a threshold where it could suddenly flip into another state is an important open research question.

With regard to measured changes in the AMOC, recent observations have provided a wealth of new insights. Specifically, data from the RAPID array in the subtropical gyre at 26.5°N (2004–present; Frajka-Williams et al., 2019; McCarthy et al., 2020); the Overturning in the Subpolar North Atlantic Program (OSNAP) array in the subpolar gyre, spanning Canada-Greenland-Scotland range (2014–present; Lozier et al., 2019); and the South Atlantic MOC Basin-wide Array at 34.5°S (2009–present; Kersalé et al., 2020) together with other observational studies (Bower et al., 2019; McCarthy et al., 2019), theoretical work (Johnson et al., 2019), and modeling efforts (Danabasoglu et al., 2019; Hirschi et al., 2020, Zhang et al., 2019), have challenged what were once accepted views of the AMOC. Such previous paradigms include the AMOC is driven by thermohaline changes and varies on time scales of years to millennia; changes in convection in the Labrador Sea play a key role in the AMOC; and the deep return flow is confined to the Deep Western Boundary Current (DWBC). It is now known that the AMOC is highly variable on all time scales, from days to millennia, and that much of that variability on shorter time scales is wind forced, though thermohaline forcing is important for longer time scales (Hirshi et al., 2020; Jackson et al., 2019; Johnson et al., 2019). As well as the DWBC, some of the AMOC return flow is via interior pathways in both the North and South Atlantic, away from the western boundary, so less meridionally coherent (Bower et al., 2019). Finally, changes in the deep flow are occurring between 3,000 and 5,000 m and, based on the short record available from the OSNAP array, these seem not to be linked to Labrador Sea convection, but to changes in the eastern part of subpolar gyre and the regions farther north (Hirshi et al., 2020; Zhang et al., 2019).

From a climate prediction perspective, it is known that Atlantic Multidecadal Variability (AMV) has many impacts that are of importance both societally and economically (Zhang et al., 2019). The impacts include meridional shifts in the Intertropical Convergence Zone and associated rainfall; and changes in the strength of the Sahel and Indian summer monsoons, frequency of Atlantic hurricanes, variability of climate across Europe, North America and Asia, and the extent of Arctic sea ice, among others. There is good evidence that the AMOC is a key driver of AMV and so of its climatic impacts, and that it is the AMOC-induced changes in the meridional heat transport (MHT) that are critical, as the heat exchange between ocean and atmosphere drives many of the climatic impacts. The AMV timescale, being multidecadal, means that the link between AMV and AMOC cannot be verified as yet from RAPID observations, the time series being less than 2 decades in length. Nevertheless, both observations, including paleo-climatic ones, and modeling strongly support the AMOC-AMV link. These links are important when it comes to making decadal predictions of climate change and its impacts, in which the ocean plays a key role through its heat content and AMOC memory. The issue of decadal predictability and the skill of decadal predictions are also critical—how well do the decadal predictions do in terms of forecasting climatic impacts, such as those listed above? There is evidence that the North Atlantic region possesses decadal predictability because of the AMOC-AMV relationship, but deficiencies in coupled ocean-atmosphere models and limited length of observational time series are challenges that need to be overcome (Zhang et al., 2019).

As well as the impacts mediated by the AMV, a potentially significant, more direct, impact of AMOC changes manifests itself in sea level rise on the eastern seaboard of the United States. Specifically, a decrease in the AMOC could lead to coastal flooding with its associated negative societal and economic consequences. Recent work (Little et al., 2019) has shown, both from observations and modeling, that the AMOC-sea level link is complex. Different models, while showing an antiphase relationship between the AMOC and sea level, differ in the amplitude of the effect and in the spatial structure of the along-coast variations. Aspects of the link such as the importance of local versus remote forcing and of coastal circulations remain to be understood. If the mechanisms leading to an AMOC-sea level link can be elucidated, then the much longer term tide gauge observations of sea level along the U.S. East Coast could be used to reconstruct the behavior of the AMOC on longer time scales.

