The GO-SHIP A02 Survey 2017

Taking the Pulse and Temperature of the North Atlantic Ocean

by Evin McGovern, Caroline Cusack, Douglas Wallace, and Peter Croot

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The small medieval Irish city of Galway, at the edge of Europe, faces the Atlantic Ocean. The city prospered in the late middle ages on maritime trade with Europe and preeminent transatlantic voyager Christopher Columbus reputedly visited in 1477. To this day, Galway has a strong maritime tradition and it seems appropriate that the Irish Marine Institute (MI) in Galway was the place where the European Union and the governments of Canada and the USA agreed upon a new Atlantic Ocean Research Alliance (AORA). The Galway Statement on Atlantic Cooperation notes that ocean observation is fundamental to understanding the ocean and forecasting its future and aims to align observation efforts to improve ocean health and promote sustainable management. The EU Horizon 2020 project AtlantOS supports and builds on the aims of the Galway Statement, as do other Atlantic basin initiatives, including Canada's recently-funded Ocean Frontier Institute. The international Atlantic-wide partnerships in AtlantOS are working to innovate, improve and enhance the existing integrated Atlantic Ocean Observing System. In this essay we highlight the GO-SHIP A02 transatlantic survey carried out over 27 days in April-May 2017, which was accomplished through the cooperative approach envisaged in the Galway Statement.

Why we Need Enhanced Ocean Observations

The major role of the oceans in regulating climate necessitates that we observe them at various spatial and time scales to document variability of ocean processes and dynamics and better understand the interactions with weather and climate. In the context of anthropogenic forcing of the climate system, the ocean plays a massive role with about 40% of the net CO_2 emissions of the past 200 years and 93% of the extra heat trapped by the Earth in recent decades currently stored there. This uptake of heat and CO_2 is subject to change which provides an urgent imperative to measure and understand variability and trends. Direct and indirect ocean climate change effects, such as changes to surface ocean temperatures, additional freshwater inputs in the Polar Regions, thermal expansion and sea level rise, changes in hydrodynamic patterns, as well as associated perturbation to biogeochemical cycles are impacting our oceans and their ecosystems and, in turn, on the services they provide to society. Moreover, these changes will feedback in complex ways to amplify or diminish climate forcing. Despite this, the oceans are grossly under-observed and addressing this requires a concerted international effort. Coordination of this effort is essential to maximize the use of the limited available resources and to deliver information of most value to the scientific community, policy makers and society. To this end, the Global Ocean Observing System (GOOS) has identified a suite of physical, biological and biogeochemical essential ocean variables (EOVs) to facilitate a common approach to observation across networks and platforms.

Ocean Observation and Ship-based Hydrography

Over recent years there have been major advancements in ocean observing technology, including many novel and robust sensors for key oceanographic parameters (e.g., oxygen, pCO_2 and pH), coupled with the emergence of new platforms for deployment of this equipment (e.g., profiling floats, gliders, advanced moorings, etc.). For example, an expanded network of ocean moorings fitted with multiple sensors can deliver high-frequency, real-time data at fixed locations; voluntary observing ships (VOS) measure sea-surface and atmospheric variables along their cruise tracks; and an array of over 4,000 Argo temperature/salinity profiling floats sample to a depth of 2,000 metres before resurfacing and transmitting data to shore. Nonetheless, while these technologies have vastly increased our observational capacity and capabilities, ship-based measurements carried out on research surveys remains the "gold standard" where a much wider range of parameters can be measured to full ocean depth and to the highest possible quality. Such surveys provide the high quality "reference" datasets that are indispensable for quality assuring data from other observing networks.

