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~~. 2022

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

- Revise near- and long-term priorities to reflect ongoing research needs extending beyond the Science Team
- Distill a set of programmatic action items to be completed through 2020
- 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 showing 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

AGU100 ADVANCING EARTH AND SPACE SCIENCE

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-Oh 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

P. Moffa-Sánchez, E. Moreno-Chamarro, D. J. Reynolds, P. Ortega, L. Cunningham, D. Swingedouw, D. E. Amrhein, J. Halfar, L. Jonkers, J. H. Jungclaus, K. Perner, A. Wanamaker, S. Yeager

Paleoceanography and Paleoclimatology | First Published: 18 June 2019

Lagrangian Views of the Pathways of the Atlantic Meridional Overturning Circulation

A. Bower, S. Lozier, A. Biastoch, K. Drouin, N. Foukal, H. Furey, M. Lankhorst, S. Rühs, S. Zou

Journal of Geophysical Research: Oceans | First Published: 19 July 2019

Stability of the Atlantic Meridional Overturning Circulation: A Review and Synthesis

W. Weijer, W. Cheng, S. S. Drijfhout, A. V. Fedorov, A. Hu, L. C. Jackson, W. Liu, E. L. McDonagh, J. V. Mecking, J. Zhang

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 Schloesser, Michael A. Spall

Journal of Geophysical Research: Oceans | First Published: 06 August 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. Piecuch, Rui M. Ponte, Matthew D. Thomas

Journal of Geophysical Research: Oceans | First Published: 09 August 2019

The Mean State and Variability of the North Atlantic Circulation: A Perspective From Ocean Reanalyses

L. C. Jackson, C. Dubois, G. Forget, K. Haines, M. Harrison, D. Iovino, A. Köhl, D. Mignac, S. Masina, K. A. Peterson, C. G. Piecuch, C. D. Roberts, J. Robson, A. Storto, T. Toyoda, M. Valdivieso, C. Wilson, Y. Wang, H. Zuo

Journal of Geophysical Research: Oceans | First Published: 06 November 2019

Sustainable Observations of the AMOC: Methodology and Technology

G. D. McCarthy, P. J. Brown, C. N. Flagg, G. Goni, L. Houpert, C. W. Hughes, R. Hummels, M. Inall, K. Jochumsen, K. M. H. Larsen, P. Lherminier, C. S. Meinen, B. I. Moat, D. Rayner, M. Rhein, A. Roessler, C. Schmid, D. A. Smeed

Reviews of Geophysics | First Published: 23 November 2019

The Atlantic meridional overturning circulation in high resolution models

Joël J.-M. Hirschi, Bernard Barnier, Claus Böning, Arne Biastoch, Adam T. Blaker, Andrew Coward, Sergey Danilov, Sybren Drijfhout, Klaus Getzlaff, Stephen M. Griffies, Hiroyasu Hasumi, Helene Hewitt, Doroteaciro Iovino, Takao Kawasaki, Andrew E. Kiss, Nikolay Koldunov, Alice Marzocchi, Jennifer V. Mecking, Ben Moat, Jean-Marc Molines, Paul G. Myers, Thierry Penduff, Malcolm Roberts, Anne-Marie Treguier, Dmitry V. Sein, Dmitry Sidorenko, Justin Small, Paul Spence, LuAnne Thompson, Wilbert Weijer, Xiaobiao Xu

Journal of Geophysical Research: Oceans | First Published: 27 January 2020

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

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

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

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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

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 th broad international ocean and climate science community. The webinars are held on the third Thursday of every month @ 11am EDT/3pm 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, Gokhan Danabasoglu, Young-Oh Kwon, Robert Marsh, Stephen Yeager, Daniel Amrhein, 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 Drijfhout, Alexey Fedorovm, Aixue Hu, Laura Jackson, Wei Liu, Elaine McDonagh, Jennifer Mecking, Jiaxu Zha

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 Köhl, Davi Mignac, Simona Masina, K. Andrew Peterson, Christopher Piecuch, Chris Roberts, Jon Robson, Andrea Storto, Takahiro Toyoda, Maria Valdivieso, Chris Wilson, Yiguo W 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 Lozier, Arne Biastoch, Kimberley Drouin, Nicholas Foukal, 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 Flagg, Gustavo Goni, Loïc Houpert, Chris Hughes, Rebecca Hummels, Mark Inall, Kerstin Jochumsen, Karin Margretha Larsen, Pascale Lherminier, Christopher Meinen, Ben Moat, Darren Rayner, Monika Rhein, Achim Roessler, Claudia Schmid, David Smeed

November 19, 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-Chamarro, David Reynolds, Pablo Ortega, Laura Kay Cunningham, Didier Swingedouw, Daniel Amrhein, Jochen Halfar, Lukas Jonkers, Johann Jungclaus, Kerstin Perner, Alan Wanamaker, Stephen Yeager

February 18, 2021
The Relationship Between U.S. East Coast Sea Level 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 Piecuch, 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 Böning, Arne Biastoch, Adam Blaker, Andrew Coward, Sergey Danilov, Sybren Drijfhout, Klaus Getzlaff, Stephen Griffies, Hiroyasu Hasumi, Helene Hewitt, Doroteaciro Iovino, Takao Kawasaki, Andrew Kiss, Nikolay Koldunov, Alice Marzocchi, Jennifer Mecking, Ben Moat, Jean-Marc Molines, Paul Myers, Thierry Penduff, Malcolm Roberts, Anne-Marie Treguier, Dmitry Sein, Dmitry Sidorenko, Justin Small, Paul Spence, LuAnne Thompson, Wilbert Weijer, Xiaobiao 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 Schloesser, Michael Spall

June 17, 2021
Perspectives on the Atlantic Meridional Overturning Circulation (AMOC) system: Linking historical and modern views of AMOC
Presenter: Hali Kilbourne (University of Maryland Center for Environmental Science) (Recording)
Co-authors: Al Wanamaker, Dan Amrhein, Marlos Goes, Malte Jansen, Alix 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)

OCEAN OBS'19

AN OCEAN OF OPPORTUNITY

September 16-20, 2019

frontiers in Marine Science

REVIEW
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Atlantic Meridional Overturning Circulation: Observed Transport and Variability

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Challenges and Prospects in Ocean Circulation Models

Baylor Fox-Kemper[1*], Alistair Adcroft[2,3], Claus W. Böning[4], Eric P. Chassignet[5], Enrique Curchitser[6], Gokhan Danabasoglu[7], Carsten Eden[8], Matthew H. England[9], Rüdiger Gerdes[10,11], Richard J. Greatbatch[4], Stephen M. Griffies[2,3], Robert W. Hallberg[2,3], Emmanuel Hanert[12], Patrick Heimbach[13], Helene T. Hewitt[14], Christopher N. Hill[15], Yoshiki Komuro[16], Sonya Legg[2,3], Julien Le Sommer[17], Simona Masina[18], Simon J. Marsland[9,19,20], Stephen G. Penny[21,22,23], Fangli Qiao[24], Todd D. Ringler[25], Anne Marie Treguier[26], Hiroyuki Tsujino[27], Petteri Uotila[28] and Stephen G. Yeager[7]