In order to make progress in understanding the dynamical behavior of the AMOC, improved theoretical understanding is required to provide a context for both the observations and the results obtained from both ocean and coupled Earth system models. Theoretical advances (Johnson et al., 2019) have shown, for example, that the wind field in both hemispheres is important for the AMOC mean strength and variability, that sloping boundaries are crucial in allowing ocean basins to remain stratified, and that eddies at high latitudes also influence the dynamics of the AMOC. Nevertheless, many questions remain to be addressed, such as the relationship of the AMOC variability to the background state, and how best to represent air-sea interactions and parameterize smaller scale processes, such as those occurring at the sub-mesoscale, in ocean circulation models to improve AMOC simulations.

An alternative way to gain understanding of the AMOC, how and why it is changing, and its variability is to combine observations and dynamically consistent models and perform ocean reanalysis (Jackson et al., 2019). Considerable progress has been in ocean reanalysis, partly due to an improved network of observations, but also to improvements in models and techniques for combining models with ocean data. When tested against the RAPID AMOC observations at 26.5°N (Jackson et al., 2019), the different reanalyses show similar behavior, reduced spread, and greater consistency, in contrast with a prior effort which considered an earlier and longer (1960–2007) period (Karspeck et al., 2017). Essentially, the availability of Argo data since the mid-2000s provides greater observational constraints on the reanalyses leading to better agreement among the reanalyses and also with moored AMOC observations. The reanalyses suggest a weakening of the AMOC between 2005 and 2009; a further rapid decrease around 2010 which is followed by an equally fast recovery; and a very small gradual strengthening thereafter with lots of variability. The reanalyses are largely consistent with the latest RAPID observations, although the AMOC increase since 2010 is not statistically significant (see Figure 3 and analysis in Moat et al., 2020). However, the reanalyses underestimate the MHT even though they have the expected strong correlation between the MHT and AMOC strength (as seen in the observations), so improvements are still required.

Many modeling advances are predicated on an increase over time in computing power and this is true of modeling of the AMOC, with much higher resolution ocean models available now as compared to those available at the start of the RAPID observations in 2004 (Hirschi et al., 2020). These higher resolution models, which can resolve or permit the oceanic eddies, have allowed the investigation of aspects such as the chaotic component of the AMOC, essentially the effect of mesoscale eddies on its short-term variability. This in turn requires running an ensemble of models at high resolution, which is now becoming possible. The existence of this chaotic component to the AMOC may affect attempts to make decadal predictions of its variability and of the AMV. As discussed in Hirschi et al. (2020), in general, high-resolution models also suggest the presence of high-frequency AMOC variability that has not been previously noted in lower resolution models or observations. Whether such variability exists in the real world remains an open question.

Despite the tremendous progress in AMOC-related research as articulated in the Special Issue manuscripts, there are many remaining challenges that should be addressed to further our understanding. From the observational side, such challenges include gaps in the observing system (e.g., shelf regions and deep oceans), disparate observational strategies, and reductions in funding that jeopardize sustained observations (Frajka-Williams et al., 2019; McCarthy et al., 2020). Earth system models continue to show persistent biases, particularly in the North Atlantic, and AMOC variability mechanisms and their characteristics vary significantly across models (e.g., Danabasoglu et al., 2019; Zhang et al., 2019).

Although the US AMOC Program formally “sunsets” in 2021, research on the AMOC in the United States will continue. The original motivation for AMOC observations, the possibility of AMOC decline or rapid collapse under anthropogenically induced climate change, remains. The latest IPCC special report on the ocean and cryosphere (Pörtner et al., 2019) states that “Observations, both in situ (2004–2017) and based on sea surface temperature reconstructions, indicate that the AMOC has weakened relative to 1850–1900 (*medium confidence*),” and that “The AMOC is projected to weaken in the 21st century under all RCPs (*very likely*), although a collapse is *very unlikely* (*medium confidence)*.” These conclusions and the above challenges present new opportunities and motivations for the community. Specifically, collaborative research that includes a hierarchy of models, theory, high-resolution paleo records, and sustained and processed-based observations promises to advance our understanding, potentially leading to improved models and prediction skills, among others, of AMOC variability and its associated climate impacts.

