explaining and predicting
the ocean conveyor

PROJECT NEWS

Issue #2 August 2024

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Sunset from the bow of N/O Thalassa during the Crossroad2204 expedition. Image courtesy Katja Schultz, UHH.

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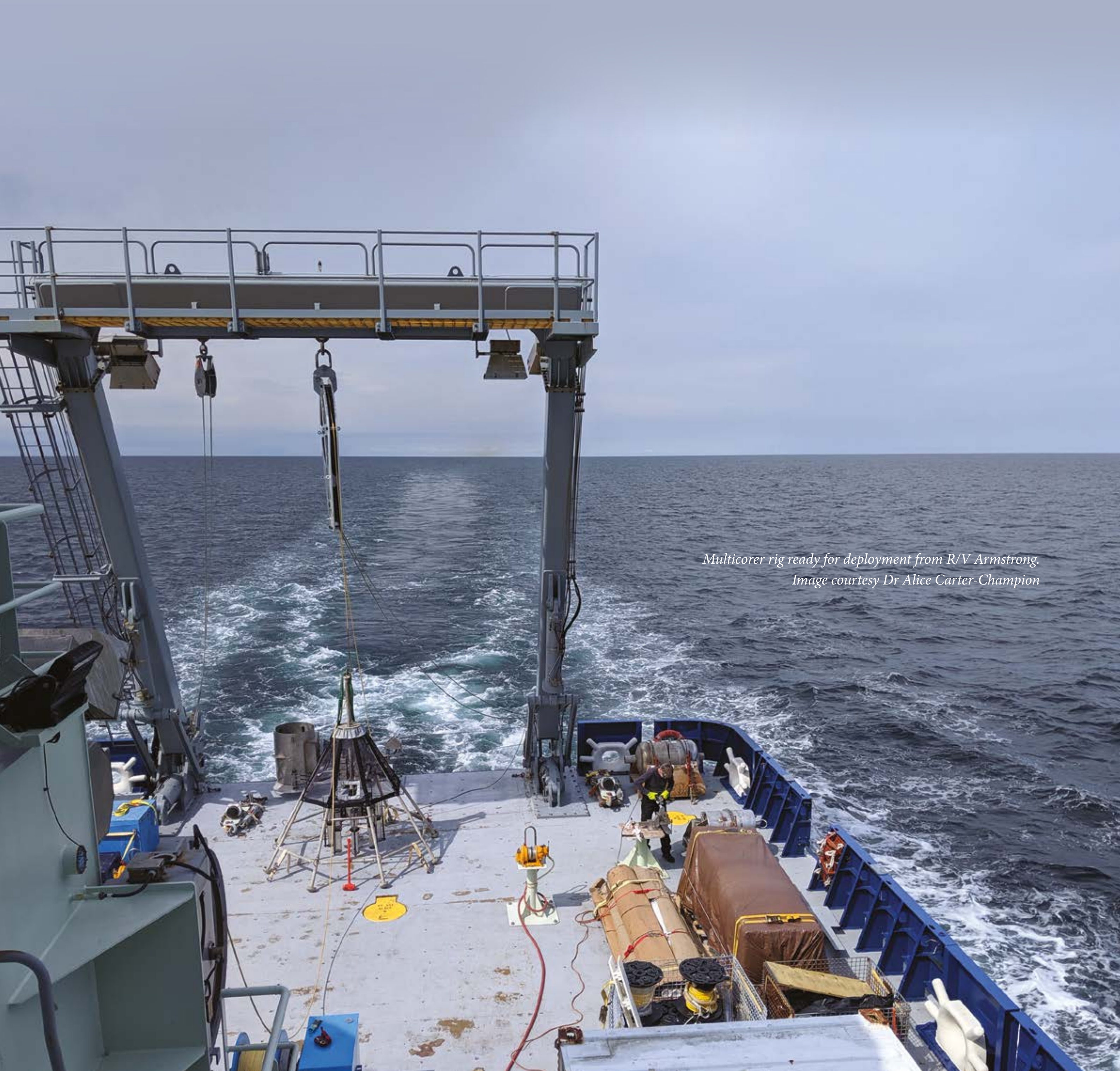
Deeper and stronger North Atlantic Subtropical Gyre during the last ice age

by Jack Wharton, University College London



Multicorer rig ready for deployment from R/V Armstrong. Image courtesy Dr Alice Carter-Champion

As part of EPOC's paleoceanographic component, researchers at University College London (UCL) have been working to better understand how the AMOC and its constituent currents, including the Gulf Stream, behaved in the past. In particular, the team has been focused on the Northwest Atlantic, investigating the meridional and vertical coherence of the Deep Western Boundary Current on a range of different timescales. While EPOC's paleo work is primarily focused on the Holocene – specifically the last 1,000 and last 150 years – new data from the last ice age, about 20,000 years ago, has revealed important new insights into the behaviour of the North Atlantic Subtropical Gyre.

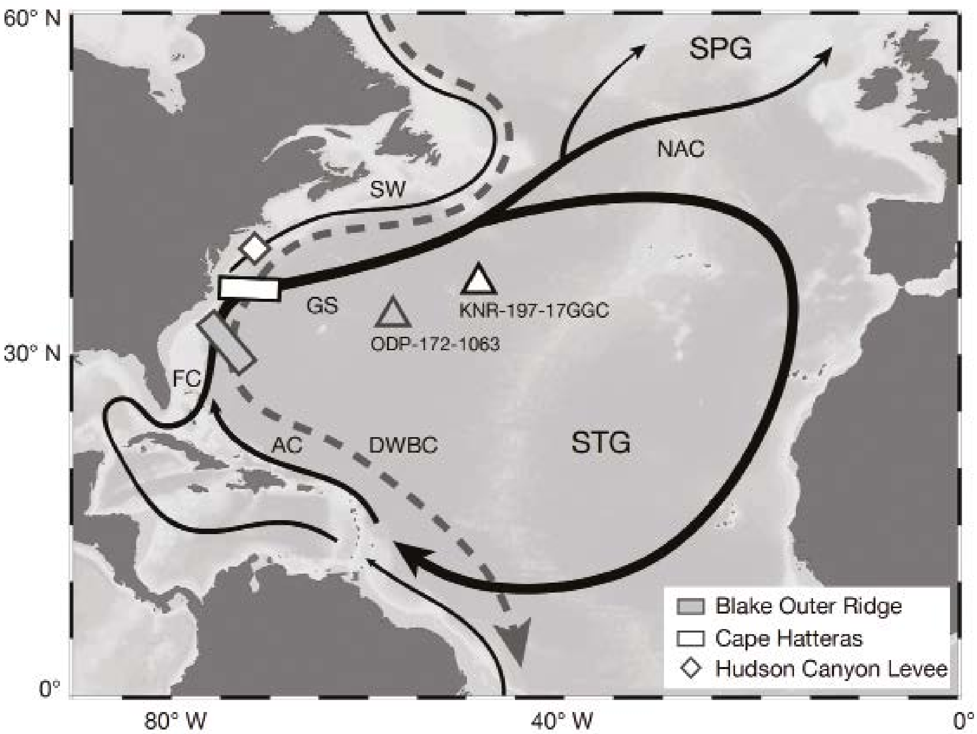
The last ice age, with its peak known as the Last Glacial Maximum (LGM), was characterised by much colder global air temperatures than today – about 6°C colder – and large ice sheets covering much of North America and Europe, resulting in global sea levels being approximately 120 metres lower. While there is a general consensus that the AMOC and Gulf Stream were likely weaker during the LGM due to increased sea ice cover in the northern North Atlantic, paleoceanographic data from the Northwest Atlantic remains relatively sparse. Thus, the glacial circulation in this region is poorly constrained.