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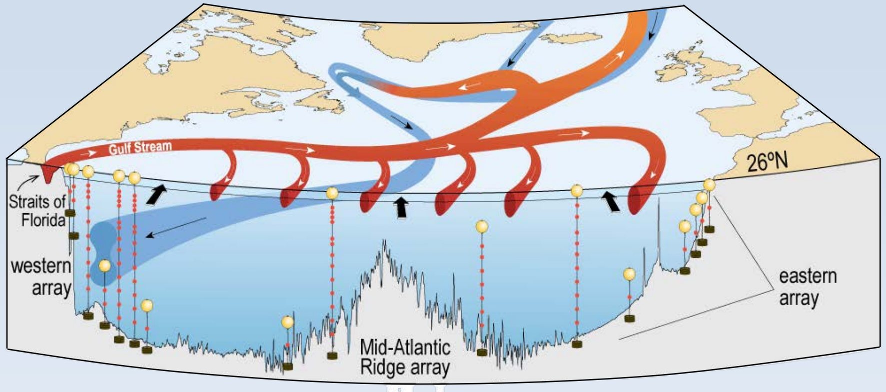
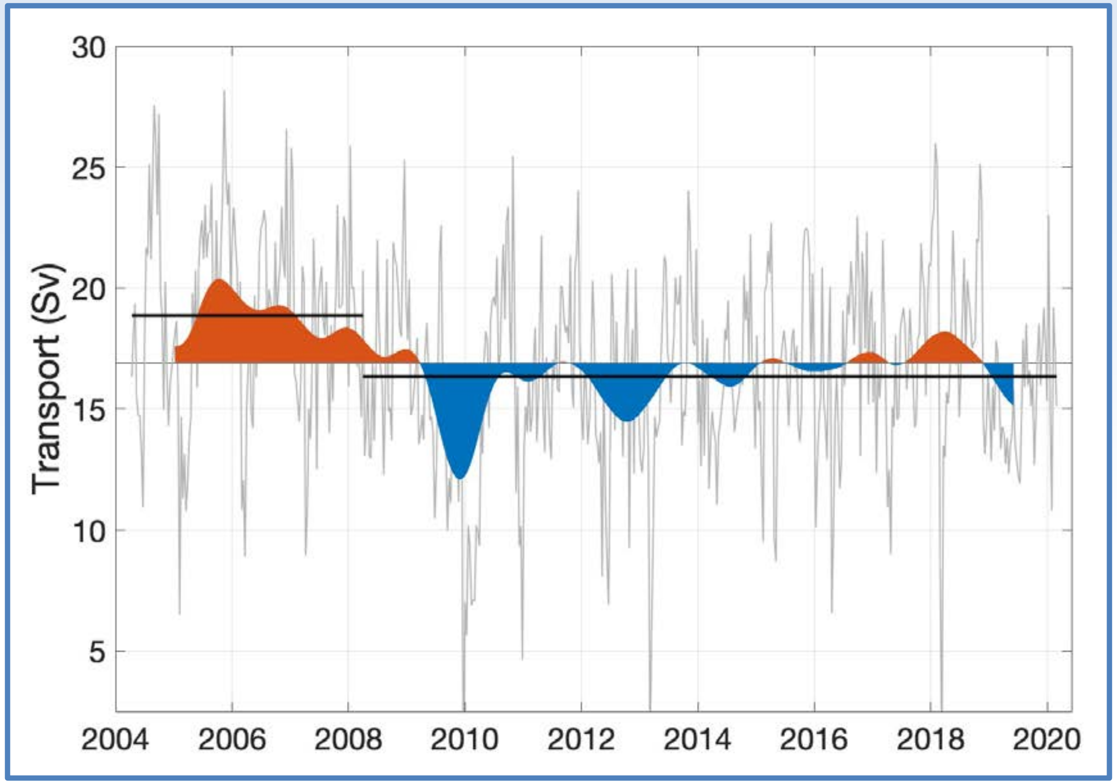
The RAPID/MOCHA time series: 2004-2020

Major findings

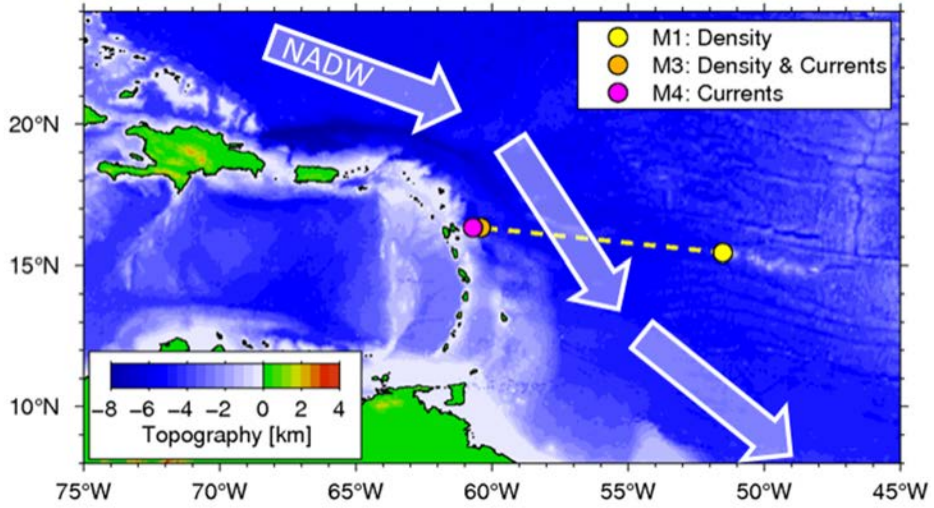
- Large short-term AMOC variability
- Abrupt AMOC downturn in 2009-2010
  ➡ Impacts on mid-latitude heat content
- Sustained AMOC reduction since 2004-2008 ➡ Impacts on subpolar gyre heat content
- Ocean meridional heat and freshwater transport highly correlated with AMOC variability



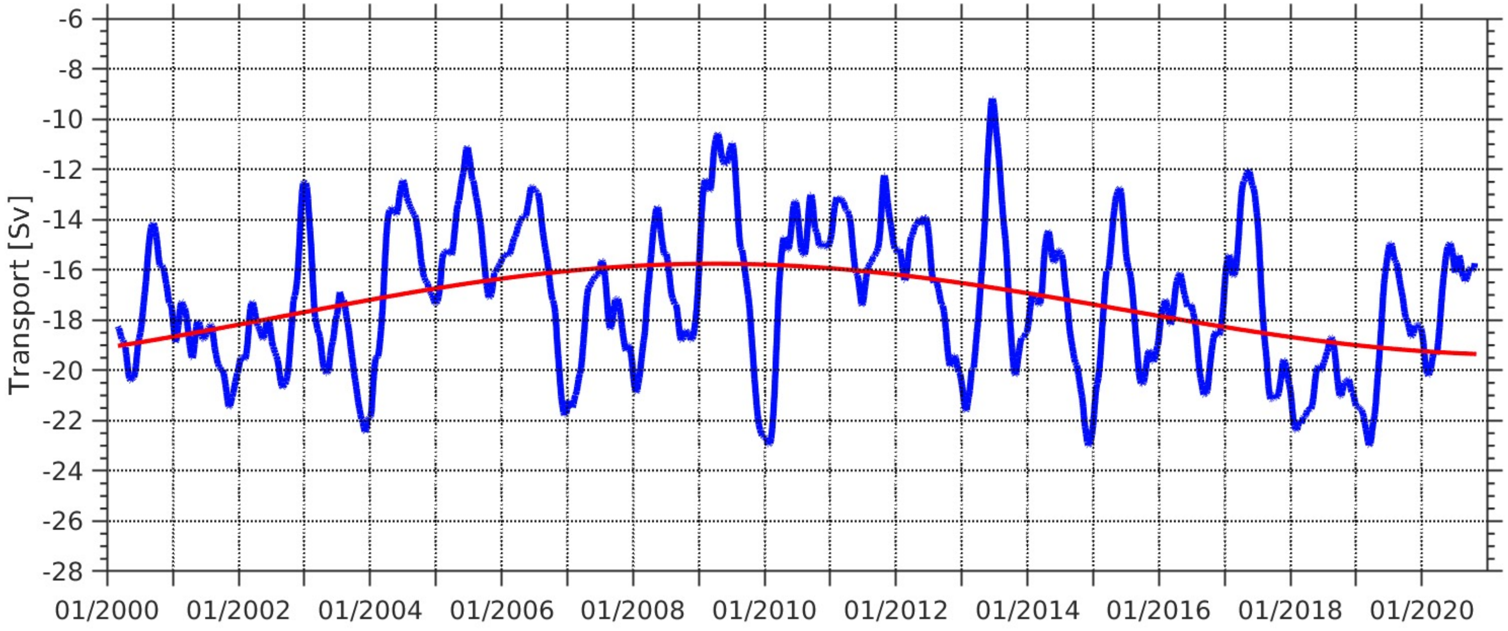


Slide: Bill Johns

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

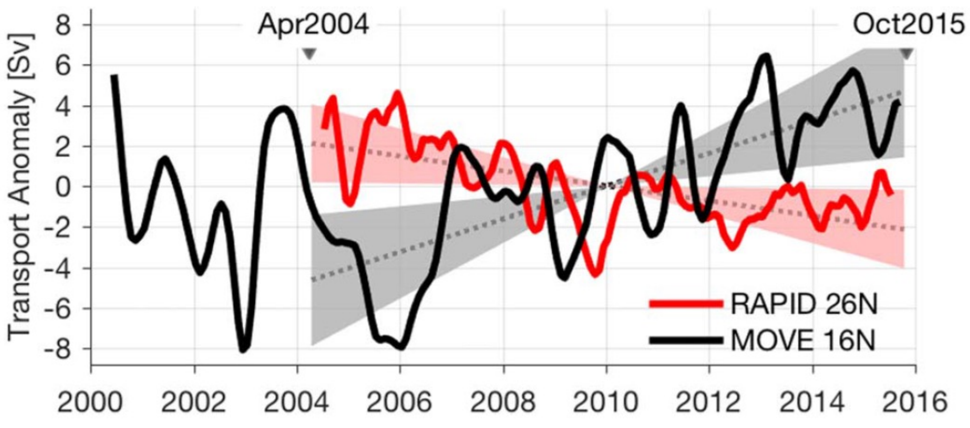


New in 2022:
Reprocessed salinity data, possibly reducing discrepancies with 26°N observations

