Scotland's Marine Monitoring Actions and their contribution to international efforts for a sustained Arctic Observing System

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To better understand and predict changing conditions in the Arctic, it is essential to monitor the properties (temperature, salinity, nutrients) and strength of currents flowing between the North East Atlantic and the Arctic. The currents around Scotland have been monitored for decades; and the Scottish oceanographic community is committed to sustaining these observations into the future, and continuing their methodological modernisation with emerging robotic technologies. In addition, the Scottish science community hosts a wealth of expertise in Arctic glacial and marine systems. This statement outlines Scotland's current commitments to a sustained Arctic Observing System, as well as ambitions for future contributions.

The balance of heat in the Arctic Ocean is a primary driver of change in the region. Extremes in weather and shifts in the climate of Europe are strongly coupled to changes in the Arctic. The North Atlantic Current (NAC) flows northward through the Iceland Basin and Rockall Trough (Figure 1). It is the principal part of the upper ocean branch of the Atlantic Meridional Overturning Circulation (AMOC), is the source of waters entering the Nordic Seas and Arctic Ocean, and is a strong influence on UK weather and conditions of shelf-sea waters (both the western shelf and in the North Sea). Surface ocean currents around Scotland transport warm and saline Atlantic-origin water masses northwards, and these pathways contribute significantly to the Atlantic water entering the Arctic Ocean. At depth, the return flow from the Arctic basin into the North Atlantic forms the lower limb of the AMOC.

