

## THE ATLANTIC OVERTURNING CIRCULATION

More Evidence of Variability and Links to Climate

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**A** unique feature of the Atlantic Ocean is the presence of regions in the Labrador Sea and Nordic Seas where surface water can convect and sink to deep levels. This process of deep water formation and the related northward transport of warm surface water are components of the Atlantic meridional overturning circulation (AMOC), which annually transports in excess of 1 PW of heat northward through the northern subtropics. Between 26°N and Greenland much of this heat flux enters the atmosphere where it is then transported eastward by the atmospheric circulation and is responsible for the mild U.K. and European climate. Coupled models suggest that one of the consequences of anthropogenic climate change will be a slowing of the

### 2013 U.S. AMOC—U.K. RAPID INTERNATIONAL SCIENCE MEETING

**WHAT:** A total of 106 U.S. and international participants, including academic and governmental climate scientists and funding agency managers, met to review current research findings using paleo- and modern observational data, theory, modeling, and predictability/prediction experiments to explore the variability of the Atlantic meridional overturning circulation (AMOC) and its impacts on climate, sea level, carbon/biogeochemistry, and ecosystems.

**WHEN:** 16–19 July 2013

**WHERE:** Baltimore, Maryland

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AMOC and an alteration of the ocean's role in climate (e.g., Cheng et al. 2013). Observing, quantifying, and understanding the detailed mechanisms controlling AMOC variability, its present circulation, and past behaviors, and the extent to which changes in the AMOC are predictable all remain preeminent scientific challenges for the twenty-first century.

The U.S. Atlantic meridional overturning circulation (U.S. AMOC) program was created in 2007 to promote research and provide direct observational estimates of the AMOC–climate connection. A central activity has been the development of an observing system building on the U.K. Rapid Climate Change (RAPID) program in the subtropical North Atlantic that began in April 2004. Now in its fifth year, U.S. AMOC, together with U.K. RAPID-

WATCH, have constructed a time series of the overturning circulation, as well as heat and salt transport across 26.5°N, extending the RAPID observations. This time series, which is approaching 10 years long, reveals striking changes on time scales ranging from weekly to interannual with a hint of even longer time scales (Fig. 1). Following this successful deployment, a basin-crossing observing array is being developed for deployment across the subpolar gyre to the north, and another is being deployed in the Southern Hemisphere. These arrays should provide the observational understanding of subseasonal, seasonal, and interannual variability that is necessary for assessing decadal climate predictions.

**WORKSHOP.** In 2011 the first joint workshop of U.S. AMOC and U.K. RAPID scientists was held in Bristol, United Kingdom. The continuing analysis of observations from the 26.5°N array, plans for further development of the observational arrays, and the high level of interest in the connection between AMOC and climate variability and change have provided ample motivation for this second U.S. AMOC–U.K. RAPID International Science Meeting, held in Baltimore, Maryland. The central feature of this 4-day workshop was a set of 50 oral science presentations divided into three sessions, followed by updates from the funding agencies and three “perspectives” talks. The agenda was also designed to allow long breaks for discussion and exploration of a set of 43 posters. The workshop was divided into three sessions:

- 1) Observations and dynamics of seasonal to interannual time scales. This session included results from recent instrument deployments and related observational studies and results from regional high-resolution modeling.
- 2) Observations and dynamics on decadal to multi-centennial time scales. This session included results from proxy studies and coupled climate model simulations.
- 3) Climate impacts and what the future may hold. This session emphasized studies focused on forecasts of societal impacts, including changes in key variables: sea level, carbon/biogeochemistry, and ecosystems.