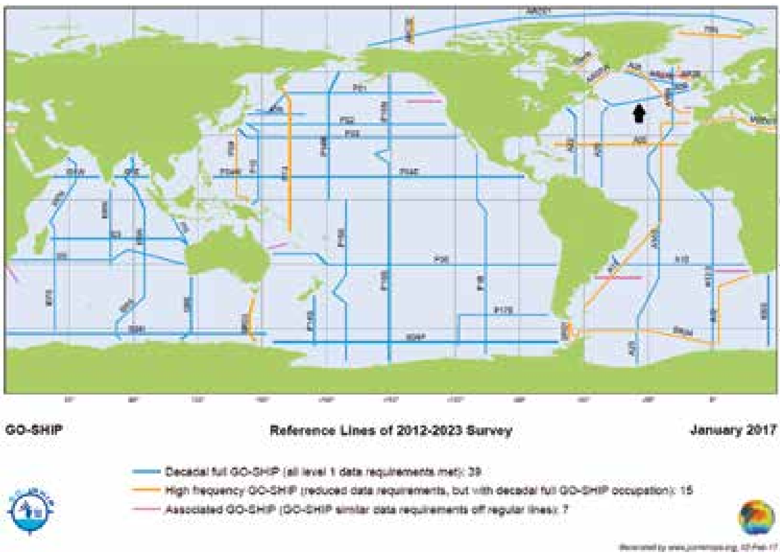

Figure 1: GO-SHIP global reference lines 2012-2023 (2017). Black arrow points to the A02 line.

Global ship-based hydrography has been undertaken since the 1960s through programs such as the World Ocean Circulation Experiment (WOCE) and CLIVAR programs. The current Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) aims to document the changes in inventories of heat, freshwater, carbon, oxygen, nutrients and transient tracers, covering the ocean basins from coast to coast or coast to ice and sampling to the full ocean depth. To this purpose GO-SHIP has identified a series of reference lines that criss-cross the world's oceans (Figure 1). GO-SHIP specifies core parameters (EOVs) which should be collected at least once per decade for each reference line, and also identifies additional desirable and ancillary parameters. GO-SHIP methodological guidelines and quality criteria support the collection of comparable data of known quality. Parameters are measured in-situ and ex-situ using a combination of underway sensors continuously gathering data in surface waters; sensors lowered on a carousel through the water column at fixed stations (profiles); and by onboard or post-survey analyses of water samples collected at specific depths throughout the water column using sampling bottles mounted on the carousel (Figure 2). Because the GO-SHIP surveys are intended to collect data of the highest required accuracy on a global scale, issues related to data quality control and intercomparability of data between international groups are of paramount importance.

GO-SHIP A02-2017 Survey

In April-May 2017, the Irish Marine Institute and National University of Ireland, Galway (NUI Galway) led an international partnership to complete the GO-SHIP A02 line on the Irish national research vessel, the 65.5 m RV *Celtic Explorer*. GO-SHIP surveys are expensive, logistically demanding and require teams of highly-trained personnel and specialized equipment. The participation of experienced international partners, bringing expertise, equipment and funding was a prerequisite to this undertaking. As such, this was a fine example of the Galway Statement in action with onboard teams from Canada, Germany, the UK, and the USA, and additional support from experts in Denmark and France (Table 1). The international nature of the participation also offered an unusual opportunity for cross-comparison of methods, data quality procedures, and exchange of technical expertise.

The A02 line runs from the margins of the Grand Banks, south of Newfoundland, to the shelf edge of the Celtic Sea off southern Ireland. Continuous underway measurements