Slide: Matthias Lankhorst

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

Pentadal, Decadal, and Multi-decadal Trends at MOVE and RAPID

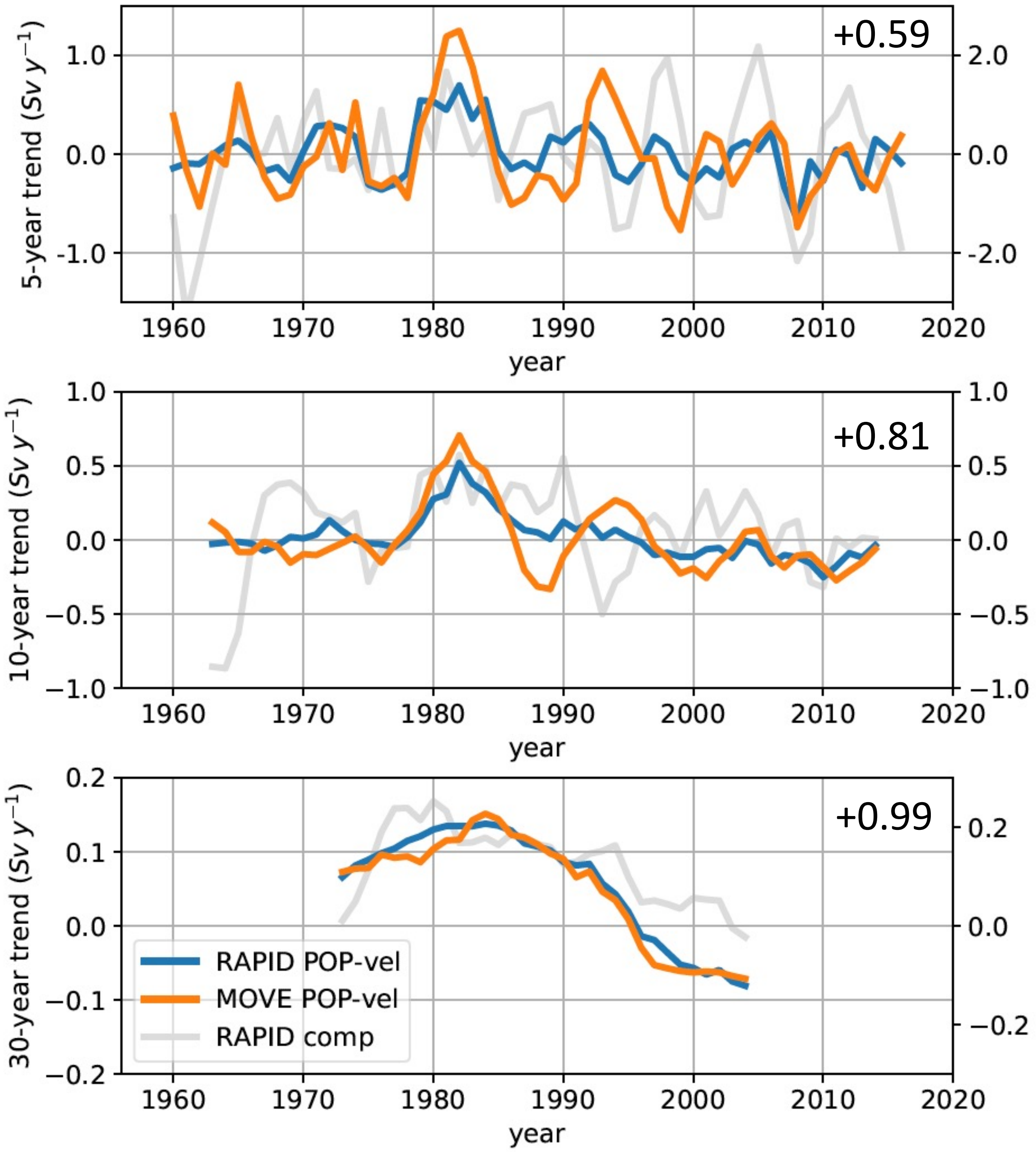


Frajka-Williams et al. (2018)
MOVE: +8.1 Sv decade^{-1}
RAPID: -3.7 Sv decade^{-1}

Sv decade^{-1}

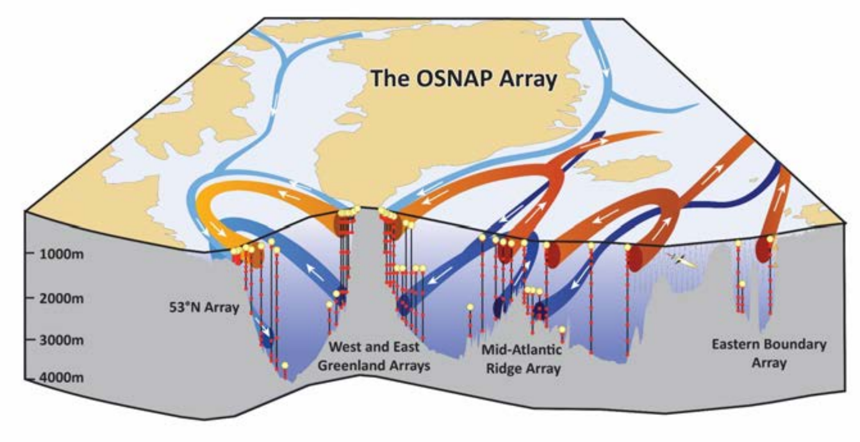
Trend Period	POP-vel RAPID	POP-RAPID	POP-vel MOVE	POP-MOVE	POP-MOVE-ref	POP-MOVE-td
2004-2015	–1.4	–1.7	–1.4	–2.0	–1.2	–2.5

Danabasoglu et al. (2021, GRL)

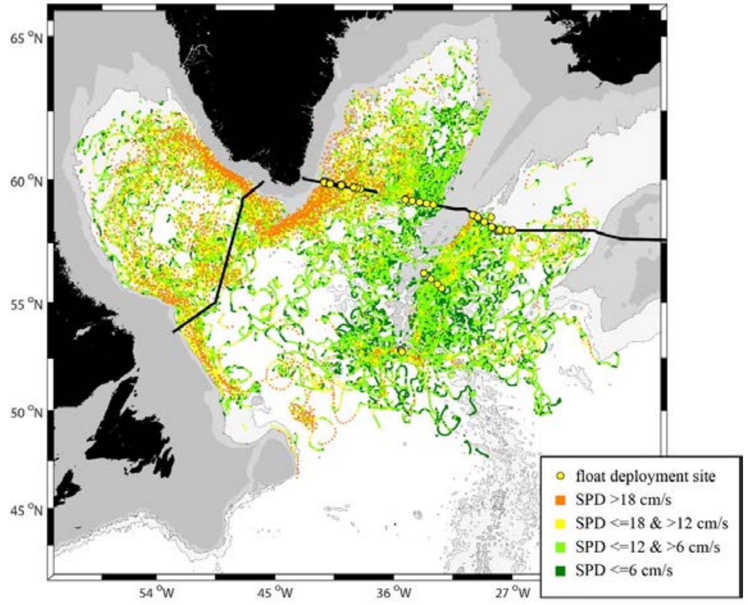


Overturning in the Subpolar North Atlantic Program (OSNAP)

