An Overview of
The U.S. AMOC Science Team:
Accomplishments and Challenges

Gokhan Danabasoglu
National Center for Atmospheric Research
Science Team Chair

NASA Earth Science Division
NOAA Climate Program Office
NSF Geosciences Program
U.S. Department of Energy Office of Science

An U.S. Inter-Agency Program
Outline

• Background on Science Team (ST) history, objectives, and organization;
• Recent activities;
• Accomplishments and challenges;
• Some thoughts on the future ....

• Strong collaborations / partnerships with the international community, particularly with the UK RAPID Program,
• The Science Team is sunsetting at the end of 2020.
U.S. AMOC Program

- January 2007: AMOC was identified as a near-term priority by the Joint Subcommittee on Ocean Science and Technology (JSOST).
- October 2007: U.S. AMOC Implementation Plan was released.
- March 2008: U.S. AMOC Science Team was formed.
- Since 2009, 7 national and 4 international meetings were held.
- Order 200 AMOC-related projects have been supported by the four agencies.
U.S. AMOC Program Scientific Objectives

• Implementation and evaluation of AMOC observing system;
• Assessment of AMOC state, variability, and change;
• Assessment of AMOC variability mechanisms and predictability;
• Assessment of the role of AMOC in global climate and ecosystems; and
• Fostering cross-disciplinary collaborations among paleo scientists with the modern AMOC community.
U.S. AMOC Program Organization

Science Team: PIs, co-Is, post-docs, and students performing AMOC-relevant research designated by the funding agencies

Executive Committee
Gokhan Danabasoglu
Chair
TT Chairs and Vice Chairs

TT1
AMOC observing system implementation and evaluation
Magdalena Andres, Kathleen Donohue

TT2
AMOC state, variability, and change
Zoltan Szuts, Claudia Schmid

TT3
AMOC mechanisms and predictability
Michael Spall, Aixue Hu

TT4
Climate sensitivity to AMOC: Climate / ecosystem impacts
Chris Little

TT5
Paleo AMOC
Hali Kilbourne, Alan Wanamaker

TT: Task Team
US AMOC Science Team

Sunset Plans

Sunsetting at the end of 2022
Maintaining momentum beyond.....

**COLLABORATION**
- Convene science meetings (2018, 2020) and coordinate conference sessions
- Organize a Paleo AMOC Task Team
- Transition current program-to-program collaborations (e.g., with UK RAPID-AMOC, EU AtlantOS) to US and International CLIVAR

**PRIORITIES**
1. Revise near- and long-term priorities to reflect ongoing research needs extending beyond the Science Team
2. Distill a set of programmatic action items to be completed through 2020
3. Establish the pathway for transitioning components of the AMOC observing system from research to sustained

**LEGACY PRODUCTS**
- Produce capstone special journal collection, including review/synthesis and science papers
- Produce white paper(s) regarding AMOC observing requirements for Ocean Obs’19
- Produce metrics for bridging the evaluation of model simulations, reanalyses, and observations
- Produce analyses of CMIP6 and CORE simulations of AMOC
- Issue final US AMOC Science Team report
- Complete bibliometrics of US AMOC Science Team research

**COMMUNICATION**
- Inform the community of the sunset plans, including a town hall at 2020 Ocean Sciences Meeting
- Include discussion of Science Team wrap-up in final two reports
- Prepare timeline graphic showcasing activities for 2018-2020 with indication of ongoing activities beyond
- Prepare graphics highlighting Science Team accomplishments
- Develop an AMOC website structure to showcase accomplishments/legacy using the above content
- Create a general AMOC listserv for the community
Final report will be published in 2022
AGU Virtual Special Issue on
Atlantic Meridional Overturning Circulation: Reviews of Observational and Modeling Advances

A Review of the Role of the Atlantic Meridional Overturning Circulation in Atlantic Multidecadal Variability and Associated Climate Impacts
Rong Zhang, Rowan Sutton, Gokhan Danabasoglu, Young-Chi Kwon, Robert Marsh, Stephen G. Yeager, Daniel E. Amrhein, Christopher M. Little
Reviews of Geophysics | First Published: 29 April 2019