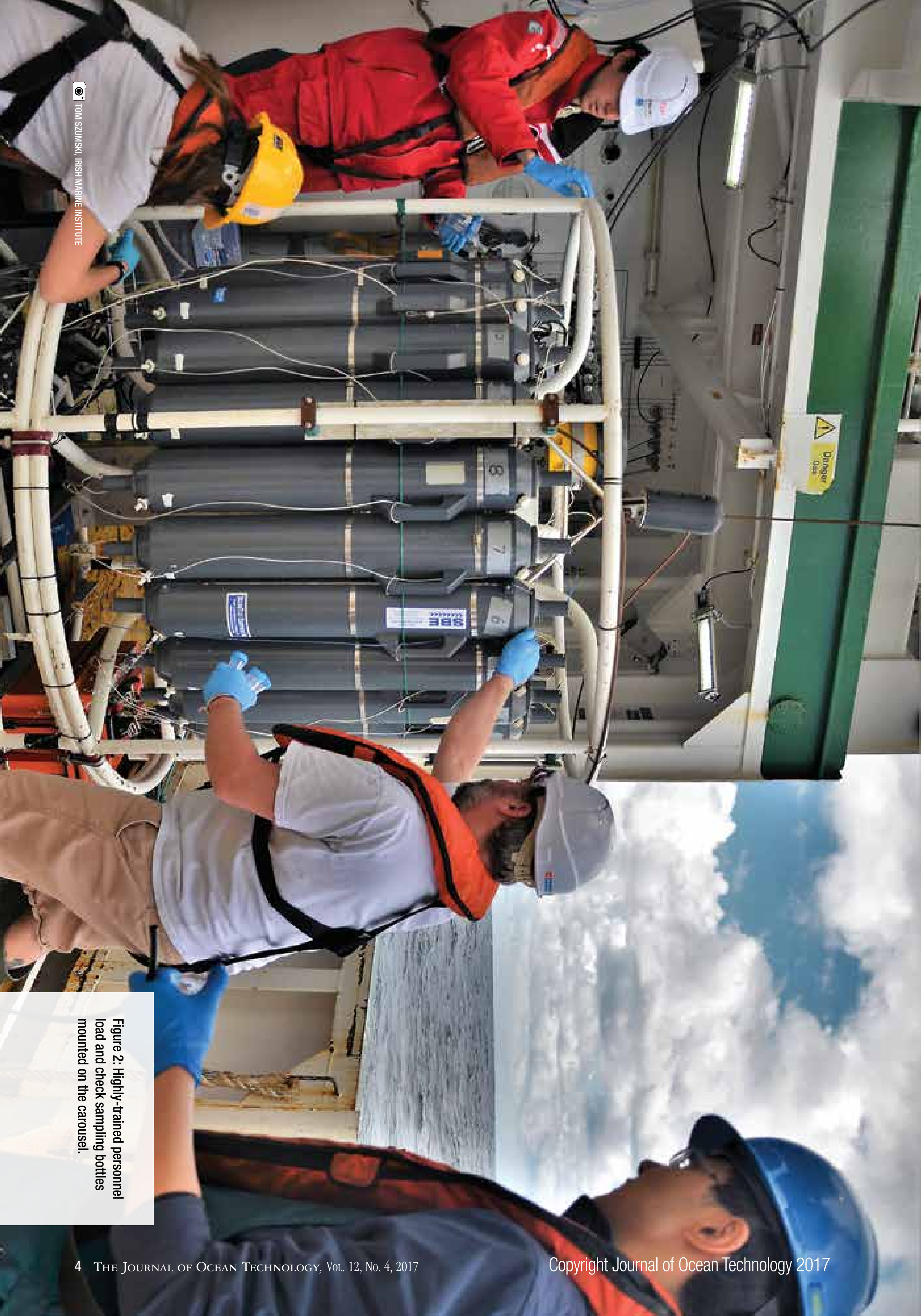

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Figure 2: Highly-trained personnel load and check sampling bottles mounted on the carousel.

Country	Organization	Role
Ireland	Marine Institute National University of Ireland, Galway	Joint lead partners Onboard nutrients, dissolved oxygen (Winkler), salinity team, pCO_2, underway system, CTD
Canada	Dalhousie University, Nova Scotia *Additional support:* Memorial University, Newfoundland Fisheries and Oceans Canada	Support onboard nutrients, $\delta^{13}C$, pCO_2 comparison
Germany	GEOMAR Helmholtz Centre of Ocean Research, Kiel	Onboard transient tracer team
UK	University of Exeter	Onboard carbon team
US	Woods Hole Oceanographic Institution Columbia University	Lowered ADCP – ocean currents
Denmark	Aarhus University	Surface ADCP – ocean currents
France	IFREMER	

Table 1: Partners and roles in A02-2017 survey.