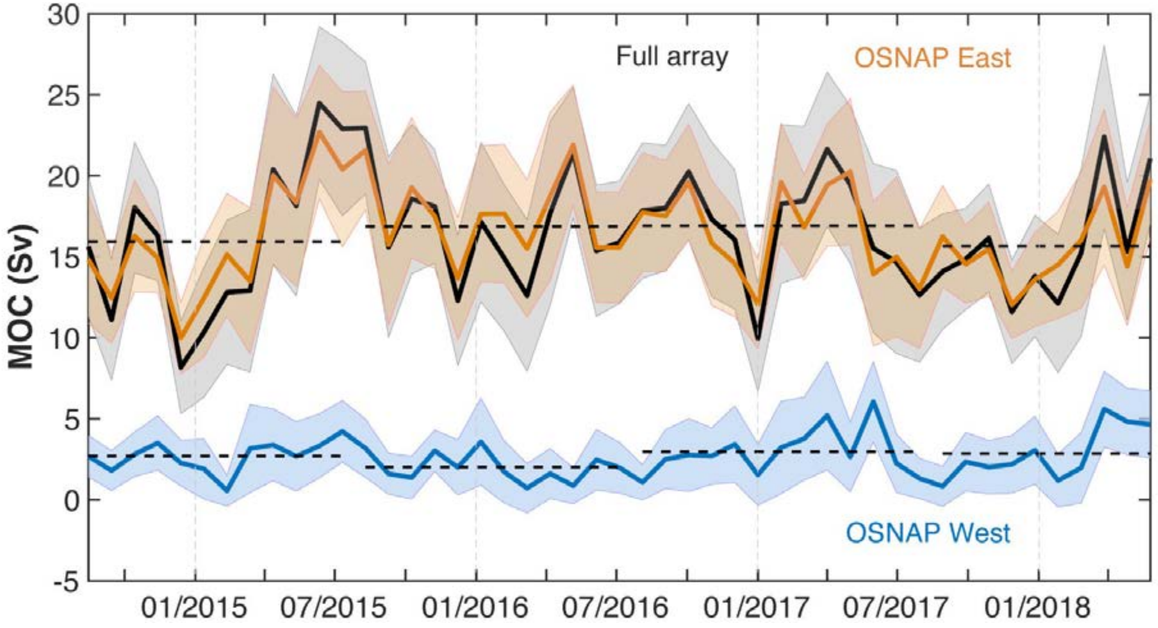
Participants:
United States
United Kingdom
Germany
Netherlands
France
Canada



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).

Slide: Heather Furey

Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL091028

Atlantic Deep Water Formation Occurs Primarily in the Iceland Basin and Irminger Sea by Local Buoyancy Forcing

Tillys Petit[1], M. Susan Lozier[1], Simon A. Josey[2], and Stuart A. Cunningham[3]

Key Points:
- New observations reveal Atlantic Subpolar Gyre deep water is formed primarily in the Irminger and Iceland basins by local buoyancy forcing
- The deep water formed by buoyancy forcing in winter is not entirely exported the following months; a portion is stored in those basins
- The transformation and subsequent export of deep water southward are twice as large in winter 2014–2015 than in winter 2015–2016

Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL089793

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

Matthew B. Menary[1], Laura C. Jackson[2], and M. Susan Lozier[3]

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Key Points:
- A coupled climate model shows agreement with recent observations (OSNAP), displaying a prominent role for the eastern subpolar gyre
- This model also demonstrates a link between AMOC and Labrador Sea densities, consistent with previous …

JGR Oceans

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

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Key Points:
- A high-resolution coupled simulation skillfully reproduces climatological water mass transformation in the subpolar North Atlantic
- Despite climatological differences between low- and high-resolution models, the Labrador Sea plays a major role in AMOC variability in both
- High-… a larg… low-f…

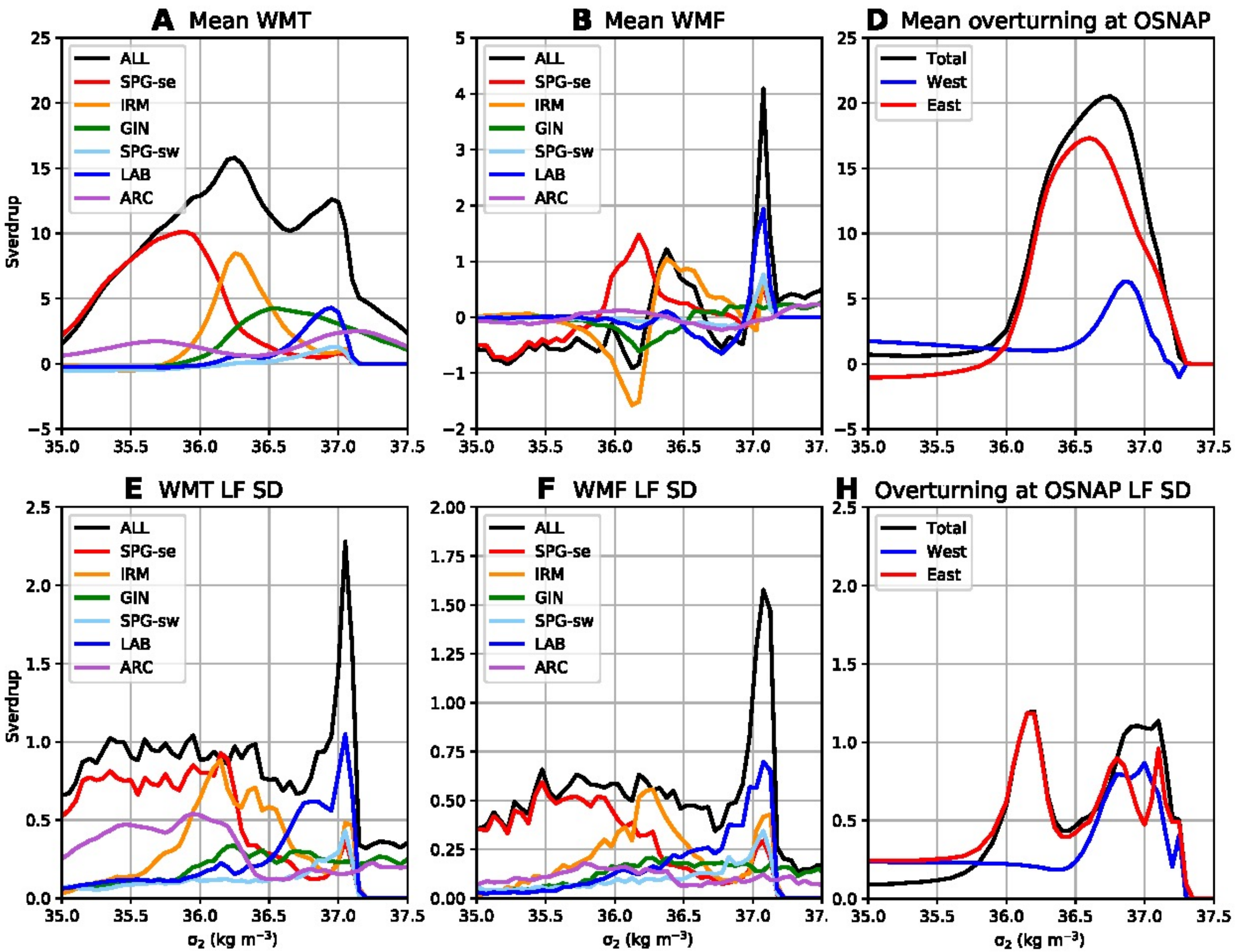
Abstract Water mass transformation (WMT) in the North Atlantic plays a key role in driving the Atl… Meridional Overturning Circulation (AMOC) and its variability. Here, we analyze subpolar North Atlanti…

