Insights and impacts: the first 10 years of continuous observations of the Atlantic overturning circulation

Gerard McCarthy, Darren Rayner, Ben Moat and David Smeed

National Oceanography Centre
UK

WITH THANKS TO: MOLLY BARINGER, ADAM BLAKER, HARRY BRYDEN, JULIE COLLINS, STUART CUNNINGHAM, AURÉLIE DUCHEZ, ELEANOR FRAJKA-WILLIAMS, JOEL HIRSCHI, BILL JOHNS, CHRIS MEINEN, CHRIS ROBERTS, TECHNICIANS AND CREW
INTRODUCTION

Why we study the AMOC:
- Impact on climate
- Evidence of major changes in the past
- Projections of decline with climate change

Atlantic Meridional Overturning Circulation (AMOC)
alt. Thermohaline Circulation, Great Ocean Conveyor Belt
INTRODUCTION

Why we study the AMOC:
• Impact on climate
• Evidence of major changes in the past
• Projections of decline with climate change


Atlantic Meridional Overturning Circulation (AMOC) alt. Thermohaline Circulation, Great Ocean Conveyor Belt
Past changes in the AMOC

Ice core evidence of abrupt changes in temperature in past.

Hypothesised link associated with abrupt changes in the overturning circulation.
Past changes in the AMOC

Ice core evidence of abrupt changes in temperature in past.

Hypothesised link associated with abrupt changes in the overturning circulation

Conceptual and intermediate complexity models show an AMOC with an ‘on’ and an ‘off’ state

Fast transitions and hysteresis between states

IPCC rank this as ‘very unlikely’ (<10%) but with high impact
The AMOC in a changing climate

It is ‘very likely’ that the AMOC will weaken over the 21st century.

There may be some decades where the AMOC increases due to large internal variability.

*1Sv = 10^6 m³s⁻¹
Measuring the AMOC and Heat Transport

A decade of inevitable surprises
Measuring the AMOC and Heat Transport
Why $26^\circ$N?

- Near the maximum of the overturning streamfunction i.e. near where the AMOC is defined in models
Why 26ºN?

- Near the maximum of the overturning streamfunction i.e. near where the AMOC is defined in models

- Florida straits measurements dating back to 1982

- A number of high quality transatlantic hydrographic sections (5 in 2004, 8 by early 2016)

- Sharp drop off of continental shelf near the Bahamas escarpment
  - Western boundary approximates a vertical wall
  - Suppression of mesoscale influence
Boundary Currents and the mid-ocean Dynamic Height and Bottom Pressure Array


*updates in McCarthy et al. (2015), Measuring the Atlantic Meridional Overturning Circulation at 26N, Prog. Oc.*

noc.ac.uk
Service Cruises

RRS Discovery: 9 cruises
FS Poseidon: 3 cruises
RRS Charles Darwin: 2 cruises
RV Knorr: 2 cruises
RV Walton Smith: 1 recovery
RV Ronald H. Brown: 5 cruises
RRS James Cook: 2 cruise
RV Seward Johnson: 2 cruises
RV Oceanus: 1 cruise

noc.ac.uk
A Mooring

Tallest mooring height 5150m

- Empire State Building: 449 m
- Eiffel Tower: 324 m
- Typical 2-storey house: ~7.6 m

NB: Mooring not drawn to scale, only total height is comparable.
The importance of millidegrees

Much of RAPID relies on accurate temperature and salinity measurements.

We estimate measurement accuracies of 0.003 g/kg salinity (~3 parts per million) and 0.002°C.

A bias of 0.003 in salinity between either side of the basin results in 0.7 Sv error in AMOC estimation.

A bias of 0.002°C results in 0.6 Sv error (0.5 Sv of this is due to temperature’s effect on salinity).

An errorbar and annual measurement accuracy estimates available online.

McCarthy et al., 2015, Measuring the Atlantic Meridional Overturning Circulation at 26N, Prog. Oc.
The AMOC calculation

\[
T_{ALL}(t, z) = T_{GS}(t, z) + T_{Ek}(t, z) + T_{WBW}(t, z) + T_{INT}(t, z) + T_{AABW}(z) + T_{comp}(t, z)
\]

Mid-ocean Transport: \[ T_{INT}(t, z) = \frac{\Delta D_{ref=4820}(t, z)}{f} \] + Compensation

The AMOC: \[ \varphi_{MAX}(t) = \int_{h_{\varphi_{MAX}}}^{0} T_{ALL}(z, t) \, dz \]
10 years of AMOC measurements

TRANSPORT [Sv]

Gulf Stream  MOC  Ekman  Upper Mid–Ocean

Mean AMOC of 17 Sv

updates in McCarthy et al. (2015), Measuring the Atlantic Meridional Overturning Circulation at 26N, Prog. Oc.
HEAT TRANSPORT

Net Heat Flux = 1.2 ± 0.4 PW (1 PW = $10^{15}$ Watts)


- Overall MHT of 1.2 PW similar to hydrographic estimates
- 90% carried in overturning circulation

Mid-Ocean heat transports now incorporate Argo to include the ‘eddy’ heat transport

Talk by Bill Johns tomorrow at 0900


*updates in* McCarthy et al. (2015), Measuring the Atlantic Meridional Overturning Circulation at 26N, Prog. Oc.
A decade of inevitable surprises

Sub-annual variability

- 5 hydrographic sections are the only source of full depth, basinwide estimates of the AMOC
- Bryden et al. indicate a 30% decline