included surface seawater conductivity (salinity), temperature and partial pressure of carbon dioxide (pCO_2), sampled via a hull water intake hose, and water current measurements to ~600 m depth using a vessel mounted Acoustic Doppler Current Profiler (ADCP). At predefined stations along the cruise track, approximately 30 nautical miles apart in the open ocean (Figure 3), the ship's CTD sensor package and bottle rosette was deployed. Fitted with a range of calibrated sensors that measure conductivity, temperature and depth (CTD), dissolved oxygen, relative fluorescence (chlorophyll), water clarity and water current measurements, the CTD carousel was lowered (Figure 4) to just above the ocean floor and then brought back to the surface in an operation that took up to five hours at the deepest stations of > 4.8 km below the ocean surface. Careful procedures were followed to ensure clean water samples were captured during the upcast and on deck the teams subsampled from the rosette bottles in a predetermined order prior to analysis in the onboard laboratories. This included four containerized laboratories situated on the aft-deck specifically for the survey. Unfortunately, storms early in the survey cost precious days when the sea state rendered it unsafe to deploy the CTD carousel so that nine from a total of 67 planned stations could not be occupied due to time constraints.

Oceans and Anthropogenic Carbon

The North Atlantic Ocean, an important arena for ocean observations, forms a part of the large scale global oceanic thermohaline circulation. The Atlantic Meridional Overturning Circulation (AMOC), a density driven circulation pattern, transports warm salty water, heat and carbon in the upper ocean to the high latitudes by the North Atlantic Current and this eventually sinks to return denser, colder, fresher water in the Atlantic deep (Figure 5). The AMOC is responsible for about half of the global oceanic deep water formation. Coupled climate models consistently predict a slowdown of the AMOC and the Intergovernmental Panel on Climate Change concluded in the 5th Assessment Report that it is very likely that the AMOC will weaken in the 21st century although the magnitude of such a slowdown is uncertain.

Since the industrial revolution over 1,500 gigatonnes of carbon dioxide (CO_2) has been released to the atmosphere due to fossil fuel burning and cement production. The climatic effects of these emissions would be more pronounced had the ocean not absorbed about 40% of these emissions. A consequence of this is that the added CO_2 shifts the balance of the inorganic carbon system in seawater and reduces the concentration of carbonate ions, while pCO_2, hydrogen ion $[H^+]$ and

Figure 3: A02 2017 survey track (green line) between St. John's Newfoundland, and Galway, Ireland, and full depth CTD deployment/water sampling stations (red diamonds).

Figure 4: The CTD carousel was lowered to just above the ocean floor and then brought back to the surface in an operation that took up to five hours at the deepest stations of > 4.8 km below the ocean surface.

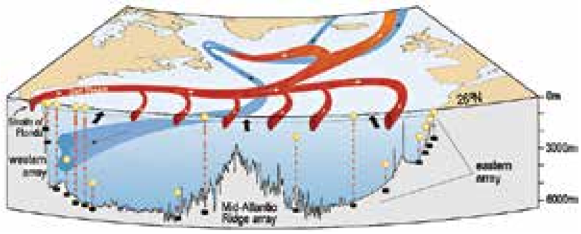

Figure 5: The North Atlantic overturning circulation with the location of the RAPID array moorings along 26°N. Modified from *A change in circulation?* by John Church, 2007 (used with permission).

bicarbonate ion concentrations are increased. This "other CO_2 problem" is known as ocean acidification (OA) as pH is reduced, and we have only become widely aware in the last fifteen years or so of the potential threat this poses to marine ecosystems. Many organisms, including many molluscs, corals, echinoderms, calcifying plankton such as coccolithophores, use carbonate ions to build their shells and skeleton and there is concern that many organisms will not be able to adapt to such a rapid environmental change, especially considering that this stress occurs in conjunction with other anthropogenic perturbations in the marine environment, such as sea surface warming. It is estimated that there has been a 26% increase in $[H^+]$, corresponding to a 0.1 pH unit decrease in the surface ocean since the industrial revolution began.