SCIENCE ADVANCES | RESEARCH ARTICLE

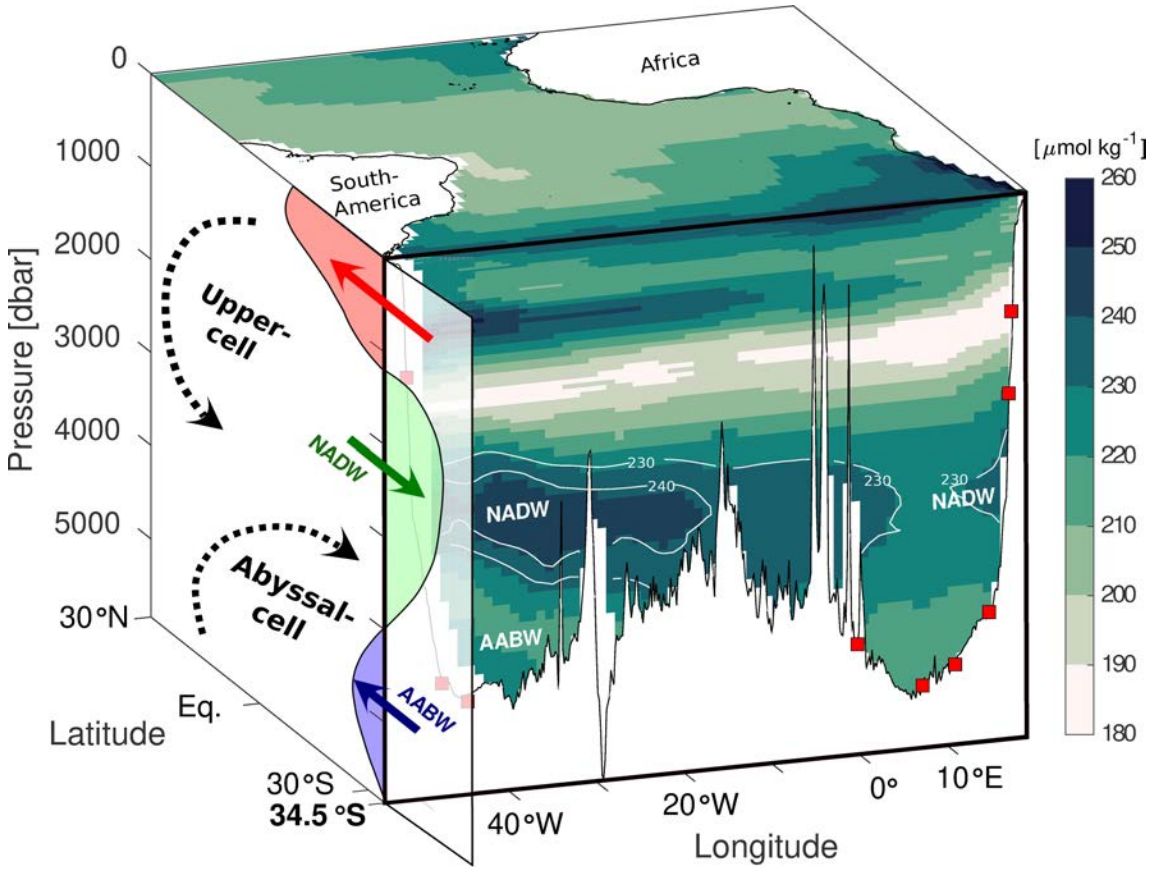
OCEANOGRAPHY

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

Stephen Yeager[1,2]*, Fred Castruccio[1,2], Ping Chang[2,3], Gokhan Danabasoglu[1,2], Elizabeth Maroon[4], Justin Small[1,2], Hong Wang[2,5,6], Lixin Wu[5,6], Shaoqing Zhang[2,5,6]

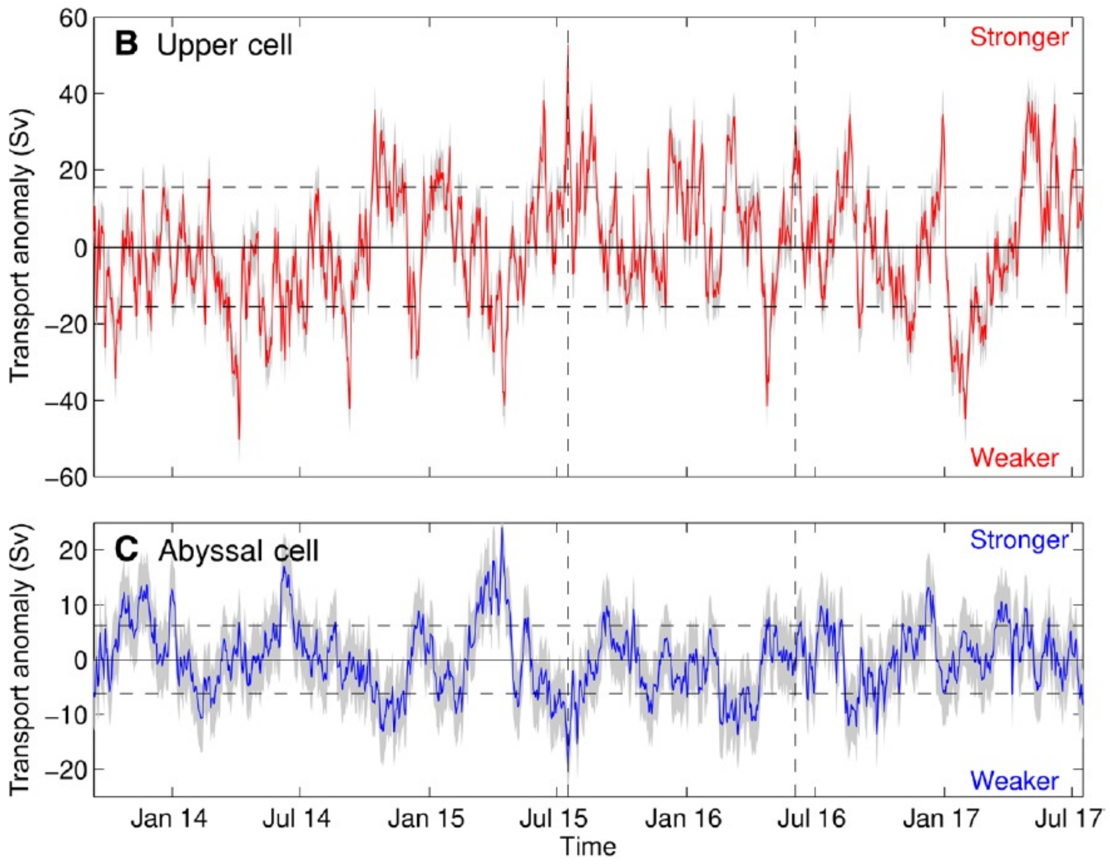


SAMBA: South Atlantic MOC Basin-wide Array (34.5°S)



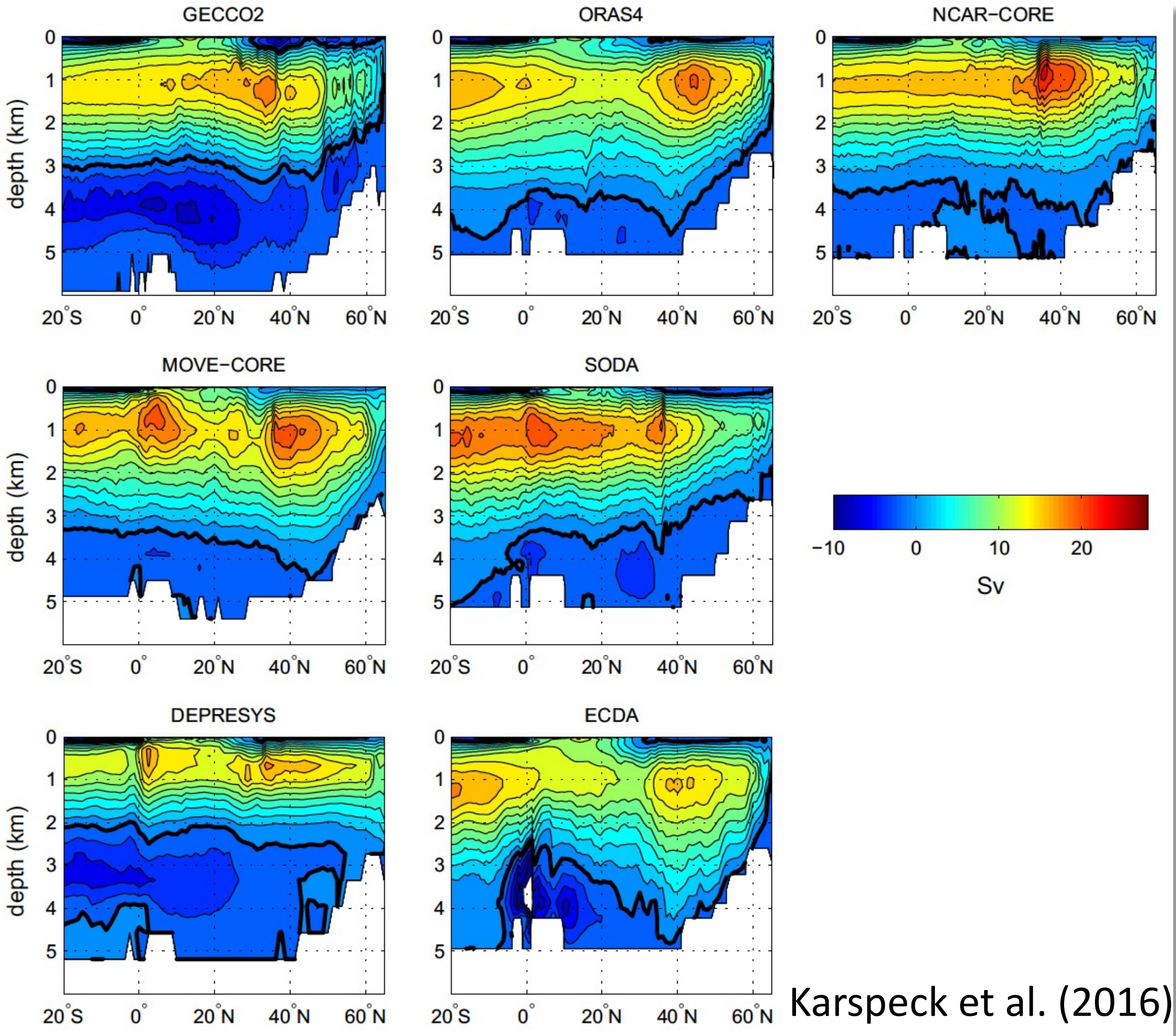
Kersalé et al. (2020)