Variability in the Northern North Atlantic and Arctic Oceans Across the Last Two Millennia: A Review
Paleoceanography and Palaeoclimatology | First Published: 18 June 2019

Stability of the Atlantic Meridional Overturning Circulation: A Review and Synthesis
Journal of Geophysical Research: Oceans | First Published: 24 July 2019

Recent Contributions of Theory to Our Understanding of the Atlantic Meridional Overturning Circulation
Helen L. Johnson, Paola Cessi, David P. Marshall, Fabian Schlosser, Michael A. Spall
Journal of Geophysical Research: Oceans | First Published: 06 August 2019

The Mean State and Variability of the North Atlantic Circulation: A Perspective From Ocean Reanalyses
Journal of Geophysical Research: Oceans | First Published: 06 November 2019

Sustainable Observations of the AMOC: Methodology and Technology
Reviews of Geophysics | First Published: 23 November 2019

Lagrangian Views of the Pathways of the Atlantic Meridional Overturning Circulation
A. Bower, S. Lozier, A. Blastock, K. Drouin, N. Foukal, H. Furey, M. Lankhorst, S. Ruhls, S. Zou
Journal of Geophysical Research: Oceans | First Published: 19 July 2019

The Relationship Between U.S. East Coast Sea Level and the Atlantic Meridional Overturning Circulation: A Review
Christopher M. Little, Aixue Hu, Chris W. Hughes, Gerard D. McCarthy, Christopher G. Prieur, Rui M. Ponte, Matthew D. Thomas
Journal of Geophysical Research: Oceans | First Published: 09 August 2019

The Atlantic meridional overturning circulation in high resolution models
Journal of Geophysical Research: Oceans | First Published: 27 January 2020
Atlantic Meridional Overturning Circulation: Reviews of Observational and Modeling Advances—An Introduction

Meric Srokosz1, Gokhan Danabasoglu2, and Michael Patterson3

1National Oceanographic Centre, Southampton, UK, 2National Center for Atmospheric Research, Boulder, CO, USA, 3US 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 JOSST, 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
AMOC Webinars

US AMOC and UK RAPID have organized a webinar series to share summaries of the papers published in the AGU special collection with the broad international ocean and climate science community. The webinars are held on the third Thursday of every month @ 11am EDT/3pm GMT. See below for the complete schedule of talks. If you are interested in attending these monthly webinars and wish to receive webinar notifications, consider signing up for the mailing list.

Learn more about the different US CLIVAR webinar series and instructions on how to join a webinar.

May 21, 2020
A Review of the Role of the Atlantic Meridional Overturning Circulation in Atlantic Multidecadal Variability and Associated Climate Impacts
Presenter: Rong Zhang (NOAA GFDL) (Recording)
Co-authors: Rowan Sutton, Golshan Danabasoglu, Young-Oh Kwon, Robert Marsh, Stephen Yeager, Daniel Amarhein, Christopher Little

June 18, 2020
Stability of the Atlantic Meridional Overturning Circulation: A Review and Synthesis
Presenter: Wilbert Weijer (LANL) (Recording)
Co-authors: Wei Cheng, Sybren Drifhout, Alexey Fedorov, Aixue Hu, Laura Jackson, Wei Liu, Elaine McDonagh, Jennifer Mecking, Jiakun Zhu

July 16, 2020
The Mean State and Variability of the North Atlantic Circulation: A Perspective From Ocean Reanalyses
Presenter: Laura Jackson (UK Met Office) (Recording)
Co-authors: Clotilde Dubois, Gael Forget, Keith Haines, Matthew Harrison, Doroteaciro Iovino, Armin Köh, Davi Mignac, Simona Masina, Kinley Pfenninger, Andrew Peterson, Christopher Piccucci, Chris Roberts, Jon Robson, Andrea Storto, Takahiro Toyoda, Maria Valdivieso, Chris Wilson, Yiguo Wang, Hao Zuo