The last time the full WOCE survey of the A02 line was carried out was in June 1997 on board the German research vessel, *Meteor*. The atmospheric CO_2 level at that time (as measured at Mauna Loa, Hawaii) was 366 ppm. A mean atmospheric concentration of 410 ppm was measured during A02-2017 reflecting the inexorable rise of atmospheric CO_2. Surface pCO_2 was recorded along the track with the teams from Dalhousie University and the MI comparing different systems. By using two independent primary systems with frequent multiple point calibration, the RV *Celtic Explorer*'s General Oceanics equilibrator system and Canadian (Dalhousie) team's SubCTech system, we have added confidence in the data produced. The Dalhousie team also tested the performance of two additional less expensive and simpler pCO_2 sensors which are potentially more practical for installation on other platforms such as volunteer observing ships.

To fully constrain the seawater carbonate system, at least two of the four carbonate parameters, dissolved inorganic carbon (DIC), total alkalinity (TA), pCO_2 and pH, must be measured. For water column sampling on A02-2017, the onboard carbon team from the University of Exeter, UK, collected and analyzed water samples for DIC and TA on board as the preferred parameters for high accuracy. An important aim of GO-SHIP is to quantify the uptake of anthropogenic carbon (C_{ANT}) by the oceans and especially its export to the deep ocean. This is a challenge as C_{ANT} represents only a small fraction of the natural DIC in the ocean and can only be indirectly determined. Moreover, given the complex biogeochemical cycles that exist and long mixing times in the ocean, distributions are heterogeneous. Various techniques are applied to estimate C_{ANT}, each with a number of underlying assumptions. Nutrient and oxygen data can be used to apply corrections for biological uptake and remineralization and transient tracer compounds can support back calculation of transport of surface perturbations such as anthropogenic carbon and temperature anomalies to the interior ocean. Chlorofluorocarbons (CFCs) are synthetic and highly persistent manmade greenhouse gases with a known atmospheric history following their widespread use, primarily as refrigerants and in aerosols in the 20th century, and subsequent control under the Montreal Protocol. These substances are therefore very useful ocean transient tracers and can provide information on ocean ventilation, ocean mixing, and transport time-scales in the interior ocean. The team from GEOMAR Helmholtz Centre for Ocean Research Kiel (Germany) measured two transient tracers, SF_6 and CFC-12, during A02-2017. Another tool to support estimations of C_{ANT} is to use isotopic signatures of carbon ($\delta^{13}C$) in DIC. The ^{13}C content of DIC is decreasing due to dissolution of fossil-fuel derived CO_2 in the oceans. The Dalhousie team measured this parameter at sea for the first time using a newly-developed analytical approach: the A02 cruise allows for intercomparison of these data with historical data measured along the same section with conventional techniques. They are also using deep water samples from the cruise as the basis for a first international comparison of measurement accuracy involving eight groups worldwide.

Availability of dissolved inorganic nutrients such as nitrate, nitrite, silicate and phosphate can be a constraint on phytoplankton growth which is in turn the base of the marine food web. Nutrients also provide useful chemical signatures to distinguish water masses. There are indications of long-term changes in nutrient levels (e.g., silicate) in the North Atlantic associated with shifting supply of water masses and, possibly, changes in the Arctic. Further, the inorganic nitrogen content of the ocean is being perturbed by pollution, including atmospheric deposition of pollution-derived nitrogen in remote regions of the ocean. Sustained long-term measurements of nutrients can help detect such perturbations to biogeochemical cycles. Analysis of water samples for nutrients was carried out by the Irish team with independent validation by Canadian researchers using a separate analyzer. Despite nutrients being a long-standing ocean measurement, the requirements for accuracy are very demanding and have proven difficult to maintain over the years. Again, the A02 cruise provided an unusual and valuable opportunity for comparison of data, exchange of approaches to data quality control, and cross-training of international measurement teams.