Acknowledgments
We especially appreciate the comprehensive effort of the lead and co-authors who organized and contributed to the review and synthesis articles comprising the AGU Special Collection on AMOC science. We are also grateful to the AGU program managers and editors of JGR-Oceans, Review of Geophysics, and Paleoceanography and Paleoclimatology for welcoming and shepherding the cross-journal collection. This introduction is provided on behalf of the UK RAPID Programme, with support of MS by the UK National Environment Research Council; the US AMOC Science Team, with support of GD through National Science Foundation funding of the National Center for Atmospheric Research (AGS-1852977); and the US CLIVAR Program, with support of MP by the National Aeronautic and Space Administration (80NSSC17MOOO7), the National Oceanic and Atmospheric Administration (NA11OAR431023), the National Science Foundation (AGS-1502208), and the US Department of Energy (DE-SC0016332).

References

Alley, R. B. (2007). Wally was right: Predictive ability of the North Atlantic “conveyor belt” hypothesis for abrupt climate change. *Annual Review of Earth and Planetary Science*, *35*, 241–272. https://doi.org/10.1146/annurev.earth.35.081006.131524

Bower, A., Lozier, S., Biastoch, A., Drouin, K., Foukal, N., Furey, H., et al. (2019). Lagrangian views of the pathways of the Atlantic meridional overturning circulation. *Journal of Geophysical Research: Oceans*, *124*, 5313–5335. https://doi.org/10.1029/2019JC015014

Broecker, W. S. (1991). The great ocean conveyor. *Oceanography*, *4*, 79–89. https://doi.org/10.5670/oceanog.1991.07

Broecker, W. S. (1997). Thermohaline circulation, the Achilles heel of our climate system: Will man-made CO_2 upset the current balance? *Science*, *278*, 1582–1588. https://doi.org/10.1126/science.278.5343.1582

Broecker, W. S., Peteet, D. M., & Rind, D. (1985). Does the ocean-atmosphere system have more than one stable mode of operation? *Nature*, *315*, 21–26. https://doi.org/10.1038/315021a0

Bryden, H. L., Longworth, H. R., & Cunningham, S. A. (2005). Slowing of the Atlantic meridional overturning circulation at 25°N. *Nature*, *438*, 655–657. https://doi.org/10.1038/nature04385

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G., & Saba, V. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature*, *556*, 191–196. https://doi.org/10.1038/s41586-018-0006-5

Danabasoglu, G., Landrum, L., Yeager, S. G., & Gent, P. R. (2019). Robust and non-robust aspects of Atlantic meridional overturning circulation variability and mechanisms in the Community Earth System Model. *Journal of Climate*, *32*, 7349–7369. https://doi.org/10.1175/JCLI-D-19-0026.1

Frajka-Williams, E., Ansorge, I. G., Baehr, J., Bryden, H. L., Paz Chidichimo, M., Cunningham, S. A., et al. (2019). Atlantic meridional overturning circulation: Observed transport and variability. *Frontiers in Marine Science*, *6*, 260. https://doi.org/10.3389/fmars.2019.00260

Hirschi, J. J. -M., Barnier, B., Böning, C., Biastoch, A., Blaker, A. T., Coward, A., et al. (2020). The Atlantic meridional overturning circulation in high resolution models. *Journal of Geophysical Research: Oceans*, *125*, e2019JC015522. https://doi.org/10.1029/2019JC015522

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., et al., (Eds.). (2001). Climate change 2001: The scientific basis. Contribution of working group I to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY: Cambridge University Press.