Using a combination of proxy data and glacial climate model simulations, the team at UCL found that the depth and strength of the North Atlantic Subtropical Gyre and its western boundary current, the Gulf Stream, were approximately doubled during the LGM due to the influence of stronger glacial winds across the subtropical North Atlantic. The impact of these stronger glacial winds on the Subtropical Gyre would likely have been twofold: firstly, they

Above: Close-up of long sediment core recently retrieved from Hudson Canyon in the Northwest Atlantic. Image courtesy Dr Alice Carter-Champion.

would have intensified the gyre circulation, causing the gyre to deepen. Secondly, stronger, cold, and dry glacial winds would have increased heat and buoyancy loss over the gyre over the western subtropical North Atlantic, leading to the formation of denser and deeper Subtropical Mode Waters.

In addition to providing new insights into the state and mechanics of the glacial circulation in the Northwest Atlantic, these results also have important implications for future climate change. For example, the data highlight the potential sensitivity of the Gulf Stream to future changes in wind patterns over the subtropical North Atlantic. If, as some modelling studies are beginning to suggest[1], there is a reduction in wind strengths over the subtropical North



Left: Oceanographic and geographic setting of marine sediment cores used in this study. The solid black and dashed grey arrows denote the main surface and deep ocean currents, respectively. The abbreviations refer to the following currents: AC, Antilles Current; DWBC, Deep Western Boundary Current; FC, Florida Current; GS, Gulf Stream; NAC, North Atlantic Current; SW, Slope Water Current. Figure courtesy Wharton et al. (2024).

Atlantic, the Gulf Stream could also weaken. This would result in a reduction in the rate of relative global warming over Europe while causing higher sea levels along the US east coast.

This work also addresses one of EPOC's main areas of investigation: the coherence of AMOC variability. Specifically, this new research shows that the Gulf Stream was strong despite the AMOC likely being weaker overall, challenging the established and perhaps oversimplistic idea that the AMOC functions as a coherent conveyor. These new glacial data instead suggest that the AMOC operates more like a series of interconnected loops. These include a subtropical loop, of which the Gulf Stream is a part, as well as a subpolar loop that carries heat further north into the Arctic. UCL's new research shows that the subtropical loop was stronger than it is today, whereas the subpolar loop is thought to have been weaker.

To constrain ice age circulation in the Northwest Atlantic, the team at UCL used paleo-proxies preserved in marine sediments deposited on the ocean floor about 20,000 years ago. The researchers measured oxygen isotopes in the shells f benthic foraminifera – tiny single-celled organisms that lived and were subsequently buried by glacial sediments – to reconstruct the vertical structure of the ocean. By comparing these data with more modern equivalents, the researchers were able to observe how the structure of the ocean had changed. Specifically, they found evidence of the North Atlantic Subtropical Gyre extending down to 2-2.5 km, whereas today the base of the subtropical gyre is at about 1-1.5 km in the Northwest Atlantic.

Read the full publication and associated articles:

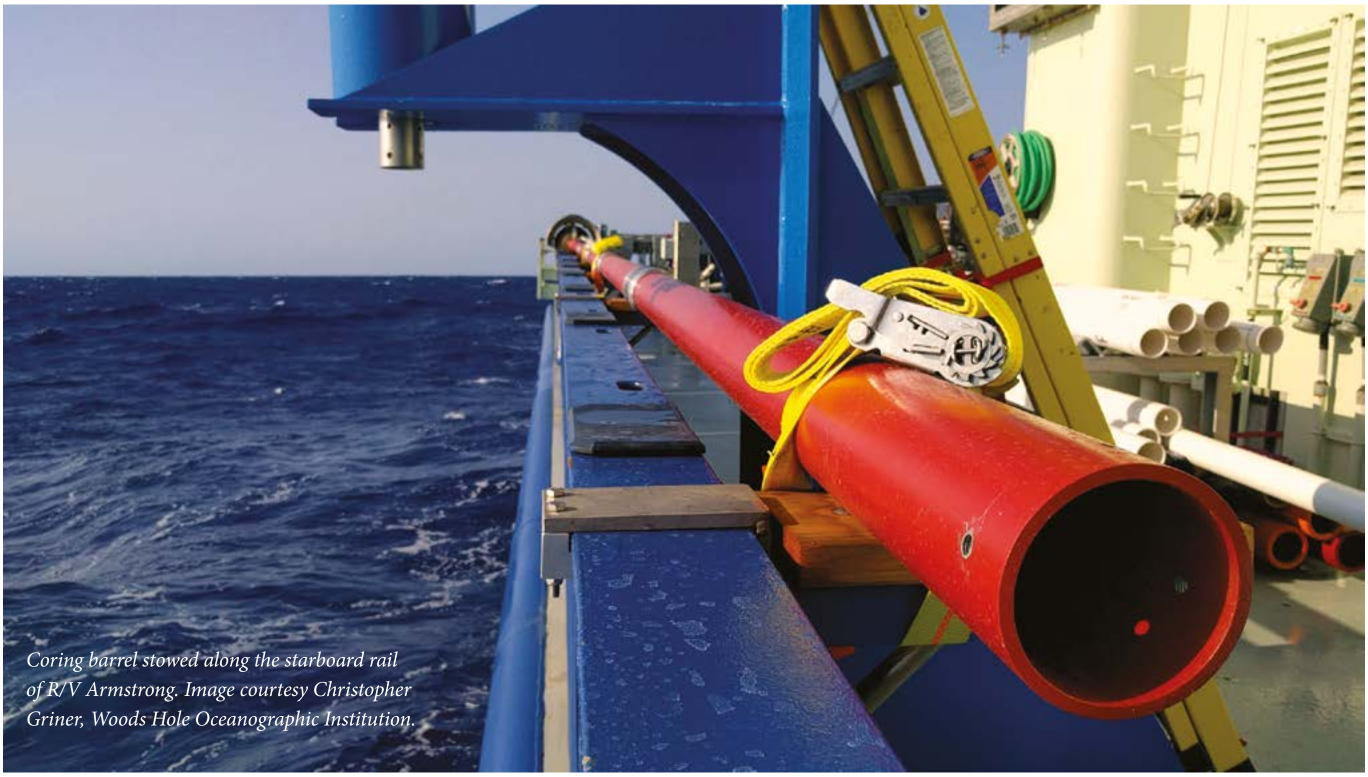
Wharton, J.H. et al. (2024) Deeper and stronger North Atlantic Gyre during the Last Glacial Maximum, Nature, doi.org/10.1038/s41586-024-07655-y