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



Slide: Renellys Perez

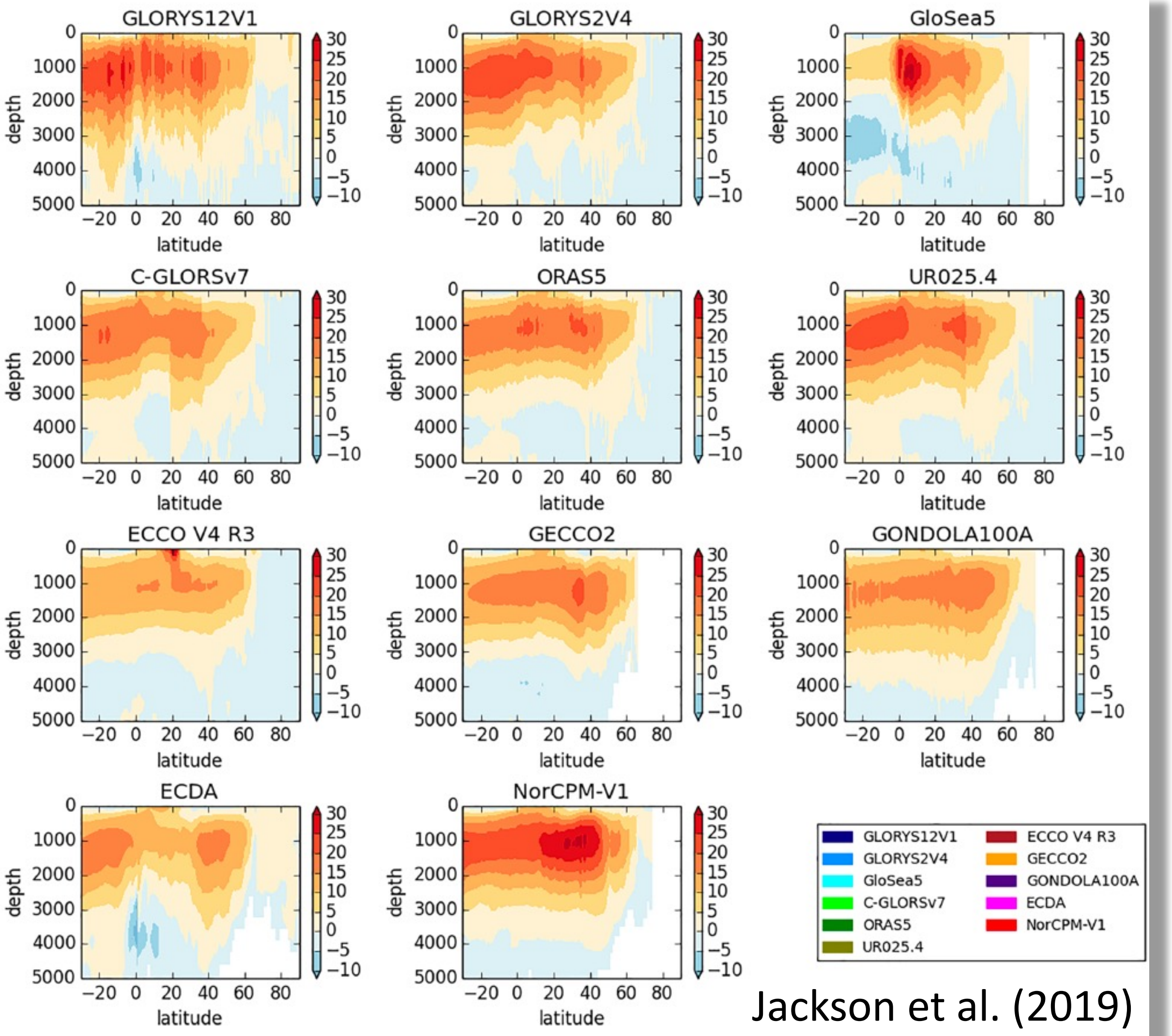
AMOC in Reanalysis Products



Karspeck et al. (2016)