August 20, 2020
No webinar

September 17, 2020
Lagrangian Views of the Pathways of the Atlantic Meridional Overturning Circulation
Presenter: Amy Bower (WHOI) (Recording)
Co-authors: Susan Gazier, Arno Blaastoch, Kimberly Drouin, Nicholas Foulak, Heather Furey, Matthias Lankhorst, Siren Rühs, Sijia Zou

October 15, 2020
Sustainable Observations of the AMOC: Methodology and Technology
Presenter: Gerard McCarthy (ICARUS, Maynooth University) (Recording)
Co-authors: Peter Brown, Charles Fagg, Gustavo Goni, Leic Houpert, Chris Hughes, Rebecca Hummels, Mark Inall, Kerstin Jochumsen, Karin Margrethe Larsen, Pascale Lhermitte, Christopher Meinen, Ben Moat, Darren Rayner, Monika Rhein, Achim Roessler, Claudia Schmid, David Smeed

November 20, 2020
Variability in the Northern North Atlantic and Arctic Oceans across the Last Two Millennia: A Review
Presenter: Paola Moffa-Sanchez (Durham University) (Recording)
Co-authors: Eduardo Moreno-Chamorro, David Reynolds, Pablo Ortega, Laura Kay Cunningham, Didier Swingedouw, Daniel Arrhenius, Jochen Halfar, Lukas Jonkers, Johann Jungclaus, Kerstin Perner, Alan Wanamaker, Stephen Yeager

February 18, 2021
The Relationship Between U.S. East Coast Seafloor and the Atlantic Meridional Overturning Circulation: A Review
Presenter: Christopher Little (Atmospheric and Environmental Research) (Recording)
Co-authors: Aixue Hu, Chris Hughes, Gerard McCarthy, Christopher Piccucci, Rui Ponte, Matthew Thomas

March 18, 2021
The Atlantic Meridional Overturning Circulation in High Resolution Models
Presenter: Joel Hirschi (National Oceanography Centre) (Recording)
Co-authors: Bernard Barnier, Claus Böing, Arne Biaosto, Adam Blaker, Andrew Coward, Sergey Danilov, Sybren Drifhout, Klaus Getzlaff, Stephen Griffies, Hiroiyasu Hamil, Helene Hewitt, Doroteaciro Iovino, Takao Kawasaki, Andrew Kiss, Nikolay Koldunov, Alice Marzocchi, Jennifer Mecking, Ben Moat, Jean-Marc Molines, Paul Myers, Thierry Puffuff, Malcolm Roberts, Anne-Marie Treguir, Dmitrey Stein, Dmitry Siderenka, Justin Small, Paul Spence, Laura Thompson, Wilbert Weijer, Xiaoxiao Xu

April 15, 2021
No webinar

May 20, 2021
Recent Contributions of Theory to Our Understanding of the Atlantic Meridional Overturning Circulation
Presenter: Helen Johnson (University of Oxford) (Recording)
Co-authors: Paola Cessi, David Marshall, Fabian Schlosser, Michael Spall

June 17, 2021
Perspectives on the Atlantic Meridional Overturning Circulation (AMOC) system: Linking historical and modern views of AMOC
Presenter: Hall Kilbourne (University of Maryland Center for Environmental Science) (Recording)
Co-authors: Al Wamamaker, Dan Arrhenius, Marius Goes, Malte Jansen, Alia G. Cage, Jake Gebbie, Alexandra Jahn, Wei Liu, Madelyn Mette, Carrie Morrill, Lisa N. Murphy, Tom Rossby, Noah Rosenberg, Nina Whitney

Available from the US CLIVAR ST website
1055 live participants
4500+ total views on YouTube (to date)
Atlantic Meridional Overturning Circulation: Observed Transport and Variability