Nature Research Briefing: www.nature.com/articles/d41586-024-02407-4

Summary article in The Conversation: theconversation.com/the-atlantic-gulf-stream-was-unexpectedly-strong-during-the-last-ice-age-new-study-233271

Reference:

[1]Asbjørnsen, H., & Årthun, M. (2023). Deconstructing future AMOC decline at 26.5 N. Geophysical Research Letters, 50(14), e2023GL103515.



Coring barrel stowed along the starboard rail of R/V Armstrong. Image courtesy Christopher Griner, Woods Hole Oceanographic Institution.

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Dolphins riding the bow wave of N/O Thalassa *in the NW Atlantic. Image courtesy K. Schultz*

CROSSROAD24: Mission to the Transition Zone

The Northwest Atlantic Transition Zone (TZ) is characterised by complex ocean circulation due to the interaction between cold, fresh subpolar deep waters and warm, salty subtropical surface waters. These waters are transported southward by the Deep Western Boundary Current and northward by the Gulf Stream and North Atlantic Current. To better understand the ocean circulation in the TZ, EPOC researchers Katja Schultz and Simon Wett from the University of Hamburg (UHH) and Jack Wharton from University College London (UCL) are participating in the Crossroad24 (CR24) expedition aboard the French research vessel *Thalassa*. This cruise, part of the closely linked CROSSROAD project, is a 4-week expedition to the TZ led by Damien Desbruyères (Ifremer). The mission aims to decipher the region's complex local ocean dynamics through a combination of *in situ* measurements, including hydrography (temperature, salinity, and oxygen), currents and turbulence, as well as data from 12 autonomous Deep Argo floats and a microstructure mooring system.

Of the 16 scientists onboard, Katja and Jack are part of one of the three teams operating the CTD (a collection of sensors measuring conductivity, temperature and depth, mounted on a steel frame collectively known as the 'rosette'), which is deployed to the ocean floor at various locations to collect vertical profiles of salinity, temperature, and oxygen concentration throughout the water column. Meanwhile, Simon is responsible for reading the PIES (bottom-moored sensors that measure sound speed in the ocean, which can be converted to estimates of density).

After 15 days at sea (at the time of writing), the cruise was working off the northern part of Flemish Cap. We caught up with Katja, Jack, and Simon to get a sneak peek of progress...

Katja Schultz (UHH): As I near the end of my master's programme, this is my first time on a large research vessel. It's my initial experience of life at sea, breathing in salty air for four weeks straight and participating in oceanic data collection, which during most of my studies only appeared as netCDF files or inputs for climate models. Finally, I'm getting my hands wet.

My responsibilities on board primarily involve taking water samples from the CTD rosette, from which oxygen concentration and salinity are measured for comparison with the CTD sensors. These additional measurements are conducted in the laboratory: a small container at the back of the boat where our chemistry team – Esterine, Caroline and Thierry – work their magic. Additionally, I handle the CTD's downcasts and upcasts while simultaneously monitoring the temperature, salinity and oxygen data transmitted in real time from the CTD. Watching three lines on a screen during a 4000-metre downcast might sound boring, but I've already learned a lot.

In the area where we are working, the sharp front between fresh, cold subpolar waters and warm, salty subtropical waters creates fascinating profiles that change rapidly from one station to the next. The distinction between these water masses is so pronounced that we feel it instantly when stepping outside on the deck. In the NW Atlantic in mid-August, whether we are sailing through subpolar or subtropical waters seems to dictate the weather, as well as the likelihood of wildlife encounters. We either experience warm summer days with a low likelihood of whale or dolphin sightings (like those pictured on the opposite page), or we have to swap our beach shorts for something substantially warmer – but there's a much higher chance of seeing whales (for the first time)!



Above, from left: Katja sampling seawater from bottles on the CTD; the view from our position in the CTD control room - warm on the left, cold on the right. Images courtesy J.Wharton (UCL) and K. Schultz (UHH).

Jack Wharton (UCL): Although this isn't my first research cruise, four weeks will definitely be the longest time I've ever spent at sea. So far, so good, and after two weeks I think I've found my sea legs (though the weather forecast might have something to say about that). I am part of the 0-4 or Zérac CTD shift ('zér' for zero and 'rac' for quatre, meaning four in French) along with Katja and our amazing team leader Pascale Lherminer. This means we are responsible for operating the CTD between midday and 16:00, and midnight and 04:00. While these hours might sound challenging, they've turned out to be the best shift to work (although admittedly I'm biased): the ship is always fantastically quiet as everyone is either sleeping after lunch or sleeping because it's the middle of the night. This kind of shift work also means that routine underpins everything. Typically, mine and Katja's day looks something like this:

- 1150: Wake up and have coffee.
- 1200-1600: CTD shift.
- 1600: Late lunch. Since lunch is typically served

between 1100 and 1300, the wonderful culinary team on board always leaves us plates of lunch to enjoy after our CTD shift.