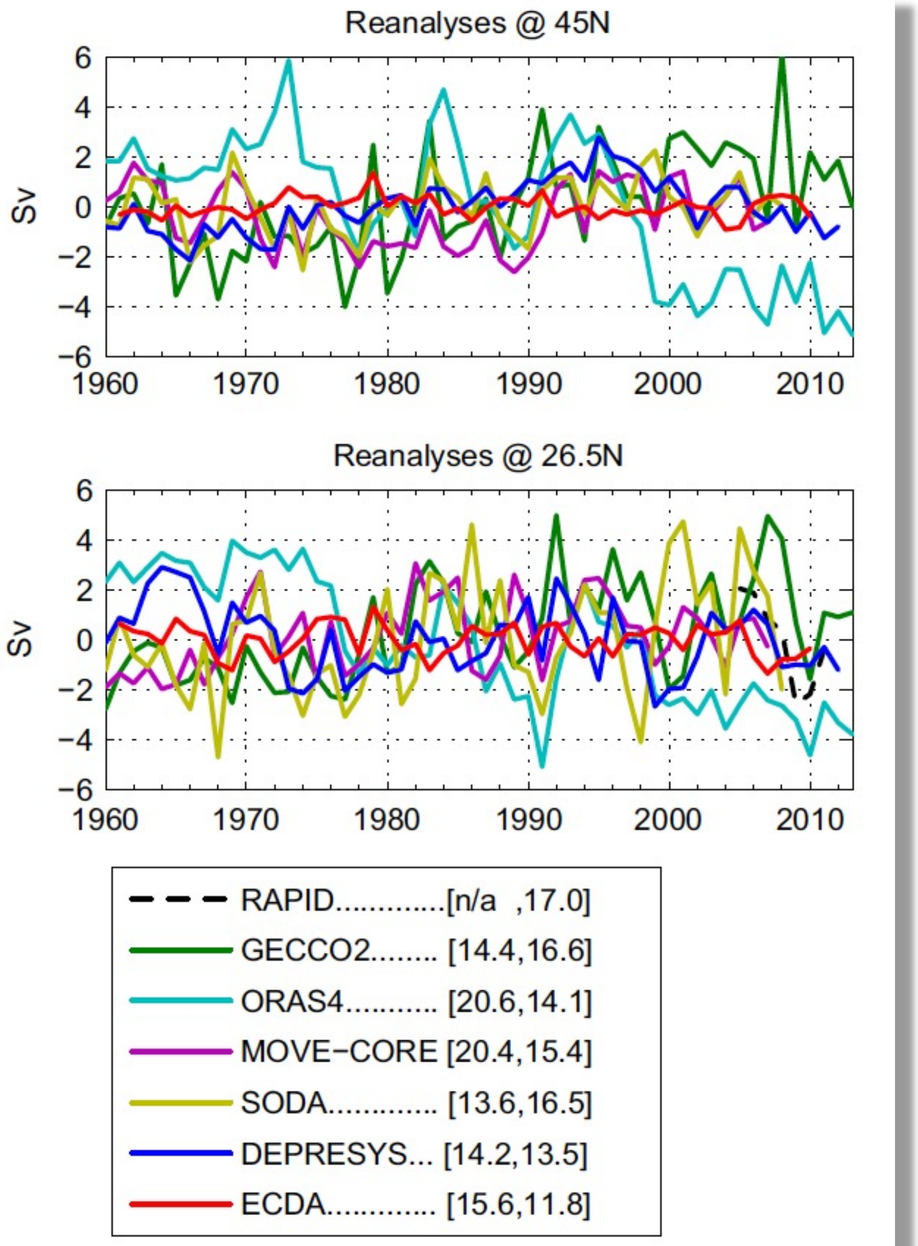
Mean over 1960-2007

Mean over 1993-2010

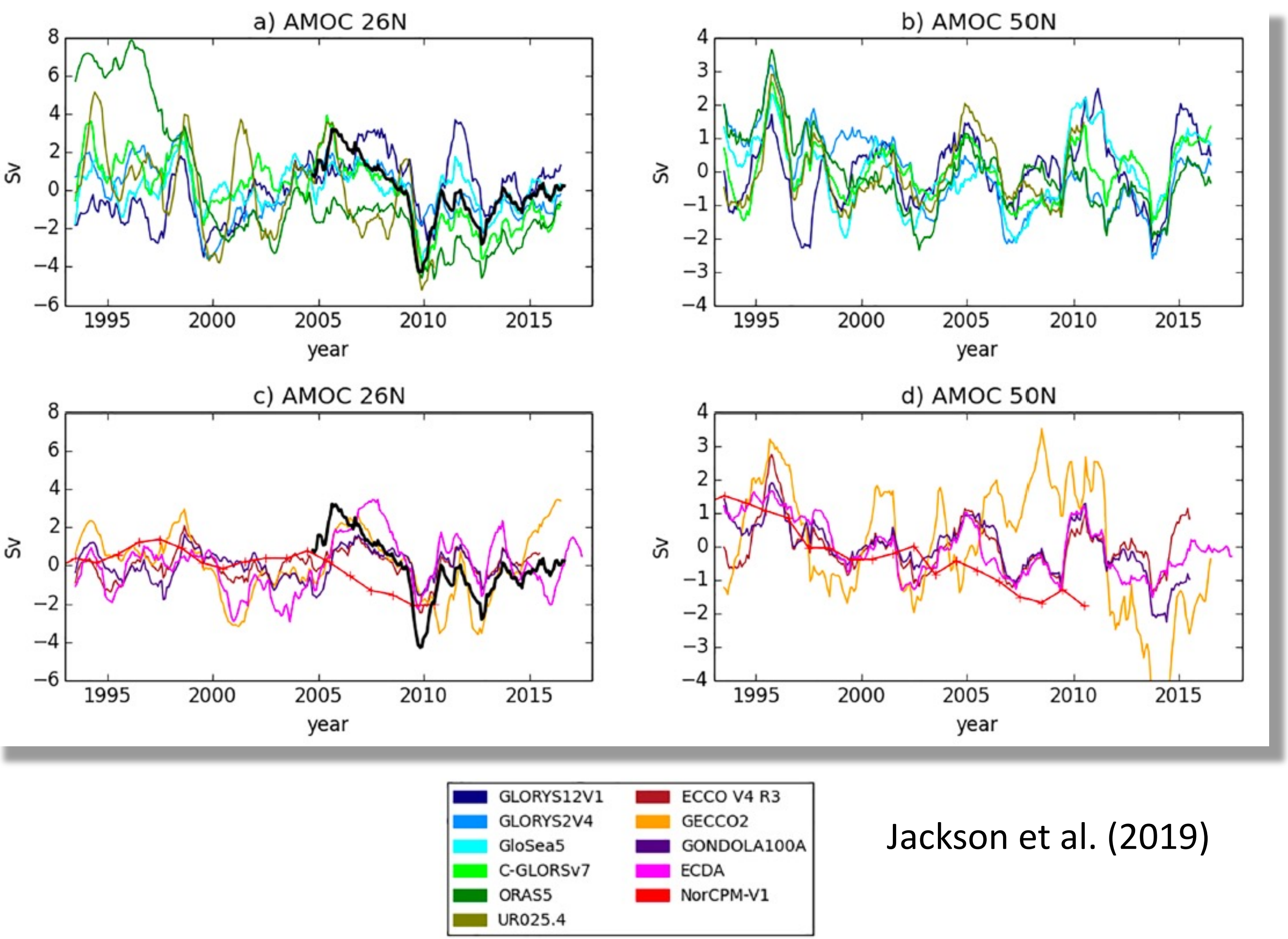


Jackson et al. (2019)

AMOC in Reanalysis Products



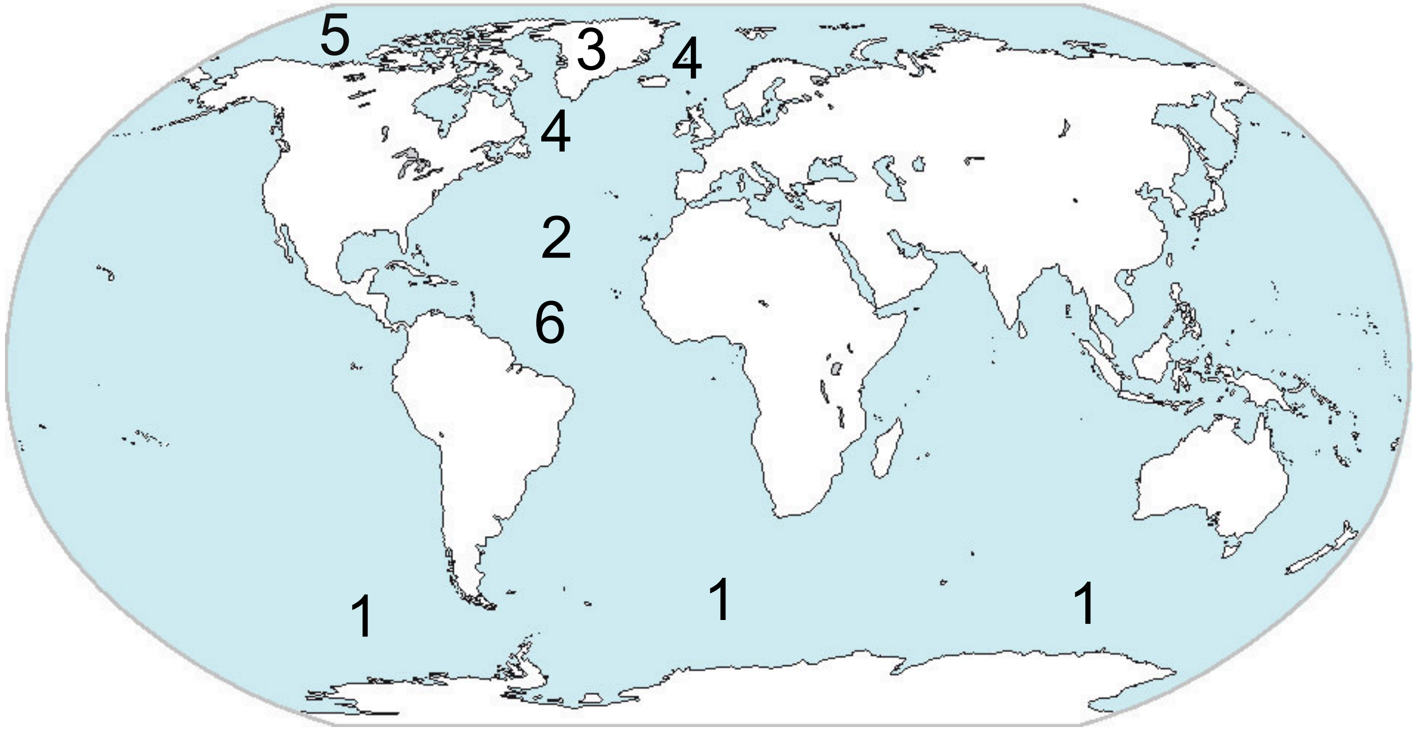
Karspeck et al. (2016)



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 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