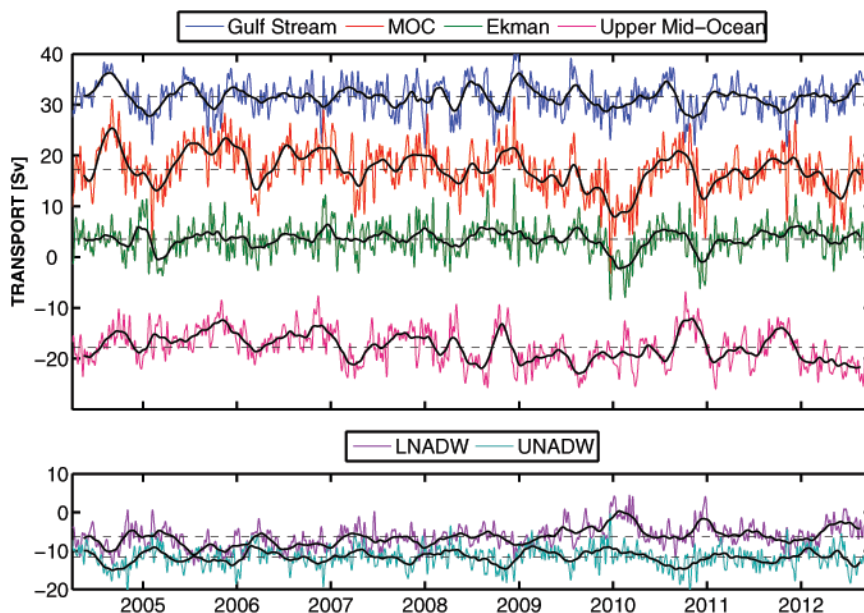
**Sessions.** The oral and poster presentations covered a vast array of current research of which we can only provide a short sampling here. Abstracts and presentations from the meeting are available for download (at [www.usclivar.org/meetings/amoc2013-agenda](http://www.usclivar.org/meetings/amoc2013-agenda)).

**SESSION 1.** Observations and dynamics of seasonal to interannual timescales began with a review of the status of the 26.5°N array by Gerard McCarthy, who was the first of several speakers to address the temporary reduction in AMOC transport (and heat flux) by 30% during the winter of 2009/10, evident in Fig. 1. A later talk by Stuart Cunningham and colleagues explored the impact of these changes on subtropical heat content, showing that cold anomalies were partly driven by anomalous air–sea exchange during the cold winters of 2009/10 and 2010/11 and, more surprisingly, by the extreme interannual variability in the ocean’s northward heat flux at 26.5°N. Cooling driven by the ocean’s meridional heat flux affects the deeper layers, which are isolated from the atmosphere on annual time scales.

Several talks addressed the role of variations in wind stress in the slowdown of AMOC and related dynamical issues, as well as the role of AMOC in transporting freshwater southward as part of the overturning circulation. Two speakers outlined plans for the extension of the observing system northward into the subpolar gyre (Monika Rhein and colleagues) and into the Southern Hemisphere (Christopher Meinen and colleagues). A key aspect of AMOC is the deep western boundary current, which transports much of the deep water into the Southern Hemisphere. In a modeling study carried out in preparation for the southern extension of the observing system, Sylvia Garzoli and colleagues showed evidence that this deep western boundary current may actually leave the western boundary and transit the basin as a result of eddy momentum flux convergence in the southern subtropics. The session also featured modeling results, in particular a presentation by Gokhan Danabasoglu of the Common Ocean–Ice Reference Experiments, highlighting the diversity of AMOC representations produced by different ocean models forced by the same surface meteorology.

**SESSION 2.** Observations and dynamics of decadal to multicentennial timescales was led by a fascinating set of presentations describing some of the increasing quantity of proxy climate records. Delia Oppo described new evidence from coral isotope studies for the existence of Atlantic multidecadal variability (AMV) of climate in the Atlantic sector stretching back to the preindustrial era. This observational theme was continued in presentations by David Thornalley and Hali Killbourne raising, among other issues, the aerosol–climate link. The observational presentations were complemented by results from coupled models that in part attempted to understand the evidence

from proxy records. The session featured talks on the predictive skill associated with the AMOC. Two presentations, by Rym Msadek and Jon Robson, showed encouraging results in predicting abrupt changes in the Atlantic subpolar gyre like the mid-1990s warming and the 1960s cooling, when the models are initialized from observations. Initial AMOC conditions were found to be key in the success of these predictions. A number of other topics were addressed, including the stability of the AMOC and the existence of thresholds (discussed by Sybern Drijfhout), its response in future climate in a talk by Wei Cheng, and the meridional connectivity with the South Atlantic and Southern Ocean in talks by Wilbert Weijer and Mojib Latif, among others. The session ended with an interesting presentation by Thierry Penduff on the role of eddies in setting the low-frequency variability of the AMOC.