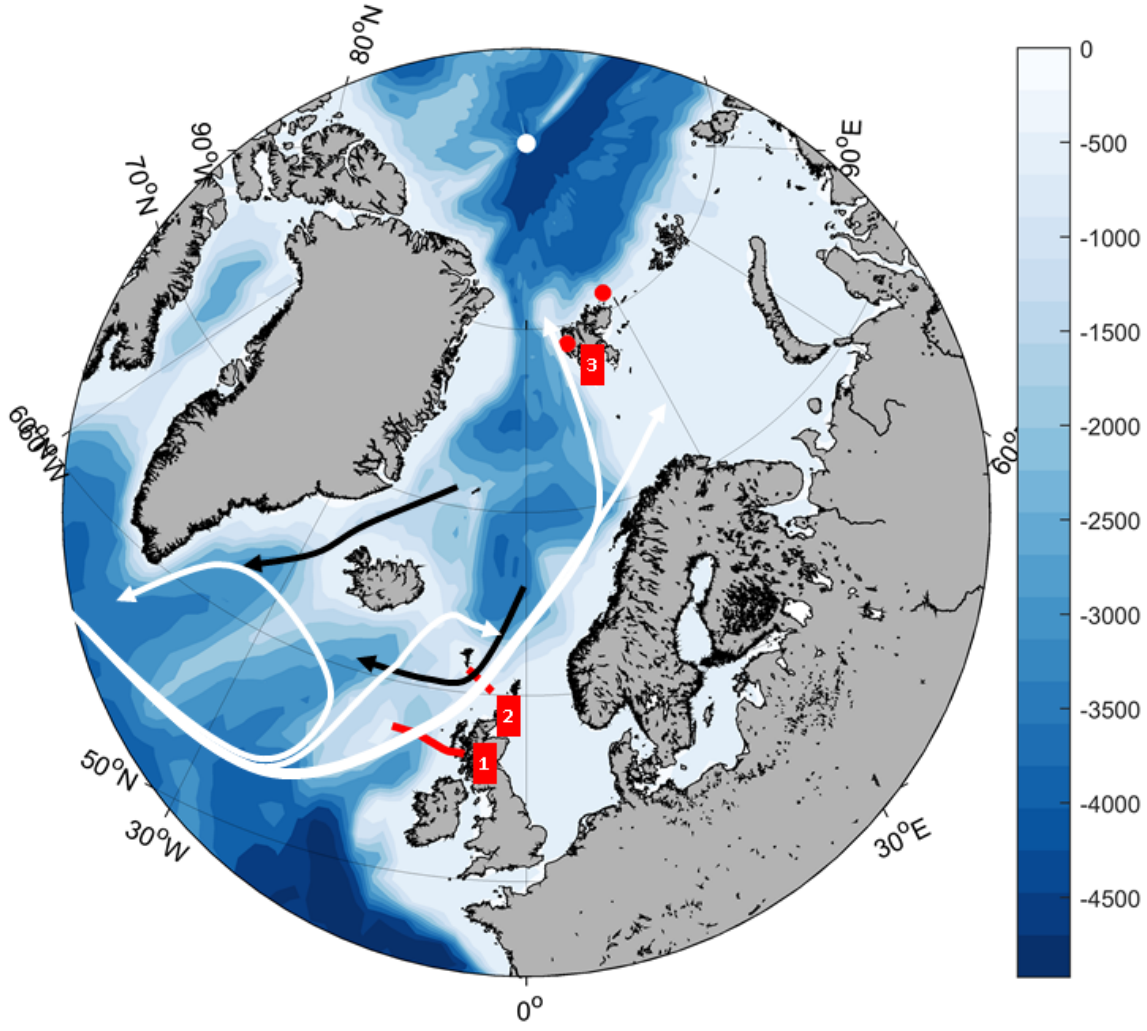

Figure 1. Scotland's Monitoring Actions and their relation to key circulation pathways: 1) the Ellett Array; 2) the Faroe-Shetland Channel; and 3) polar monitoring around Svalbard. White arrows highlight Atlantic Water pathways, black arrows the deep Arctic-origin overflows. Shaded colour shows bathymetry in metres, land has been shaded grey.

In addition to observing the variability of temperature, salinity, nutrients and ocean currents, there is a strong interest from the Scottish community in a wide range of other areas related to Arctic observing including:

- *Invasive non-native species (INNS)*: The possibility of trans-Arctic shipping routes being open throughout the year and therefore becoming a significant transport route to/from the Pacific increases the risk of the introduction of INNS to the Arctic and waters south of the Arctic.
- *Marine litter* (plastics, macro-litter, micro-litter and nanoparticles): an increasing problem due to the resistance of plastic to degradation and their mechanical break up into micro-particles which can be ingested by marine organisms. Marine litter impacts on marine flora

and fauna and is carried by the currents such that areas remote from the source are affected.

- *Contaminants*, especially persistent organic pollutants (POPs) such as halogenated hydrocarbons in top predators: POPs have population consequences for top predators (cetaceans, seabirds), while industrial POP emissions and discharges can be transported in the atmosphere to the Arctic, impacting the Arctic ecosystem. Understanding the impact in the Arctic builds an evidence base to support the decisions of Governments and inter-Governmental organisations.
- *Ocean acidification*: Ocean acidification is more likely to be detected in Northern waters, which can provide potential early warning signals for more southerly waters. However, more critical is that global observation is fundamental in providing the required evidence to support regulation that reduces the emissions of carbon dioxide.
- *General marine observations* with the objective of contributing to the World Ocean Assessment 2: The continual flow and movement of water around our globe dictates that we must continue to make marine observations worldwide, to understand what the global changes that are taking place and their drivers. Cooperative observing systems, with common reporting can provide sound evidence and recommendations, and are key to such delivery.
- Development of *marine indicators* covering both pressure and state: this is particularly relevant given the fact that the UK is a Contracting Party to OSPAR and the OSPAR North-East Atlantic Environment Strategy. The status of the OSPAR Maritime Area, which includes Arctic Waters (OSPAR Region I) will be assessed using common indicators in the Quality Status Report 2023 (OSPAR, 2017).

The Ellett Array – Sustained Observations In The Sub-Polar North Atlantic

The Ellett Array (Figure 1) is a new observing programme that builds on the scientific knowledge generated through observations on the Ellett line since 1950, the Extended Ellett Line (EEL) since 1996 (UK NERC National Capability programmes, operated by SAMS and NOC jointly) and the Overturning in the Subpolar North Atlantic Program (OSNAP) since 2014 (Holliday and Cunningham, 2013). The Ellett Array (UK NERC funding) will utilise moored instruments and ocean gliders across the Rockall Trough at a latitude of 57° N to continuously observe the strength and structure of the North Atlantic Current (NAC) and European Slope Current. The purposefully designed Ellett Array reduces hydrographic survey time from ships, for sustained climate monitoring, by using moorings and ocean gliders. We continuously observe mass, heat and freshwater transports of the NAC through the continuous measurement of velocity, temperature and salinity from instruments on moorings. These data will be augmented by mid-summer and mid-winter high-resolution ocean glider sections, observing the warm throughflow of the shallow Hatton-Rockall Basin. Taking advantage of the new technology development work, we aim to enhance the mooring sensor array to include key biogeochemical parameters, and technological advances in full ocean depth (6,000 m) gliders will be trialled from 2019.