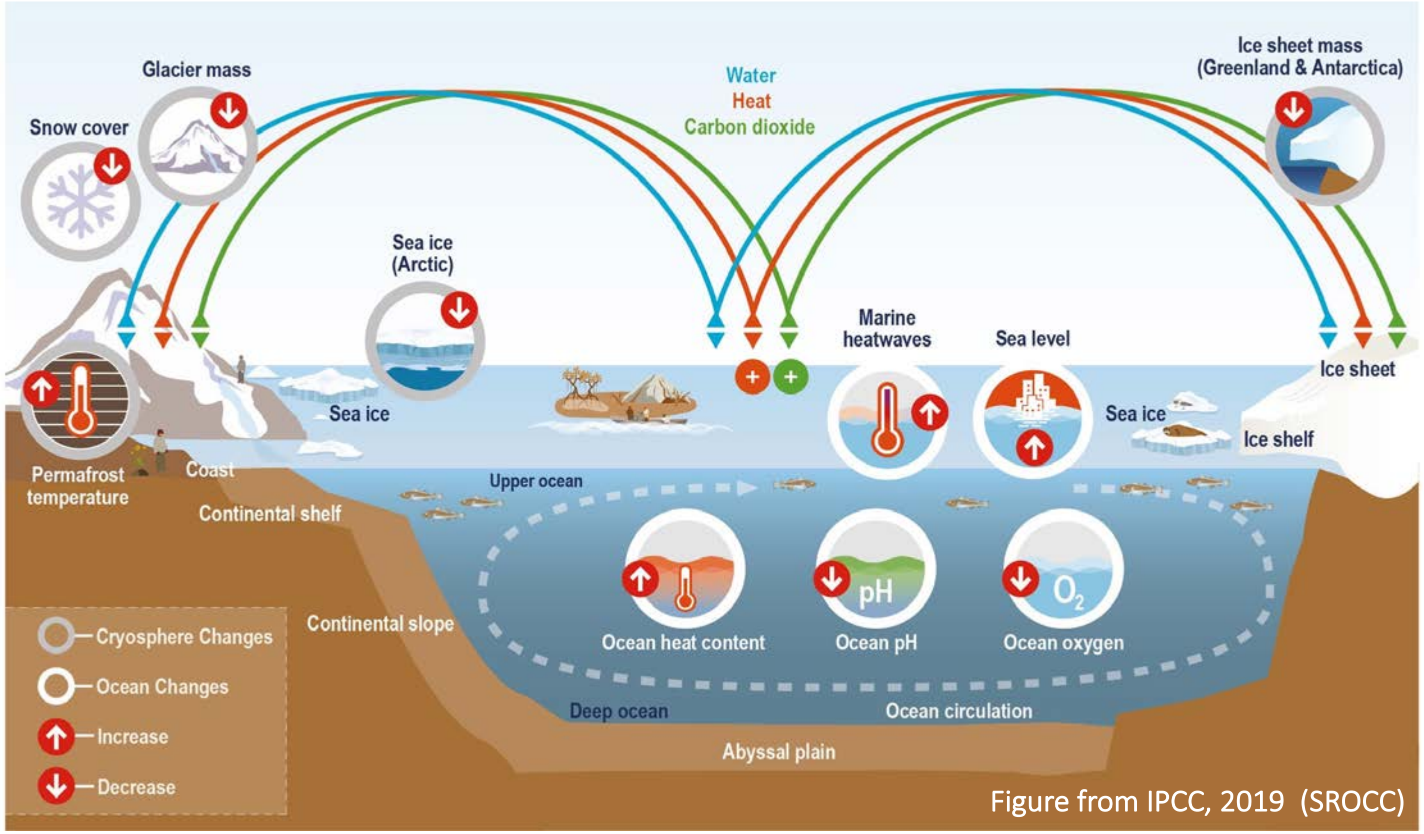


Figure from IPCC, 2019 (SROCC)

Slide: Chris Little

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

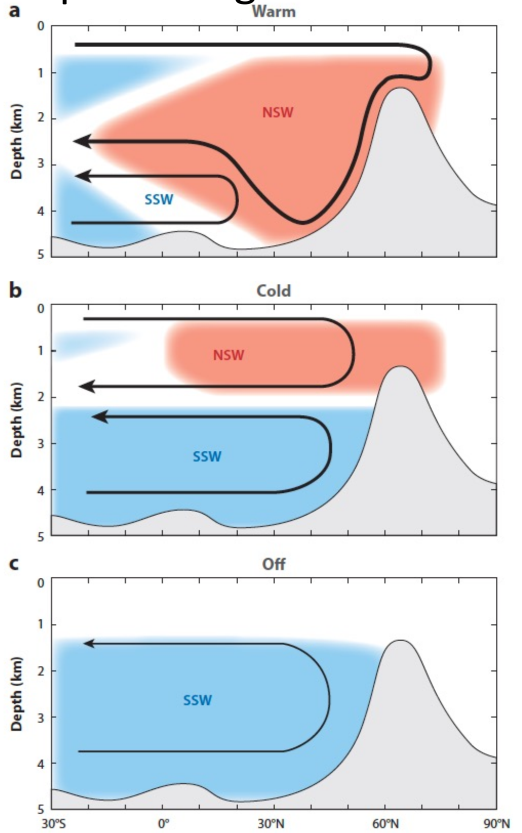
Heinrich Events are not all the same

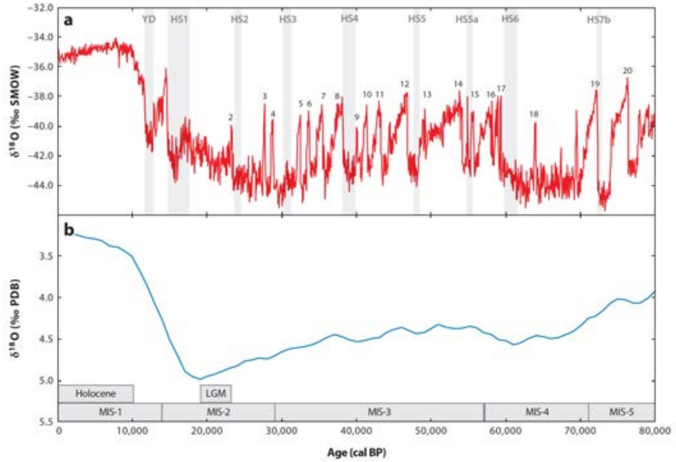
Conceptual Diagram of AMOC

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



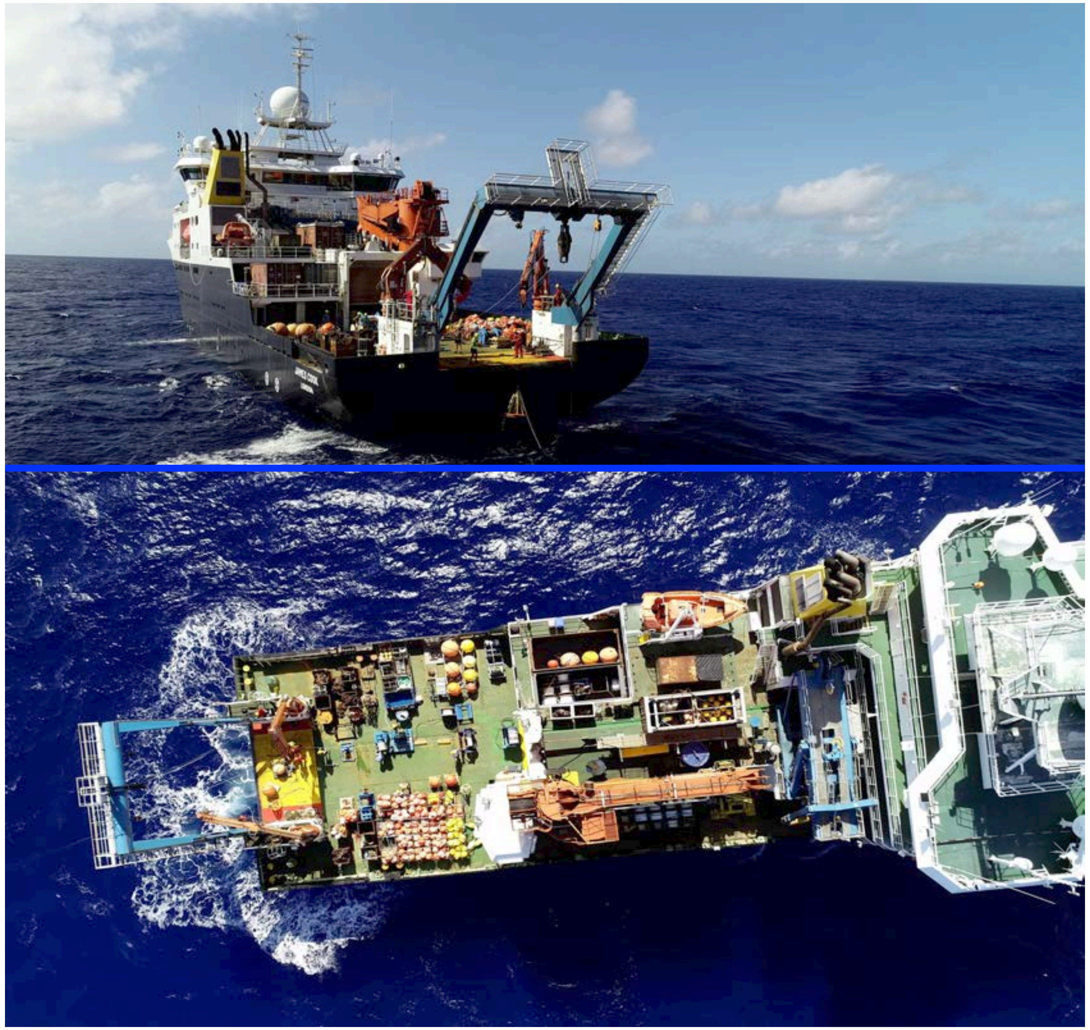


Figures from Lynch-Stieglitz (2017)

Slide: Hali Killbourne and Al Wanamaker

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.

U.S. AMOC

Thank you!

AMOC =