- 1600-1900: A mix of napping, whale watching (or lack thereof), working out in the gym (if conditions aren't too rocky), and personal work.
- 1900: Dinner.
- 1900-0000: Another opportunity to catch up on the same activities as 1600-1900.
- 0000-0400: CTD shift.
- 0400-1150: Sleep!

As a paleoceanographer, hydrographic data has always been a bit of a black box to me. It's something I use frequently, but I didn't fully appreciate the incredible effort required to collect these data. Having now been part of these efforts at sea, I now have a tremendous amount of respect for every hydrographic data point collected on a ship!

Right: Simon Wett, Katja Schultz and Jack Wharton on board N/O Thalassa. *Image courtesy V. Thierry, IFREMER.*

Simon Wett (UHH): I am responsible for acoustic communication with instruments at the ocean bottom. These so-called PIES (Pressure sensor-equipped Inverted Echo Sounders) were deployed during previous cruises and can send the data they've collected through acoustic signals. This means my schedule on board is less structured compared to the CTD watch teams, as I'm on duty whenever the ship reaches one of the instrument locations.

PIES use sound to determine the physical properties of the water column. By measuring how long it takes for a sound signal to travel to the ocean surface and back, we can calculate the vertical distribution of temperature and salinity, as these factors affect the speed of sound in seawater. Some of these PIES were deployed on a different cruise last year and are scheduled for recovery next year. In the meantime, we are curious about what they have measured so far and want to get a first look at the data. To do this, the PIES are equipped with a feature that lets us read the data without retrieving the instruments. Using a hydrophone – a device for sending and receiving sound signals in water – I communicate with the PIES and instruct them to send the daily averages of their recorded data. At the same time, using a computer on board, I monitor the data received from the ocean bottom. While communicating with scientific instruments 4000 meters below the ship can be challenging, this procedure has been successful, and the preliminary data looks promising. Now the PIES can continue taking measurements until their recovery on a future cruise.

I am also responsible for processing the ship's ADCP data (Acoustic Doppler Current Profiler), which is used to calculate water velocity. This data is collected by instruments that send out pulses of sound that bounce off tiny particles, like plankton, in the water. By analysing the returning echoes we can calculate the speed of these particles, which tells us how fast the water is moving. One ADCP is mounted in the ship's hull and continuously measures the velocity beneath the vessel, while another is attached to the rosette frame, providing a vertical profile of velocity throughout the water column. In combination with CTD measurements of temperature and salinity, these data provide a comprehensive view of the water properties in our study area.

During the second half of the cruise, we will continue our measurements around the Flemish Cap. In the coming days, weather conditions are expected to worsen as the remnants of hurricane Ernesto approach. By the time you read this, we will have weathered the storm and will be busy analysing the data collected during the cruise.

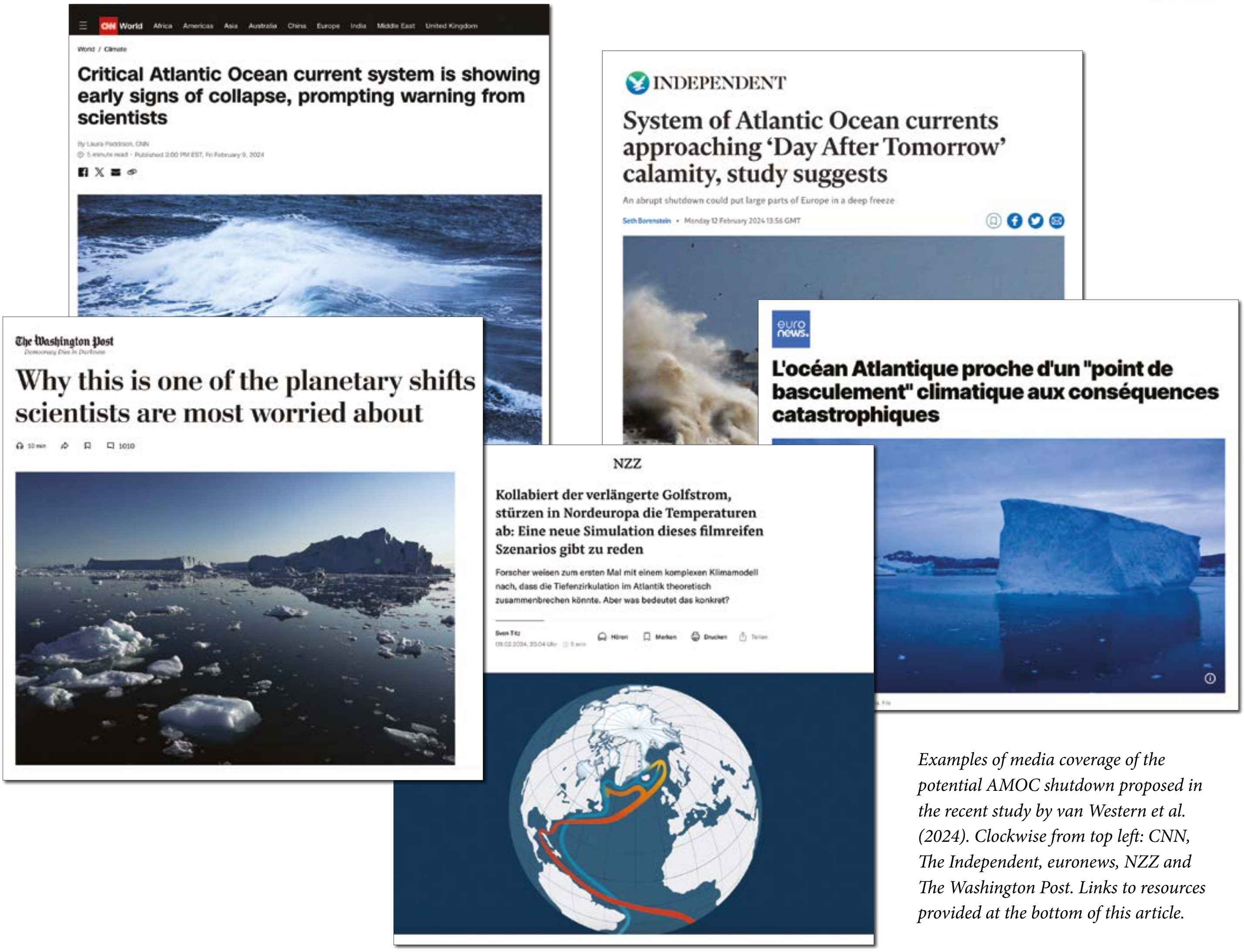
Is the AMOC on course for shut down? A commentary on recent studies

by Joel Hirschi[1], Hege-Beate Fredriksen[2], Laura de Steur[2], Adam Blaker[1], David Thornally[3], Yevgeny Aksenov[1], Eleanor Frajka-Williams[4] & Jon Robson[5]