Eleanor Frajka-Williams, Isabelle J. Ansorge, Johanna Baeehr, Harry L. Bryden, Maria Paz Chichich trio, Stuart A. Cunningham, Golshan Danabasoglu, Shenju Dong, Kathleen A. Donovan, Shane Elipot, Patrick Heimbach, N. Penny Holloway, Rebecca Hummels, Laura C. Jackson, Johanna Karstenrock, Matthias Larkhorst, Isabela A. Le Bras, Noam Susan Lozier, Elaine L. McDonagh, Christopher S. Meinen, Herli Herrera-Mercier, Benjamin I. Moat, Renelly C. Perez, Christopher G. Picasso, Monika Riebes, Meric A. Stroczek, Kevin E. Tremblay, Sheldon Bacon, Grant Forget, Gustavo Goni, Dagmar Kleek, Jannes Koelling, Taron Lamont, Gerard O. McCarthy, Christian Metzner, Uwe Send, David A. Smeed, Sabrina Speich, Marcial van den Berg, Denise Volkov and Chris Wilson

OPEN ACCESS

Edited by: Fei Chi, Second Institute of Oceanography, China
Reviewed by: Fei Chi, University of California, Los Angeles, United States
Helen Elizabeth Phillips, University of Tasmania, Australia, Wian Zhou Zhang, Xi’an University, China
Correspondence: Eleanor Frajka-Williams

Speciality section: This article was submitted to Ocean Observation, a section of the journal Frontiers in Marine Science

Received: 15 November 2018

Challenges and Prospects in Ocean Circulation Models


Edited by: Xavier Che, Japanese Agency for Marine-Earth Science and Technology, Japan
Reviewed by: Fabien Roquet, University of Gothenburg, Sweden Markku Jokela, National Bureau of Investigation, Finland
Correspondence: Baylor Fox-Kemper

Published: 28 February 2019 doi: 10.3389/fmars.2019.00066
The RAPID/MOCHA time series: 2004-2020

Major findings

• Large short-term AMOC variability

• Abrupt AMOC downturn in 2009-2010
  \[\Rightarrow\] Impacts on mid-latitude heat content

• Sustained AMOC reduction since 2004-2008
  \[\Rightarrow\] Impacts on subpolar gyre heat content

• Ocean meridional heat and freshwater transport highly correlated with AMOC variability

Slide: Bill Johns
MOVE at 16°N (Meridional Overturning Variability Experiment)

- Cold, southward limb of AMOC
- Observations started 2000
- Decadal variability
- Open questions:
  - Decadal trends not consistent with 26°N observations, but validated against GRACE
  - Assumptions and trends only partially reproduced by numerical models

Acknowledgements: MOVE was supported by NOAA GOMO (and the German BMBF in earlier years). Figures adapted from Send et al. (GRL, 2011)

New in 2022:
Reprocessed salinity data, possibly reducing discrepancies with 26°N observations
Pentadal, Decadal, and Multi-decadal Trends at MOVE and RAPID

Frajka-Williams et al. (2018)
MOVE: +8.1 Sv decade$^{-1}$
RAPID: -3.7 Sv decade$^{-1}$

Danabasoglu et al. (2021, GRL)
Overturning in the Subpolar North Atlantic Program (OSNAP)

Participants:
United States
United Kingdom
Germany
Netherlands
France
Canada

Over the OSNAP time period, the conversion of warm, salty, shallow Atlantic waters into colder, fresher, deep waters that move southward in the Irminger and Iceland basins is largely responsible for overturning and its variability in the subpolar basin.

RAFOS floats were released in deep subpolar boundary currents transporting overflow waters (DSOW, ISOW) to determine their spreading. Overflow water pathways are more boundary-trapped around Greenland than around the Reykjanes Ridge; floats were trapped in deep cyclones around the southern tip of Greenland; ISOW pathways mapped east and west of the Reykjanes Ridge.

