Many-sided monitoring of the subpolar North Atlantic

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ADCPs in long-term studies of deep currents

The last couple of decades have seen a sea change in understanding deep currents in the North Atlantic Ocean. And this change has fundamental importance for explaining the ocean's role related to climate change.

The deep circulation provides a buffer for increased heat and carbon dioxide that would otherwise reside in the atmosphere. For climate studies, understanding the mechanisms driving changes in the meridional overturning circulation (MOC) is essential.

Various basin-scale observational programmes have toppled the traditional view of the deep circulation system. We'll look at examples of Teledyne RDI's (TRDI) ADCPs in programmes observing the MOC in the subpolar North Atlantic.

LONG TIME SERIES OF REPEATED VOS TRANSECTS

For 25 years, Tom Rossby (University of Rhode Island, USA) and Charles Flagg (State University of New York, USA) have sustained their powerful approach to studying the currents of the Gulf Stream. For measuring frequent transects, they devised an automated system for use on volunteer observing ships (VOS). The

Figure 1. An automated ADCP-based system is aboard VOS Nuka Arctica*, which runs regularly across 60°N between Greenland and Denmark.* Photo courtesy of Royal Arctic Line A/S, Greenland (www.ral.gl)

ongoing programme combines and controls a hull-mounted 75kHz ADCP with satellite-based positioning. The ADCP uses TRDI's phased array technology for profiling to 800 metres.

Next, Rossby and Flagg applied their proven VOS-based method using ADCPs to study the meridional overturning circulation. They anticipated that changes in the warm Atlantic inflow (upper limb of MOC) might be a forerunner to changes in deepwater formation. They looked to establish long-term monitoring at key sections across 60°N. The researchers wanted to clarify pathways and volume fluxes of Atlantic Waters into the Nordic Seas.

INFLOW TO NORDIC SEAS

In 1999, Rossby and Flagg replicated their automated ADCP system aboard a container ship (the *Nuka Arctica*) which runs between Greenland and Denmark. While making its three-week round trip, the ship sails on two different tracklines – outbound vs inbound. The programme ran for four years, restarted in 2012, and is ongoing.

Together with colleagues at University of Bergen (Norway), Rossby and Flagg fitted a Teledyne RDI 150kHz ADCP in the ship's hull. They measured currents along repeated sections. Their goal was to illuminate the mean state and variability of the circulation in the upper 400 metres.

Despite challenges due to mountainous seas, the team collected more than 60

Overturning circulation

The Gulf Stream's warm surface waters carry heat poleward. Some of these waters reach subpolar regions.

There they cool due to discharging heat content to the atmosphere while also absorbing its carbon dioxide. These cooler waters sink and return equatorward as deep cold currents.

With respect to climate control, this overturning system redistributes heat and also hides away anthropogenic CO_2 in the deep ocean.

Understanding the mechanisms driving changes in the overturning circulation is essential for climate studies – notably, for accurate climate models.

sections during the initial programme. Their results demonstrated advantages of a VOS-based sampling programme.

During a single transect in this region, the mean flow is masked by the eddy velocity field. Yet the mean flow emerges when many transects are averaged. Notably, narrow mean flows steered by major subsea ridges were clear. The averaged data also showed well-defined flows through the principal basins.

Making direct and closely-spaced (2.5-kilometre) measurements with the ADCP is invaluable for seeing narrow mean flows. They are less apparent to indirect methods – like hydrographic sections and satellite altimetry – that unavoidably average currents over wide distances.

In late 2012, the programme using *Nuka Arctica* was restarted. Now using a Teledyne RDI phased array 75kHz, the VOS work is an ongoing partnership with Henrik Søiland and other researchers from Norway (Institute of Marine Research). Accurately measuring deep ocean currents from a fast-moving ship (16 knots) demands that shipboard ADCPs operate at a low frequency yet keep narrow acoustic beams. This is a benefit of phased array technology.

The ADCP's data set reports currents with an accuracy of one centimetre per second, close along track (2.5-kilometre) spacing, and deep into the ocean – 700-800 metres, or about twice the depth of the earlier measurements. This provides detailed coverage of the velocity field. It also provides a unique basis for recording directly the volume of water transported by the upper waters.

MERGING MODERN TECHNOLOGIES

The researchers merged their VOS-based ADCP data sets with data from several other technologies – GPS, satellite altimetry, Argo drifters (profiling to 2000 metres). From their composite data set, the team made direct and accurate estimates of volume, heat and freshwater fluxes between Greenland and Scotland.