[1] National Oceanography Centre, UK; [2] Norwegian Polar Institute, Norway; [3] University College London, UK; [4] Universitaet Hamburg, Germany; [5] University of Reading, UK

A recent study by van Westen et al. (2024) has suggested that the Atlantic meridional overturning circulation (AMOC) may be on course for an abrupt shut down. Due to the potential climatic consequences on the North Atlantic region and much of the Northern Hemisphere, an AMOC shut down has been one of the figureheads of climate change related impacts since the late 1980s (e.g. Manabe and Stouffer 1988; Vellinga and Wood 2002; 2008; Jackson et al. 2015 and many others). This new study has re-ignited the conversation about AMOC stability and the climate impacts of an AMOC shutdown and received considerable media attention. In this article, EPOC experts reflect on the scientific evidence to date.

unsplash/Annie Spratt


Critical Atlantic Ocean current system is showing early signs of collapse, prompting warning from scientists

INDEPENDENT
System of Atlantic Ocean currents approaching 'Day After Tomorrow' calamity, study suggests
An abrupt shutdown could put large parts of Europe in a deep freeze

The Washington Post
Why this is one of the planetary shifts scientists are most worried about

euronews.
L'océan Atlantique proche d'un "point de basculement" climatique aux conséquences catastrophiques

NZZ
Kollabiert der verlängerte Golfstrom, stürzen in Nordeuropa die Temperaturen ab: Eine neue Simulation dieses filmreifen Szenarios gibt zu reden
Forscher weisen zum ersten Mal mit einem komplexen Klimamodell nach, dass die Tiefenzirkulation im Atlantik theoretisch zusammenbrechen könnte. Aber was bedeutet das konkret?

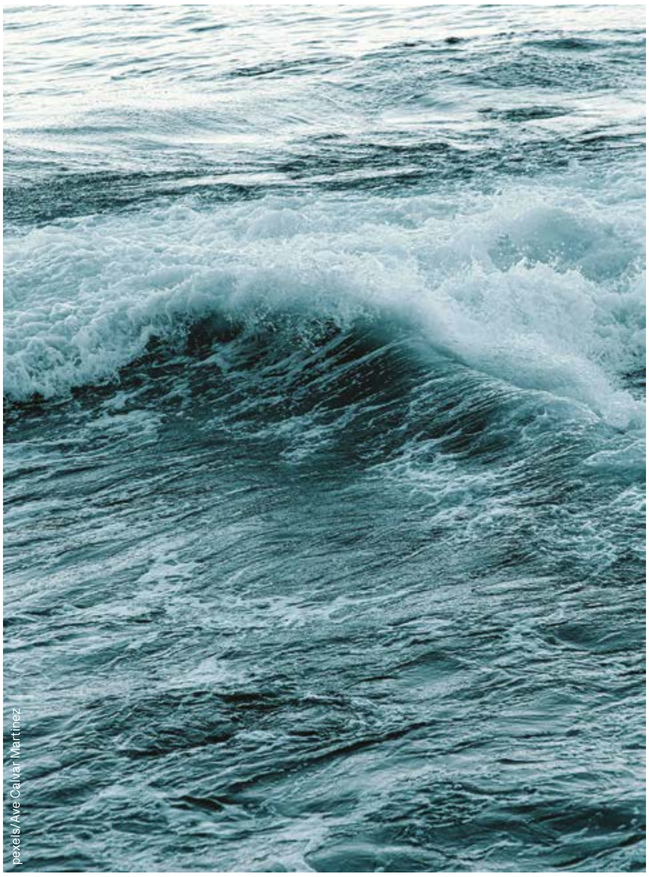
Examples of media coverage of the potential AMOC shutdown proposed in the recent study by van Western et al. (2024). Clockwise from top left: CNN, The Independent, euronews, NZZ and The Washington Post. Links to resources provided at the bottom of this article.

Is the AMOC slowing and will it reach a tipping point?

Studies based on paleo observations (i.e. proxies of past ocean conditions that are stored in sea sediments) have suggested that the AMOC is at its weakest for the last millennium (e.g. Caesar et al., 2022; Thornalley et al., 2018). In contrast, contemporary AMOC estimates based on direct observations of ocean (temperature, salinity, velocities) and atmospheric (wind) conditions acquired by the Rapid-MOCHA observing system in the North Atlantic do not show any significant weakening of the AMOC during the last 20 years (Worthington et al. 2021). That period may be too short to detect a longer term weakening trend though (e.g. Jackson et al. 2022). Whether the AMOC strength is currently reducing is therefore still an open question which is being debated in the ocean and climate community (e.g. Kilbourne et al. 2022; Caesar et al. 2022).

What about a possible AMOC tipping point?

Again, paleo observations show that the AMOC is likely to have undergone rapid changes during the last ice age (Dansgaard et al. 1993; Broecker et al. 1985 and many later studies; see Loriani et al., 2023 for an overview). Evidence of abrupt changes in the past has been one of the key motivations for many later and current studies and indeed for the current AMOC observing systems. How likely is an AMOC shut down in response to global warming and what are the warning signs we should be looking out for? Whereas the paleo proxies show us that the AMOC has undergone rapid changes, numerical models are ideal tools to test likely future AMOC scenarios. It is accepted that if subjected to large enough perturbations the AMOC shuts down in the latest generation of high resolution models (e.g. Mecking et al., 2016). High resolution models also suggest that the AMOC may be bistable – i.e., after a shut down the AMOC can remains in the "off" state (i.e., severe reduction in AMOC strength) long after the fresh water perturbation has stopped (Mecking et al. 2016). Observations and high resolution ocean models suggest that presently there is a net fresh water transport out of the Atlantic ocean at 34°S (e.g. Deshayes et al., 2013; Mecking et al., 2016, van Westen et al., 2024). Van Westen et al. (2024) and to some extent an earlier study by Hawkins et al. (2011) suggest that the AMOC-driven fresh water transport at the southern boundary of the Atlantic reaches a minimum shortly before an abrupt decline



in AMOC strength and van Westen et al. also identify a coincident change in temporal variability of the fresh water flux as a precursor of the AMOC change. In classical AMOC stability theory, a net fresh water transport out of the Atlantic at its southern boundary is considered an indicator of AMOC bistability. This view has been questioned by some authors though and the debate about the role of the AMOC-driven fresh water transport is not yet settled (e.g. Weijer et al., 2019; Mecking et al., 2016).