Ship-based hydrography is the primary method for obtaining high quality physical and chemical samples with high spatial and vertical resolution measurements over the full water column (especially for the deep ocean below 2,000 m, e.g. 52% of the global ocean volume cannot currently

be sampled by profiling floats). The Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP) provides climate-quality observations that are the basis of our understanding of the decadal heat, salt and carbon variability in the ocean. As part of the UK's GO-SHIP contribution a hydrographic section, with biogeochemistry observations will be repeated (first occupied in 2014 also by the UK) across the North Atlantic basin at 57° N (A25/AR07) in 2021/22.

The Faroe-Shetland Channel – gateway to the Arctic

Atlantic-origin water passes from the NE Atlantic through the Faroe-Shetland Channel (FSC) on its pathway to the Nordic Seas, and beyond to the Arctic (Figure 1). At depth a return flow of cold and fresh Arctic water flows back to the Atlantic. Hydrographic data have been collected from two standard hydrographic sections in the FSC on a regular basis since 1893 by researchers from many nations, although the most consistent effort has been by Scottish and Faroese scientists.

In the mid-1990s, regular monitoring of the Atlantic inflow and deep-water overflow by direct measurement using moored current meters was initiated in the FSC (Berx et al., 2013) and Faroe Bank Channel (Hansen et al., 2016). Since then, research has demonstrated the integration of satellite-based measurements of sea surface height (altimetry) to estimate transport of Atlantic water via the FSC (Berx et al., 2013) optimises the *in situ* monitoring effort.

Through funding from EU projects, such as AtlantOS and Blue-Action, and the commitments of the Scottish and Faroese governments to monitor the marine environment, the FSC monitoring programme will continue its measurements of the transport and properties of the exchange between the North Atlantic and Arctic basins. Ambitions to enhance the observational potential of the transport mooring array and associated monitoring programmes are currently being explored as part of the AtlantOS project.

Monitoring Programmes within the Arctic

The passage of Atlantic Water northwards ultimately brings it to the Fram Strait. Here, the balance of Atlantic versus Polar Waters makes it a region of considerable oceanographic importance, and it is often cited as a location where we will see the impact of warming ocean conditions on the Arctic marine system. Indeed, over the last decades there has been a recognition of the steady "Atlantification" occurring in this sector of the Arctic (Polyakov et al., 2017). In an effort to observe the impact of increased Atlantic inflow on oceanographic conditions in Svalbard, the Scottish Association for Marine Science (SAMS) has maintained a fixed mooring in Kongsfjorden, NW Spitsbergen since 2002. To accomplish this, the mooring operations and provision of instrumentation have been a collaborative activity been SAMS and key Norwegian institutes, such as the University Centre in Svalbard, UiT The Arctic University of Norway, and the Norwegian Polar Institute.

The 15-year time series includes measurements of physical, biological and geochemical parameters. During this period, we have observed years with varying Atlantic dominance which is mirrored in observations as diverse as pelagic zooplankton populations, bloom dynamics and glacial melt rates. One of the key oceanographic changes has been the persistent lack of sea ice formation in the west Spitsbergen fjords, and a gradual increase in the winter water temperatures. In addition to long time series analyses, the moorings have permitted insight into Arctic processes such as zooplankton

migrations (Wallace et al., 2010) and glacial calving events (Luckman et al., 2015). These observations are further supplemented by a second mooring with identical instrumentation being placed in the far north east of Svalbard in a Polar Water dominated fjord (in place since 2006). This pair of sustained observatories has enabled us to make direct comparisons of the role that Atlantic water plays in modifying an Arctic marine system. These monitoring platforms are an important element in the Svalbard Integrated Observing System, an international program that aims to support long-term measurements of key environmental properties on and around the Svalbard archipelago to address questions of Earth System Science.

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