When they compared their two ADCP studies from *Nuka Arctica* – 13 years apart – the researchers calculated almost the same upper ocean transport between Greenland and Scotland. They reported a mean transport for the MOC of about 18 million cubic metres per second. This is about half the volume of water flowing through the Florida Straits – nozzle of the Gulf Stream. They also found largely unchanged values for the transport of currents flanking mid-ocean ridges.

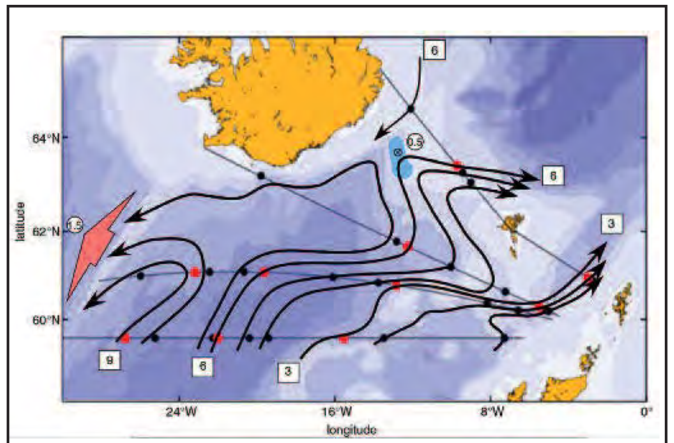

*Figure 2. Volumes of water transported into Nordic Seas, measured along VOS routes (*Nuka Arctica, Norröna*). Image: Childers et al. (2015). See text*

FERRY-BASED PROGRAMME

About a decade ago, Rossby and Flagg rigged a fast-moving ferry (*Norröna*) that makes weekly runs between Denmark and Iceland. In this case, they again opted for a 75kHz TRDI Ocean Surveyor ADCP for deeper measurements.

After the ADCP was first installed aboard *Norröna*, much effort was directed to rectify issues due to acoustic inference from bubbles. The determination of these researchers has paid off. Early results revealed some key findings that sparked interest about pathways of the currents. One example is recirculation in the Faroe-Shetland Channel.

Exploring candidate pathways for this current generated ongoing scrutiny of the thermal field and its variability in this region. In turn, spatial and temporal patterns in the temperature data raised questions that were examined in the ADCP data sets from *Norröna*'s transects. Volume transport and heat flux through these sections can be readily dissected into specific contributions.

The researchers are working to combine the shipboard sections of ADCP-based

Shipboard ADCP

ADCP technology was invented for continual measurement of water current profiles from moving ships.

These ADCP data sets are 2D spatial transects – along the ship's path and through depth. They show the details of circulation patterns of current systems.

At sea, they also provide real-time data to aid decision-making and to adapt field operations. Many research vessels worldwide now carry ADCPs.

For observing currents from a ship underway, two different types of measurements are merged:

- apparent velocity of the water when seen from the moving ship
- velocity of the ship.

Away from coastal regions, a GNSS system generally supplies the latter.

currents with moored data sets and altimetry. The ensemble dataset will benefit from complementary advantages in resolution, time and space.

20-YEAR TIME SERIES OF OVERFLOW OBSERVATIONS

In the Nordic Seas, deep currents in the returning limb of the MOC move along the seabed. At just a few locations, they cross topographic barriers to enter the North Atlantic. These are sills or deep channels where the passing currents are called overflow.

The Faroe Bank Channel (FBC) is the deepest passage across the Greenland-Scotland Ridge. The Faroe Bank Channel overflow is a continuous bottom flow of cold and dense water passing southward into the North Atlantic.

Since 1995, a team of researchers from the Faroe Islands and Norway have monitored the FBC overflow. Teledyne RDI's ADCPs have been used at four different sites, always with at least one ADCP mooring located mid channel.

At these sites, ADCPs were upward looking, mostly deployed in short moorings. After 20 years, the record comprised 6750 days of ADCP velocity profiles. Reaching at least 400 metres above the bed, the profiles contained the overflow layer.