Mechanisms and feedback in the Earth climate system may cause the AMOC to shut down or to switch to a different stable state. However, it is unclear if the warming would be strong enough for the climate system to reach this tipping point. Since the 1990s the question many studies, including van Westen et al. (2024), have been trying to answer is whether the AMOC will shut down as the climate warms due to human-induced greenhouse gas emissions and the ocean receives increased fresh water input from ice sheets such as Greenland (starting with Manabe & Stouffer (1993) and many others since). Over the years the pendulum has swung from a marked AMOC decline / shut down being considered likely to this being an unlikely scenario. Currently, the prevalent view is somewhere between the two and in the latest IPCC report an AMOC collapse in the 21st Century is considered unlikely – a statement made with a medium level of confidence. If and when we could reach the point where the AMOC would switch off is therefore still an open question. There is no consensus yet in the AMOC science community and the recent study by van Westen et al. (2024) has to be viewed in this context. The study is a valuable addition to the ongoing discussion about the AMOC and its stability but in the following we summarise why it does not reduce the present uncertainty about a future AMOC shutdown.

Simulating an AMOC shutdown scenario using a CMIP6 class model is an impressive achievement by van Westen et al. (2024), as running such a model for thousands of years is computationally very expensive. It is both time and energy consuming. However, it should be noted that similar results were obtained by Hawkins et al. (2011) who were the first to simulate an AMOC shut down (and hysteresis) in a 3D coupled ocean atmosphere model - albeit one not as complex as in van Westen et al. (2024). Common to both Hawkins et al. (2011) and van Westen et al. (2024) is that the fresh water perturbations applied over thousands of years amount to water discharge volumes which exceed the total volume of fresh water contained in the Greenland Ice Sheet. The fresh water flux perturbations of 0.1 to 0.6 Sv used in van Westen et al. (2024) are small when compared to e.g. the 10 Sv pulse applied over 10 years in Mecking et al. (2016), but by the time the AMOC shuts down after about 1700 years about 15 million km^3 of fresh water has been discharged. This is about 6 times the fresh water volume currently stored in the Greenland Ice Sheet. The total freshwater volume discharged in Mecking et al. (2016) corresponds to the freshwater stored in the Greenland Ice Sheet. Neither the sharp and extremely strong freshwater perturbation used in Mecking et al. (2016) nor the weaker but much more prolonged perturbation used in van Westen et al. (2024) are possible in the real world. It is also worth mentioning that in van Westen et al. (2024) the fresh water hosing experiment is performed under pre-industrial conditions – i.e. without enhanced greenhouse gas forcing – leaving the background climate cooler than today. It is not clear what the response would be if the model experiment were performed in a warming climate scenario. This would have been a more realistic choice given that rising temperatures are consistent with an increased meltwater discharge from Greenland. Under pre-industrial conditions there is no reason for the Greenland Ice Sheet to melt. Admittedly, one could argue that in a greenhouse gas warming scenario the AMOC may be more sensitive to fresh water hosing and that the AMOC could already shut down in response to a smaller fresh water input (e.g. Lin et al., 2023).

Finally, even though complex, the Earth System Model used by van Westen et al. (2024) has a resolution of about 100 km in the ocean. At this resolution a model cannot simulate fast-flowing currents such as the Gulf Stream and the associated sharp temperature and salinity fronts are not adequately resolved. In reality, a fresh water discharge would not spread evenly across the entire basin between 20°N and 50°N but would be entrained in the fast boundary currents around Greenland (e.g. Marsh et al., 2010; Frajka-Williams et al., 2016) and subsequently the Subpolar Gyre. How much a higher model resolution and a more realistic discharge rate of fresh water along the coast of Greenland would affect the sensitivity of the AMOC to fresh water perturbations is not yet known. Neither do we know if the fresh water discharges we can realistically expect from the Greenland Ice Sheet in the coming decades to centuries are large enough to push the AMOC past a tipping point. The past can only serve as a partial analogue for the future here: the rapid changes found in the paleorecord during ice ages happened in a climatic background very different to today's, with lower temperatures and about three times as much fresh water locked in land ice than today (global sea level was about 130 m lower than today during the Last Glacial Maximum). On the other hand there is emerging evidence that the AMOC may have undergone prolonged phases (up to 1000+ years) of reduction during previous interglacial periods (the warm periods between ice ages; Galaasen et al., 2020) suggesting that large AMOC changes can occur in warm climates.

The AMOC's likely future fate remains an important question, though one that we cannot yet answer based on our current level of understanding.

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Links to examples of media coverage shown in figure on page 9:

Washington Post, 9 February 2024

CNN, 9 February 2024

NZZ, 9 February 2024

The Independent, 12 February 2024

euronews, 13 February 2024

The next generation

Meet some of EPOC's early career researchers

EPOC has an expanding community of Masters students, PhD candidates and postdoctoral researchers who provide much of the brainpower and effort within the project. In addition to Jack, Katya and Simon who penned the *Crossroad2024* article on p6-8, some of our new early career researchers introduce themselves...

Brady Scott Ferster, CERFACS

My academic journey has been firmly rooted in climate sciences and oceanography, with a particular focus on understanding complex oceanic processes and their broader impact on global climate systems. I received my BSc in Meteorology from the Pennsylvania State University in 2016. I earned my PhD in Marine Science from the University of South Carolina in 2019, where I explored the critical role of the Southern Ocean in global ocean circulation and climate variability. My work there was funded through the NASA/South Carolina Space Grant Consortium Graduate Assistantship and recognised with the university's Breakthrough Graduate Scholar Award in 2019.

Following my PhD, I embarked on postdoctoral research that delved into the intricate relationships between intra-tropical and tropical to mid- and high-latitude teleconnections and their influence on ocean dynamics. During my time at LOCEAN (Sorbonne Université, Paris, FR), under the Make Our Planet Great Again (MOPGA) initiative, I focused on understanding the sensitivity of the Atlantic Meridional Overturning Circulation (AMOC) to significant climatic shifts, such as Indian Ocean warming and Arctic sea ice decline. Afterwords, I began a new postdoc at Yale University (USA), where I investigated AMOC multi-decadal variability and its dependence on the mean AMOC state. More recently, I collaborated with the IPSL climate modeling group to further explore parametric uncertainty and model development through perturbed parametric ensembles. These studies have provided crucial insights into the mechanisms driving AMOC variability and their broader implications for global climate systems.