Jackson, L., Dubois, C., Forget, G., Haines, K., Harrison, M., Iovino, D., et al. (2019). The mean state and variability of the North Atlantic circulation: A perspective from ocean reanalyses. *Journal of Geophysical Research: Oceans*, *124*, 9141–9170. https://doi.org/10.1029/2019JC015210

Johnson, H. L., Cessi, P., Marshall, D. P., Schloesser, F., & Spall, M. A. (2019). Recent contributions of theory to our understanding of the Atlantic Meridional Overturning Circulation. *Journal of Geophysical Research: Oceans*, *124*, 5376–5399. https://doi.org/10.1029/2019JC015330

Karspeck, A., Stammer, D., Köhl, A., Danasaboglu, G., Balmaseda, M., Smith, D. M., et al. (2017). Comparison of the Atlantic meridional overturning circulation between 1960 and 2007 in six ocean reanalysis products. *Climate Dynamics*, *49*, 957–982. https://doi.org/10.1007/s00382-015-2787-7

Kersalé, M., Meinen, C. S., Perez, R. C., Le Hénaff, M., Valla, D., Lamont, T., et al. (2020). Highly variable upper and abyssal overturning cells in the South Atlantic. *Science Advances*, *6* (32), eaba7573. https://doi.org/10.1126/sciadv.aba7573

Little, C. M., Hu, A., Hughes, C. W., McCarthy, G. D., Piecuch, C. G., Ponte, R. M., & Thomas, M. D. (2019). The relationship between United States East Coast sea level and the Atlantic meridional overturning circulation: A review. *Journal of Geophysical Research: Oceans*, *124*, 6435–6458. https://doi.org/10.1029/2019JC015152

Lozier, M. S., Li, F., Bacon, S., Bahr, F., Bower, A. S., Cunningham, S. A., et al. (2019). A sea change in our view of overturning in the subpolar North Atlantic. *Science*, *363* (6426), 516–521. https://doi.org/10.1126/science.aau6592

McCarthy, G. D., Brown, P. J., Flagg, C. N., Goni, G., Houpert, L., Hughes, C. W., et al. (2020). Sustainable observations of the AMOC: Methodology and technology. *Reviews of Geophysics*, *58*, e2019RG000654. https://doi.org/10.1029/2019RG000654

Moat, B. I., Smeed, D. A., Frajka-Williams, E., Desbruyeres, D. G., Beaulieu, C., Johns, W. E., et al. (2020). Pending recovery in the strength of the meridional overturning circulation at 26°N. *Ocean Science*, *16*, 863–874. https://doi.org/10.5194/os-16-863-2020

Moffa-Sánchez, P., Moreno-Chamarro, E., Reynolds, D. J., Ortega, P., Cunningham, L., Swingedouw, D., et al. (2019). Variability in the northern North Atlantic and Arctic oceans across the last two millennia: A review. *Paleoceanography and Paleoclimatology*, *34*, 1399–1436. https://doi.org/10.1029/2018PA003508

NRC: National Research Council Committee on Abrupt Climate Change (2002). *Abrupt climate change: Inevitable surprises*. Washington DC: National Academy Press.

NSTC Joint Subcommittee on Ocean Science and Technology (JSOST). (2007). *Charting the course for ocean science in the United States for the next decade: An ocean research priorities plan and implementation strategy*. Washington, DC: USGCRP/CCSP Office.

Pörtner, H.-O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, et al. (Eds.). (2019). IPCC special report on the ocean and cryosphere in a changing climate. Cambridge, UK and New York, NY: Cambridge University Press.

Stommel, H. (1961). Thermohaline circulation with two stable regimes of flow. *Tellus*, *13*, 224–230. https://doi.org/10.1111/j.2153-3490.1961.tb00079.x

Thornalley, D. J. R., Oppo, D. W., Ortega, P., Robson, J. I., Brierly, C. M., Davis, R., et al. (2018). Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150 years. *Nature*, *556*, 227–230. https://doi.org/10.1038/s41586-018-0007-4

Weijer, W., Cheng, W., Drijfhout, S. S., Federov, A. V., Hu, A., Jackson, L. C., et al. (2019). Stability of the Atlantic meridional overturning circulation: A review and synthesis. *Journal of Geophysical Research: Oceans*, *124*, 5336–5375. https://doi.org/10.1029/2019JC015083

Zhang, R., Sutton, R., Danabasoglu, G., Kwon, Y. -O., Marsh, R., Yeager, S. G., et al. (2019). A review of the role of the Atlantic meridional overturning circulation in Atlantic multidecadal variability and associated climate impacts. *Reviews of Geophysics*, *57*, 316–375. https://doi.org/10.1029/2019RG000644