Using ADCP data, the researchers constructed time series of volume

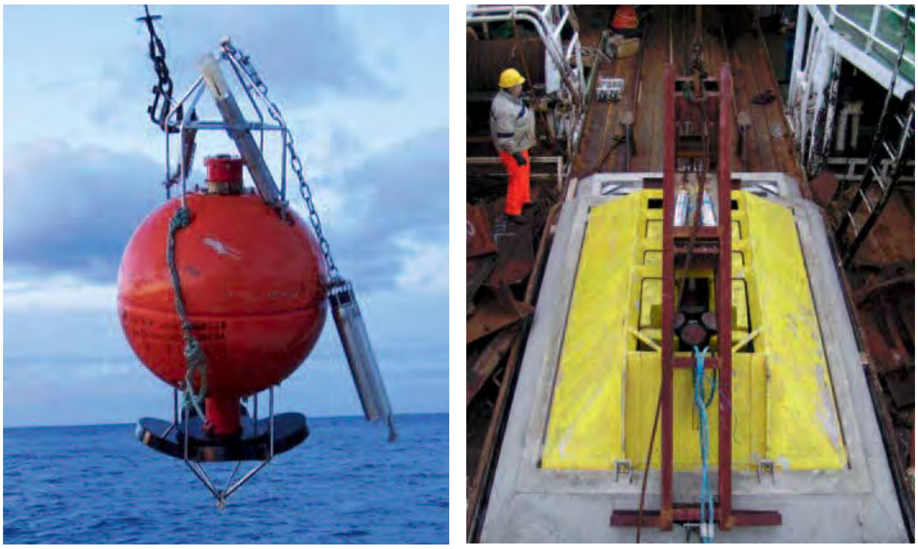

Figure 4. ADCPs were mostly deployed atop short moorings. At the shallowest site, the ADCP was put in a seabed frame to reduce the chances of being snagged by fishing trawlers. Photos: Hansen et al. (2015) Technical Report. *See text*

transport for the FBC overflow. Results show a stable volume transport of about 2.2 million cubic metres per second. That volume is more than four times the outflow of the Amazon, which is the largest river on earth.

Scientists interpret these overflow records as a proxy for deepwater formation in the high northern latitudes. Traditionally, the latter was thought to be tightly linked to changes in the overturning circulation system. For this period, the steady value noted here was matched at other sills in the region.

Yet large swings in volume transport were reported for the MOC monitored at 26.5°N. So the assumed tight link is now being reassessed, notably how changes in deep circulation are to be modelled in climate studies. The long-term ADCP time series in Faroe Bank Channel provides a key piece to the puzzle.

LONG-TERM LOWERED ADCPS

On the western side of the subpolar North Atlantic is the Labrador Sea. Located between Labrador and Greenland, this is another source for North Atlantic deep water in the lower limb of the MOC.

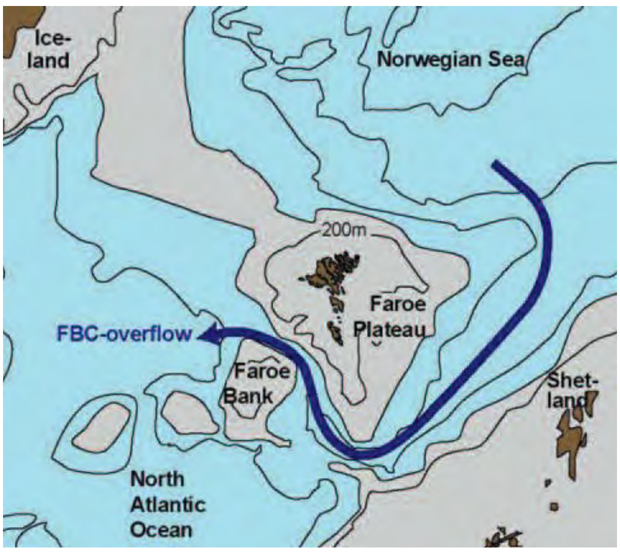

Figure 3. The Faroe Bank Channel is the deepest passage across the Greenland-Scotland Ridge. Image: Hansen et al. (2015) Technical Report. *See text*

From 1997, German researchers have installed an ocean observatory at 53°N. It is located downstream from deepwater formation. Their goal is to monitor closely water transports at all levels – from surface to seabed. The observatory comprises

Lowered ADCP

For current profiling below the range of ship-mounted ADCPs, scientists worldwide lower compact ADCPs to the seabed.

The ADCPs are attached to a hydrographic package that is lowered routinely to catch water samples and measure water properties. Careful processing of measured currents corrects for the motions of the lowered package and the ship.

Sometimes dual ADCPs are used – looking up and down respectively.

During descent and ascent, the ADCP continues to measure current profiles with ranges to 100 metres. Later these short segments are stitched together to produce a full-depth profile.