Currently, as a postdoctoral researcher at CNRS-CECI / CERFACS (Toulouse, FR), I am contributing to the EPOC project through WP4. My research focuses on understanding the climate uncertainty of abrupt-4xCO_2 simulations, particularly in relation to the models' background climate state and the varying mechanisms driving climate responses at different resolutions. My work continues to explore the sensitivity and stability of key climate processes under the influence of anthropogenic warming, with the ultimate goal of enhancing the accuracy and reliability of climate models. By quantifying and demonstrating the various sources of climate model uncertainty – stemming from background state, resolution, and sub-gridcell parameterizations – I aim to contribute to the improvement of global climate modeling efforts. Additionally, I am part of the Fresh Eyes on CMIP early career group, where I am further trying to participate and collaborate to the global climate modeling effort.

Joining the EPOC project in April 2024 marked an important milestone in my career, working at a new research lab and team. Outside of work, in August 2024 my fiancé and I will be married in Toulouse, France. In addition, I enjoy cycling through the French countryside, hiking in the Alps, and exploring new destinations across Europe. My latest hobby is making hot sauces using homegrown peppers and fruits.

Hege-Beate Fredriksen, NPI

I am a postdoctoral research fellow in physical oceanography at the Norwegian Polar Institute. I finished my PhD in applied mathematics at UiT the Arctic University of Norway in 2017. After that I had some short-term contracts involving a lot of teaching and then a postdoc period at the same University. My current postdoc started in October 2022.

My role in EPOC is to quantify how much water is transported in and out of the Arctic through the four main gateways (Fram Strait, Barents Sea Opening, Davis Strait and Bering Strait), and the associated heat and freshwater transport. With this we want to quantify how much of the Atlantic overturning is happening inside the Arctic Ocean. Most of the data used is obtained from instruments at moorings in the ocean, measuring e.g., temperature, salinity and velocity of the water year-round.

Images courtesy Trine Lise Sviggum Helgerud, NPI

Here I am (above) on board the research vessel *Kronprins Haakon* loading data from the mooring instruments recovered during the Fram Strait cruise 2023.

Gaurav Madan, NCAS

I am from Delhi, India. Beginning with an undergraduate degree in Computer Science and Engineering, my academic path has been an interesting junction of several fields. Growing fascinated by the tornadoes, I chose to study Atmospheric and Planetary Sciences and graduated from India with a Master of Science. As I progressed, it dawned upon me that the Arctic and sub-Arctic is probably the most exciting region to study for how rapidly it is changing, and the sea ice may vanish in my lifetime. Tornadoes could wait! This curiosity led me to an MSc in Physical Oceanography in Canada, culminating in my recent work: a PhD in Physical Oceanography at the University of Oslo, which I will shortly defend.

During my PhD, I focused on quantifying the complex physical processes governing large-scale ocean circulation, particularly the Atlantic Meridional Overturning Circulation (AMOC) in climate models. My research primarily concentrated on the subpolar North Atlantic region. Using CMIP6 models, my project explored potential changes in ocean currents under varying CO_2 emission scenarios. I aimed to quantify the relative importance of different physical ocean characteristics such as surface temperature, salinity and temperature gradients, and wind stress. This experience has deepened my understanding of the ocean's critical role in our climate system, equipping me with essential skills in model simulations and data analysis.

Currently, I am contributing to the EPOC project as a postdoctoral research scientist at the National Centre for Atmospheric Science (NCAS) in Reading, UK – specifically within WP3. Our primary goal is to utilise model simulations to attribute past changes in the AMOC, exploring the role of external forcing in its variability using large ensemble single-forcing simulations. We aim to characterise AMOC across the entire Atlantic over the historical period and rigorously evaluate it against AMOC reconstructions, with special attention to RAPID data comparisons.

Given evidence suggests AMOC may be weakening, it is essential to assess the mechanisms by which external forcing drives AMOC, looking at the role of atmospheric circulation versus thermodynamic changes in driving surface density fluxes. Our work in EPOC aims to differentiate between the effects of external forcing and internal variability by analysing ensemble means and spreads. I just joined EPOC in August 2024. My journey thus far has been deeply enriching, and I look forward to contributing further to our understanding of oceanic and climatic processes.

EPOC out and about

Ocean Sciences 2024, New Orleans

The Ocean Sciences Meeting took place in New Orleans, USA in February 2024. Here, EPOC scientist Jon Robson co-convened a session on the Atlantic Meridional Overturning Circulation: Variability and Connectivity which included contributions from EPOC and the wider community on the AMOC research that has been ongoing over the past decades. In the poster session, EPOC early career researcher María Jesús Rapanague presented a poster on *Strong meridional connectivity of the AMOC in an eddy-resolving coupled simulation compared to lower resolution simulations* and EPOC newcomer Gaurav Madan (see p13) presented a poster entitled *The weakening AMOC under extreme climate change*.

In addition to the AMOC-specific session, EPOC researchers also participated in two townhall meetings:

1. A townhall on the use of ocean bottom pressure for oceanographers and geophysicists to discuss joint approaches. Here, Eleanor Frajka-Williams presented on the experience of deploying new drift-free bottom pressure sensors (from the MSM121 cruise in September 2023), and a colleague from WHOI (Kate Rychert) presented on the deployment of drift-free bottom pressure sensors at 26°N for EPOC research.
2. A townhall on Subpolar North Atlantic Ocean Biogeochemistry and OSNAP workshop, where Eleanor Frajka-Williams and Pete Brown presented on the biogeochemical observational efforts in the North Atlantic (see plot below). These were both efforts aligned with WP5 of EPOC, which aims to develop and deploy elements of a next generation AMOC observing system.