Change in AMOC [1 Sv = $10^6$ m$^3$s$^{-1}$]

Bryden, Longworth and Cunningham (2005), Nature
Sub-annual variability

Change in AMOC [1 Sv = $10^6$ m$^3$s$^{-1}$]

- First year of continuous measurements in RAPID show AMOC variability encompass Bryden estimates

Cunningham et al., 2007, Science

noc.ac.uk
The AMOC displays a large seasonal cycle of 6 Sv
- Peak in July when Gulf Stream and Ekman strongest and coherent
- Largest single component is the Upper Mid-Ocean transport
- Driven by wind stress curl at the eastern boundary


Duchez, A., et al. (2014), Seasonal to interannual variability in density around the Canary Islands and their influence on the Atlantic Meridional Overturning Circulation at 26.5°N. JGRO

Perez-Hernandez et al. (submitted), The Canary Basin contribution to the seasonal cycle of the Atlantic Meridional Overturning circulation at 26°N. JGRO
Interannual Variability: Downturn in winter 2009/10

- 18 month weakening of AMOC: 30% decline
- Anomalously southward UMO: shift from overturning to gyre circulation

*Seasonal cycle was removed, and data smoothed with 180-day filter

Interannual Variability: Downturn in winter 2009/10

Magnitude of this downturn is outside the range sampled by state-of-the-art climate models.

Implications for Heat Content

- The downturn in the AMOC substantially cooled the subtropical Atlantic
- The divergence in ocean heat transport played a much larger role than ocean-atmosphere heat exchange

Talk by Bill Johns tomorrow at 0900

Cunningham et al., (2013), AMOC slowdown cooled the subtropical ocean, *GRL*

Implications for Sea-level

New York sea level jumped 13 cm in response to the AMOC drop

13-17 mm rise in sea level per Sv drop in AMOC

Yin Poster Thursday afternoon: T2-02
Double Dip: Winter 2010/11

Ocean re-emergence of sea-surface temperature (SST) links the two events

Double dips have occurred a number of times previously including 1969-70 and 1978-79

Taws SL, Marsh R, Wells NC, Hirschi JJM (2011) Re-emerging ocean temperature anomalies in late-2010 associated with a repeat negative NAO. GRL

Blaker et al. 2015, Historical analogues of the recent extreme minima observed in the Atlantic meridional overturning circulation at 26°N. Clim. Dyn.
Impact on the Atmosphere

- The SST pattern in winter 2010 pushed the NAO into a negative state


- Evidence that this second negative is predictable due to correct initialisation of Atlantic SST

Impact on SSTs

AMOC leads NA SSTs by 5 months and is associated with a dipole pattern.

Implications for forecasting esp. hurricane forecasting.

Duchez et al., Clim. Dyn. (submitted)
Decadal Changes: Evidence of a decline

- IPCC predicts an AMOC downturn of 0.5 Sv per decade
- We see a decline of 0.6 Sv per year
- Even excluding the extreme of 2009, this is significant at 90% level
- Downturn is concentrated in UMO i.e. geostrophic gyre return

Smeed et al. (2014) Observed decline of the Atlantic Meridional Overturning Circulation, *Ocean Science*
The Atlantic is a region of large multi-decadal variability e.g. sea-surface temperatures.

The rapid decline we observe is larger than the long slow decline predicted by the IPCC.

Smeed et al. (2014) *Ocean Science*
Smeed et al. (2014)
*Ocean Science*

- Larger trend in first 8 years than in CMIP5 models
- Implication that these models may not capture magnitude of decadal variability

Trend or Oscillation?

AMO: Atlantic Multidecadal Oscillation of SSTs

2014: (joint) hottest year on record… but cold spot in the North Atlantic

(from State of the Climate in 2014, Blunden and Arndt eds)
Reconstructing the past: A circulation index

- Tide gauges along the US offer long timeseries of sea level
- The gradient of sea level along the coast relates to the strength of the overturning circulation (Yin et al., *Nat. Geosci.*, 2009)
- We construct a circulation proxy by subtracting the sea level north of Cape Hatteras (subpolar estimates) from those south of CH (subtropical estimates)

McCarthy et al., *Nature*, 2015
Ocean control of decadal Atlantic climate variability revealed by sea-level observations
Relating to heat content changes

- Circulation is proportional to heat transport e.g. Johns et al, 2011, *J. Clim.*
- Therefore accumulation of the sea-level index estimates heat content
- In fact, as a measure of transport in the intergyre region, it leads subpolar heat content by 2 years
- This in turn relates to sea-surface temperature and the AMO
- Both subtropical and subpolar contributions needed so maybe RAPID and OSNAP together
In 1960 Charles Keeling published two years of CO$_2$ measurements.

Much like this talk, he focused on shortish timescales.
In 1960 Charles Keeling published two years of CO\textsubscript{2} measurements.

Much like this talk, he focused on shortish timescales.

However, as the Keeling curve continued, it is famous as a record of the continual rise of anthropogenic CO\textsubscript{2} in the atmosphere.

In 50 years time, will the RAPID measurements have documented the predicted AMOC slowdown due to anthropogenic climate change?
“Understanding of climate change is a problem for multiple generations. One generation of scientists has to make provisions for the needs of successor generations, rather than focusing solely on its own immediate scientific productivity. Today’s climate models will likely prove of little interest in 100 years. But adequately sampled, carefully calibrated, quality controlled, and archived data for key elements of the climate system will be useful indefinitely.”

Wunsch, Schmitt and Baker, *PNAS*, 2013