**FIG. 1.** The 10-day (colors) and 3-month low-pass (black) time series of (top) Gulf Stream transport (blue), overturning transport (red), Ekman transport (green), and upper midocean transport (0–1100 m; magenta), and (bottom) lower (3000–5000 m; purple) and upper (1100–3000 m; cyan) North Atlantic Deep Water transport for the period 1 Apr 2004–1 Oct 2012. Positive transports correspond to northward flow. Dashed lines indicate mean values of 31.5, 17.5, 3.5, -17.5, -6.5, and -11.6 Sverdrups (Sv;  $1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$ ), respectively. Large interannual variability saw a drop of 30% in the strength of the AMOC in 2009/10 (McCarthy et al. 2012). This was driven on short time scales (3 months) by anomalous Ekman transports. A second short-time-scale dip occurred in the winter of 2010/11, driven by anomalous Ekman transports associated with reemerging wintertime SSTs (Taws et al. 2011). However, on longer time scales, a strengthening of the southward upper midocean transports was more important for the downturn. This marked a shift from overturning to gyre circulation at  $26^\circ\text{N}$ . This weakening of the overturning circulation has continued and now we can report a significant weakening of the AMOC of about  $0.5 \text{ Sv yr}^{-1}$  over the observed time period (Smeed et al. 2014). Data are freely available online (from [www.rapid.ac.uk/rapidmoc/](http://www.rapid.ac.uk/rapidmoc/)).

**SESSION 3.** Climate impacts began with presentations by Jianjun Yin, Tal Ezer, and Joseph Park on sea level rise and its links to changes in AMOC in models as well as the historical tide gauge record. Another theme of this session, introduced in a lead talk by Yochanan Kushnir, was on the implications of AMOC variability for SST and continental climate. These presentations also made an interesting counterpoint to some of the presentations of proxy data in Session 2. Andreas Schmittner and Ric Williams presented work on the role of the AMOC and its impact on biogeochemistry and atmospheric  $\text{CO}_2$ , contrasting different ocean processes leading to outgassing of  $\text{CO}_2$ .

**FUTURE DIRECTIONS.** Following Session 3, three invited speakers, David Marshall, Laurent

Terray, and Mingfang Ting, shared their views on the topics of the three sessions and opportunities for future research directions. The three speakers led a roundtable discussion that identified the following key research needs:

- faster real time availability of RAPID data;
- adoption of new technologies as they mature (e.g., autonomous gliders) to sustain the monitoring arrays over many decades;
- development of proxies of AMOC variability using long records of sea level, SST, and paleo data;
- development of data assimilation and other estimation techniques to combine available oceanic and meteorological observations in ways consistent with the equations governing the two systems;

- understanding of the impact of ocean model biases on coupled models;
- identification of similarities and differences between the AMV in the historical record, the corresponding variability in coupled climate models, and their relationships to AMOC;
- exploration of the role of aerosol forcing in impacting the climate of the North Atlantic sector; and
- investigation of AMOC variability and biogeochemistry/carbon sequestration.

The research findings presented at the meeting and suggested future research needs from the final session will help guide future planning of the U.S. AMOC and U.K. RAPID programs. The benefit of international collaboration fostered by the meeting is acknowledged by the sponsoring programs with an expression of intent to convene a *Third International AMOC Science Meeting* in 2015 in the United Kingdom.

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## REFERENCES

- Cheng, W., J. Chiang, and D. Zhang, 2013: Atlantic meridional overturning circulation (AMOC) in CMIP5 models: RCP and historical simulations. *J. Climate*, **26**, 7187–7197, doi:10.1175/JCLI-D-12-00496.1.
- McCarthy, G., and Coauthors, 2012: Observed interannual variability of the Atlantic meridional overturning circulation at 26.5°N. *Geophys. Res. Lett.*, **39**, L19609, doi:10.1029/2012GL052933.
- Smeed, D. A., and Coauthors, 2014: Observed decline of the Atlantic Meridional Overturning Circulation 2004–2012. *Ocean Sci.*, **10**, 29–38, doi:10.5194/os-10-29-2014.
- Taws, S. L., R. Marsh, N. C. Wells, and J. Hirschi, 2011: Re-emerging ocean temperature anomalies in late 2010 associated with a repeat negative NAO. *Geophys. Res. Lett.*, **38**, L20601, doi:10.1029/2011GL048978.