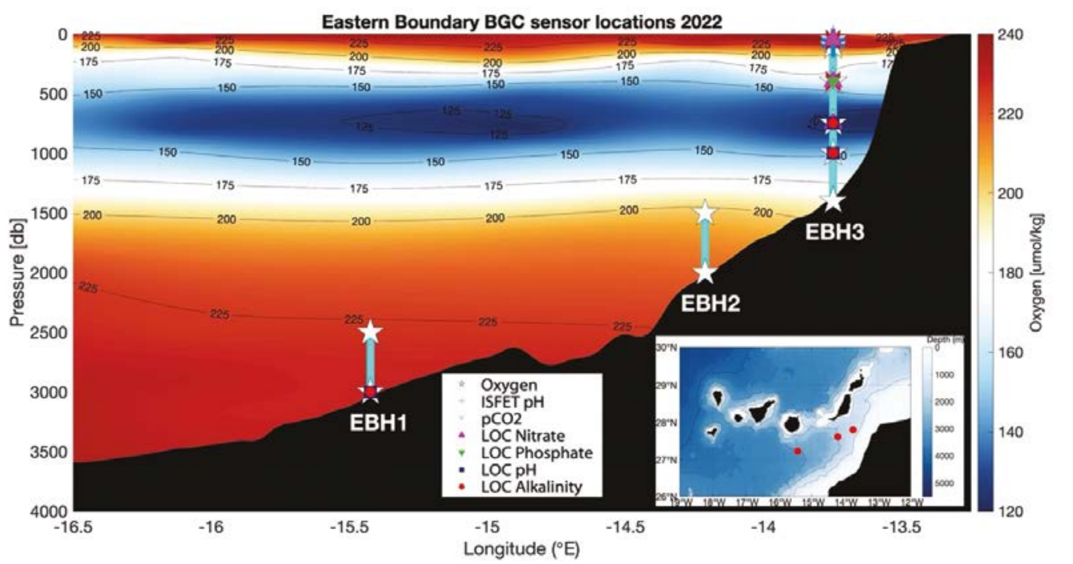
EGU General Assembly 2024, Vienna

Later in the spring, the meeting of the European Gesciences Union (EGU) took place in Vienna, providing another key opportunity to showcase EPOC work. Researchers from across the project engaged in a number of sessions, presenting EPOC progress and work in related projects.

AAORIA / Partnership for Atlantic Cooperation: Workshop on Observations and Modeling, Washington, 26-30 August 2024

The All-Atlantic Ocean Research Alliance (AAORIA) is the result of science diplomacy efforts involving countries from both sides of the Atlantic Ocean, aiming at enhancing marine research and innovation cooperation across the Atlantic anywhere between the Arctic and Antarctica.

A recent workshop in Washington, co-organised with the US Partnership for Atlantic Cooperation, represented the first step in the Ocean Observing and Modeling Area of Action that was agreed during the 2023 AAORIA Annual Forum (Cape Town, 21-22 Nov 2023). The ultimate goal of this workshop was to gather the necessary input needed to formulate a work plan for submission to the AAORIA High Level Board and to share with the Partnership for Atlantic



Left: Sensors deployed on the eastern boundary of the RAPID 26°N array, including:

Parameters: oxygen (10), nitrate (3), phosphate (1), pH (5), alkalinity (3) and pCO2 (2)

Targeting: the oxygen minimum zone, N:P maximum, deep chlorophyll maximum and upwelling/ offshore filaments.

Cooperation prior to the 2024 AAORIA Forum, which will take place in Ottawa in October 2024.

Opened by Ambassador Jessye Lapenn, Senior Coordinator for Atlantic Cooperation at the US Bureau of Oceans and International Environmental and Scientific Affairs, the workshop aimed to:

1. Create a comprehensive list of ocean observation and modeling work that has been completed in the Atlantic Basin;
2. Share information on ocean observation and modeling work that is currently underway or is already planned but not started in the Atlantic Basin;
3. Identify gaps in ocean observation and modeling work that needs to be completed in the Atlantic Basin; and
4. Create a prioritised list of gaps in ocean observation and modeling work in the Atlantic Basin and recommendations for how to fill those gaps to share with AAORIA and the Partnership for Atlantic Cooperation.

EPOC was represented at this workshop by Eleanor Frajka-Williams, pictured above (third from left) with fellow EU project representatives (L-R) Patrizio Mariani (MissionAtlantic), Maria Hood (EU4OceanObs) and Lina Mtwana Nordlund (BioEcoOcean).

Coming up...

Agulhas Current Observing System Design Workshop

Cape Town, South Africa, 9-12 September 2024

This workshop, convened as part of the GOOS Ocean Observing Co-Design Programme, aims to understand priority gap areas, develop observational requirements and a draft design of an ocean observing system to better understand key features in the Agulhas Current region that influence critical areas - such as tropical cyclones, marine life and marine heatwaves. Online and in person; pre-registration required. More details at https://goosocean.org/event/4196.

EPOC 2nd Annual Meeting

University of Reading, UK, 18-20 September 2024

The EPOC community will meet at the University of Reading in the UK for its second annual meeting. Project partners will present latest results, discuss progress to date and plan work for the year ahead.

CLIVAR workshop on Improving Modelling of the AMOC

Met Office, Exeter, UK, 23-25 September 2024

This workshop will discuss how to improve the modelling of the AMOC in climate models. The goals of this workshop will be to provide recommendations to the community about how to improve our modelling of the AMOC, including suggestions of specific activities. Topics to be discussed include how to assess models' fidelity, the role of resolution, and how to improve representation of important processes. Details at www.clivar.org/events/workshop-improving-modelling-amoc.

explaining and predicting the ocean conveyor

About EPOC

EPOC (**E**xplaining and **P**redicting the **O**cean **C**onveyor) is a 5-year research project funded under the European Union's Horizon Europe programme. Involving 21 institutions from France, Germany, Norway, UK, USA and Canada, and led by Universität Hamburg, EPOC aims to generate a new concept of the Atlantic meridional overturning circulation (AMOC), its function in the Earth system and how it impacts weather and climate.

EPOC has five overarching scientific objectives:

- Generate comprehensive records of AMOC transports across the whole Atlantic, to assess the timescales of transport variability and the degree to which the AMOC behaves as a conveyor belt.
- Determine key processes that make or break meridional connectivity of ocean transports, and assess their representation in models, especially in high resolution coupled simulations.
- Identify the processes and drivers of recent change in the AMOC, and infer the likely roles of natural and anthropogenic forcings, and internal variability.
- Assess the key processes of future AMOC changes, and identify indicators of abrupt changes and AMOC-related climate impacts with societal relevance.
- Design, and deploy elements of, a next generation observing system for the entire system of the AMOC.

www.epoc-eu.org info@epoc-eu.org @epocproject EPOC Project

explaining and predicting the ocean conveyor

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