One of the most important features of the GO-SHIP network is that, once the data are collected, validated and quality checked, participating scientists ensure the data are submitted to international databases with an open data policy, such as the CLIVAR and Carbon Hydrographic Data Office (CCHDO) and the Ocean Carbon Data System (OCADS). This allows the global scientific community to use the data many times for different purposes e.g., international scientific assessments, basin scale and regional inventories on a decadal scale on anthropogenic carbon, ocean acidification, ventilation, dissolved oxygen, and organic matter recycling. While individually these surveys provide useful data, as repeat surveys they provide considerably more insight. However, when taken together, the full GO-SHIP program, along with the other ocean observing system networks such as ARGO and OceanSITES, provides a global picture of temporal changes to fundamental ocean properties and phenomena. This knowledge is vital to inform society and instigate measures to protect the ocean and to mitigate or adapt to the consequences of these changes.

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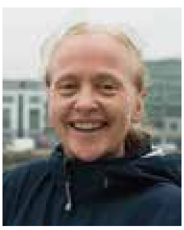
Evin McGovern has over 30 years' experience in marine and environmental sciences. He heads the Marine Chemistry Group at the Irish Marine Institute in Galway – the state agency responsible for marine research in Ireland. Dr. McGovern oversees national marine monitoring relating to marine pollution, seafood safety and chemical oceanography, and his wide-ranging research interests are measurement, fate and effects of hazardous substances in the marine environment, nutrient and carbon cycling, and ocean acidification. He is delegate to multiple international expert groups on the marine environment and has served terms as chair for the International Council for the Exploration of the Sea and OSPAR expert groups on Marine Chemistry and Ocean Acidification. Dr. McGovern has a B.Sc. and M.Sc. from Dublin City University, and a PhD from Trinity College Dublin.



Caroline Cusack is an Oceanographic Services team leader in the Irish Marine Institute, Ocean Sciences and Information Services group. Her main professional interests include understanding the impact of both human pressures (e.g., nutrient enrichment, climate change) and natural phenomena (e.g., harmful algal blooms) on the state of the marine environment. Dr. Cusack's past projects have focused on biological oceanography, water quality (Water Framework Directive, Marine Strategy Framework Strategy Directive), marine food safety (harmful algal blooms, shellfish biotoxins), climate change, and ocean observation.

Doug Wallace is a Professor at the Department of Oceanography at Dalhousie University, Canada, where he holds the Canada Excellence Research Chair in Ocean Science and Technology. He gained his B.Sc. at the University of East Anglia and his PhD in Chemical Oceanography from Dalhousie University, and worked previously at Brookhaven National Laboratory in the USA and the Helmholtz Centre for Ocean Research Kiel (GEOMAR) in Germany. His research topics are chemical oceanography, atmospheric-ocean interaction, and the oceanic cycling of carbon and nitrogen. He is currently Scientific Director of the Marine Environmental Observation, Prediction and Response Network: a national Network of Centres of Excellence which supports research on marine environmental risk across Canada. He leads a trans-national research module of the Ocean Frontier Institute which is focused on "auditing" the carbon sink in the Northwest Atlantic Ocean.

Peter Croot is a marine biogeochemist whose research focuses on understanding the role of biogeochemical processes on the concentration and distribution of trace elements and chemical species in the ocean. His work combines different strands of ocean observations (in-situ and satellite, physical and biological) with laboratory studies to elucidate the kinetics and mechanisms underpinning the transformation of chemical species in the ocean from the surface to the deep. Dr. Croot undertook his PhD studies in the chemistry department at the University of Otago in Dunedin, New Zealand. He subsequently completed post-doctoral studies at Woods Hole Oceanographic Institute (USA) and Gothenburg University (Sweden), and was a researcher at NIOZ (Netherlands), IFM-GEOMAR (Germany), and the Plymouth Marine Laboratory (United Kingdom). Since 2012 he is the Established Professor of Earth and Ocean Sciences at the National University of Ireland, Galway. Dr. Croot has extensive at sea experience in the oxygen minimum zones of the Tropical Atlantic and Pacific and in the iron limited Southern Ocean (participating in four iron enrichment experiments: SOIREE, SOFeX, EisenEx, EIFeX). He is an active collaborator in the marine biogeochemical community through the GEOTRACES, IMBER, GO-SHIP and SOLAS communities.