When the seabed is within acoustic range, the ADCP's bottom tracking is used in the data processing.

These lowered ADCPs must endure great mechanical stress during hundreds of cycles, going from air pressure to great depth.

Figure 5. Ready to be lowered to the seabed, ADCPs (yellow) are fitted on a hydrographic package. Photo: Mia Taylor (miataylor.co.uk)

current meter moorings and recurring shipboard sections.

Combining both ship-mounted and lowered ADCPs, these shipboard sections were made during 13 cruises over a 17-year period (1996–2014). Hydrographic packages carrying ADCPs were lowered to the seabed. Data from 150 lowered ADCP stations supplement the moorings to describe outflow from the Labrador Sea.

The researchers identified three significant advantages to using lowered ADCPs. (1) Much improved spatial resolution across the section: 12–15 stations cf. three–five moorings. Improved understanding of spatial scales underpins more accurate transport calculations from moored data. (2) Better definition of the inner and outer edges of the boundary current. (3) Seeing the strength and extent of recirculating currents seaward of the undercurrent edge.

The researchers observed that the boundary current was 120 kilometres wide and that its spatial structure was stable. The volume of deep water exported southward was 30 million cubic metres per second. For comparison, a similar volume is transported northward through the Florida Straits to supply the Gulf Stream.

In Figure 6, you can see a composite section of lowered ADCP data collected across the boundary currents of the Labrador Sea. At the top left is the Labrador Current to 500 metres depth. Deeper and seaward are stronger currents of the Deep Western Boundary Current. The high-speed core near the deep-sea floor is water from the Nordic Seas. Blue colour shows southward currents in centimetres per second. Green lines separate water masses from different sources.

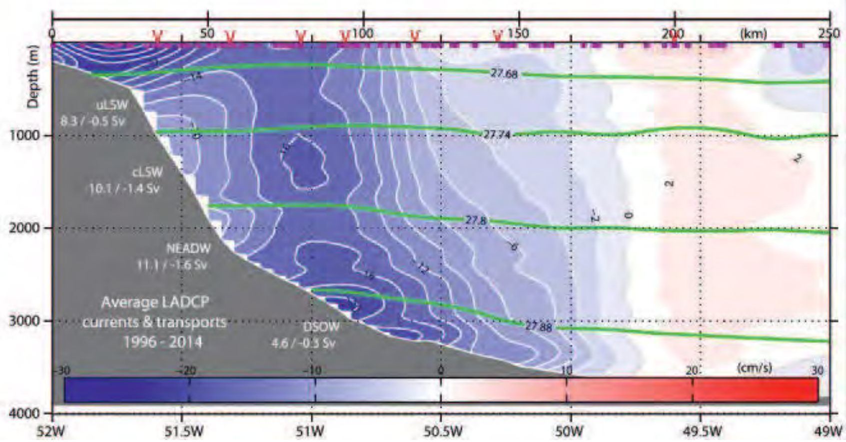

Figure 6. Composite section of lowered ADCP data showing outflow (blue) from the Labrador Sea. Data come from 150 stations during 1996–2014. Image: Zantopp et al. (2017). *See text*

ADCP: ONE TOOL, MANY USES

Although conducted by scientists from different countries, these studies share a common intent – to develop an observational basis for climate work. Surprisingly, they each used the ADCP in a different way. Considered together, these studies reveal the remarkable versatility of the ADCP as a powerful tool for addressing a fundamental challenge for ocean science. ■

Picture Credits

Figs. 1, 5: See caption of figure.

Fig. 2: Credit: Childers, K. H., C. N. Flagg, T. Rossby, and C. Schrum, 2015: Directly measured currents and estimated transport pathways of Atlantic Water between 59.5°N and the Iceland-Faroes-Scotland Ridge. *Tellus A, 67, 28067*, http://dx.doi.org/10.3402/tellusa.v67.28067.

Figs. 3, 4: Credit: Bogi Hansen, Karin M. H. Larsen, Regin Kristiansen, Ebba Mortensen, Svein Osterhus. Faroe Bank Channel Overflow 1995-2015 – Technical Report (2015) Havstovan nr.: 15-02.

Fig. 6: Credit: Zantopp, R., J. Fischer, M. Visbeck, and J. Karstensen (2017), From interannual to decadal: 17 years of boundary current transports at the exit of the Labrador Sea, *J. Geophys. Res. Oceans*, *122*, 1724–1748, doi:10.1002/2016JC012271.