The 30-day mean MOC from 2014 to 2018 is derived for the full array, the OSNAP West and OSNAP East subsections. This figure is adapted from Li et al. (2021).
Atlantic Deep Water Formation Occurs Primarily in the Iceland Basin and Irminger Sea by Local Buoyancy Forcing

Tillys Petit1, M. Susan Lozier2, Simon A. Josey7, and Stuart A. Cunningham1

Reconciling the Relationship Between the Labrador and Labrador Sea in OSNAP Observation and Climate Models

Matthew B. Menary1, Laura C. Jackson2,3,4, and M. Susan Lozier2

Resolution Dependence of Atmosphere–Ocean Interactions and Water Mass Transformation in the North Atlantic

Dylan Oldenburg1, Robert C. J. Wild2, Kyle C. Armour1,2, and LaAnne Thompson1

An outsize role for the Labrador Sea in the multidecadal variability of the Atlantic overturning circulation

Stephen Yeager1,2, Fred Castruccio1,2, Ping Chang2,3, Gokhan Danabasoglu1,2, Elizabeth Maroon, Justin Small1,2, Hong Wang2,5,6, Lixin Wu5,6, Shaoqing Zhang2,5,6
SAMBA: South Atlantic MOC Basin-wide Array (34.5°S)

Enhanced spatial resolution afforded by using nine SAMBA moorings from 2013-2017 allows observations of the variability of volume transports in both the upper and abyssal cells.
AMOC in Reanalysis Products

Mean over 1993-2010

Karspeck et al. (2016)

Mean over 1960-2007

Jackson et al. (2019)
AMOC in Reanalysis Products

Karspeck et al. (2016)

Jackson et al. (2019)
Many influences of winds in AMOC mean and variability have become much clearer ....

1. Southern Ocean winds close NADW and AABW overturning loops
2. Mid-latitude winds dominate MOC variability from seasonal to interannual time scales, a leading mechanism for upper ocean heat storage
3. Winds near Greenland force exchange of low salinity water with basin interiors
4. Cyclonic winds pre-condition deep convection sites
5. Beaufort Gyre winds impact storage and release of fresh water
6. Near equatorial winds force very strong, $O(100\ \text{Sv})$, high frequency overturning

Credit: Mike Spall and Aixue Hu
AMOC interactions with

- Surface ocean state (e.g., SSTs)
- Global atmospheric and ocean circulation
- Hydrological cycle
- Coupled phenomena (e.g., ENSO, monsoons)
- Cryosphere (sea and land ice)
- Offshore and coastal sea level
- Marine and terrestrial ecosystems, including marine extremes
- Carbon and biogeochemical cycles
Some Recent Things We Have Learned About AMOC

The Pacific/Arctic sector maybe more important than we thought for abrupt changes

Simulated AMOC is potentially biased towards a mono-stable state

Glacial AMOC was definitely shallow, changing global MOC

Heinrich Events are not all the same

Holocene (Modern) and millennial-scale warm events (DO interstadials) recorded in Greenland

Glacial Maximum AMOC Shallow
Southern Source water (AABW) filled the basin

Heinrich Events; AMOC Off due to iceberg inputs

Figures from Lynch-Stieglitz (2017)
Observing the AMOC – the future

• Observing the AMOC, determining its meridional coherence, how it is changing over long times scales (decades), and the consequent impacts (weather, climate, sea level) continue to be a challenging problem.

• In addition to *in situ* observations, satellite observations (winds, sea level / sea surface height, ocean bottom pressure, SSS, and SST) can contribute.

• The overarching challenge is to build a sustained AMOC observing system.

From Meric Srokosz
Some thoughts.....

• Many unresolved issues remain....
• AMOC-related research will continue after the ST sunsets.
• Important elements of the ST that should continue include sustained observations, collaborations, coordination, and communication (at both national and international levels).
• Important to keep the efforts focused and identify emerging / future research directions.
• Move towards tight coordination (merging) of observational, modeling, and data assimilation efforts towards more process based understanding.
• We have formed an AMOC Task Team under the CLIVAR Atlantic Regional Panel (ARP) to coordinate and continue some aspects of AMOC-related efforts.
Thank you!

AMOC =