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Grant Proposal

BIOPOLE - Biogeochemical processes and ecosystem functioning in changing polar systems and their global impacts

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Abstract

The export of elements (particularly carbon, nitrogen and phosphorus) from the Poles critically supports global marine biodiversity and major fisheries as well as the sequestration of atmospheric carbon to the deep ocean. Ecosystem processes regulate this export, but major uncertainties remain in terms of how and by how much. Progress on understanding key ecosystem interactions is hindered by lack of data and their representation in Earth system models is poor. The two polar regions share similarities in environmental extremes which make them sensitive to the impacts of climate change. They both receive nutrients from multiple and diverse sources and the delivery of these nutrients to other oceans is regulated by similar ecosystem processes. However, the extent to which these ecosystem processes will be modified by climate change is unclear and urgently needs to be determined. BIOPOLE will determine how polar ecosystems regulate the balance of carbon and nutrients in the world’s oceans and, through it, their effect on global fish stocks and carbon storage. It will address this challenge by integrating ambitious fieldwork campaigns and innovative modelling in a multidisciplinary and highly coordinated approach. BIOPOLE will capitalise on world-leading capabilities and infrastructure in ocean and high-latitude research, including cutting-edge land-based facilities, state-of-the-art polar research vessels and innovative autonomous instrumentation. Collaboration with national and international partners will further strengthen BIOPOLE’s multidisciplinary approach and efficient use of infrastructure. BIOPOLE’s legacy will be the first assessment of the global impact of polar ecosystems on biogeochemical cycling and fish stocks; technologically-novel approaches and strong partnerships between leading international science groups.

Keywords

Arctic, Antarctic, marine, glacial, riverine, biogeochemistry, ecosystem processes, Earth system modelling, carbon sequestration, lipid pump, plankton, sea-ice, isotope tracers

List of participants

British Antarctic Survey, The National Oceanography Centre, UK Centre for Ecology & Hydrology, UK Cente for Polar Observation and Modelling, British Geological Survey

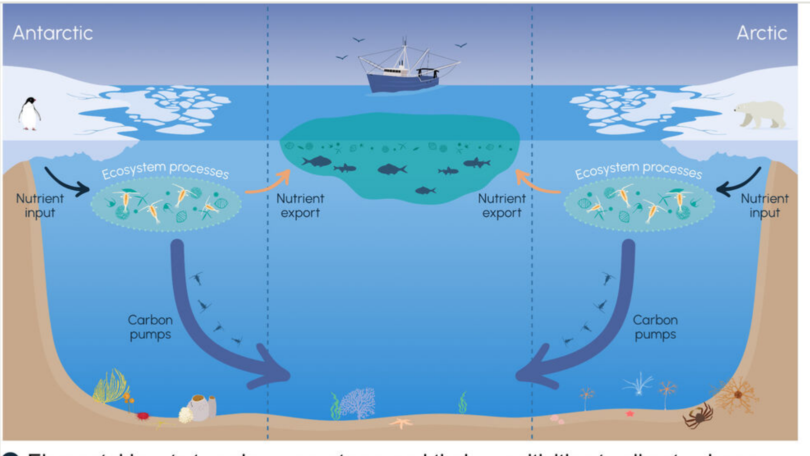
Third parties involved in the project

Bedford Institute of Oceanography, Alfred Wegener Institute (Helmholtz), University of Alaska - Fairbanks, Danish Technical University, Senckenberg BIK-F, University of Washington, Rutgers State University of New Jersey, University of Liverpool, Integrated Carbon Observation System (Lund University), Norwegian Institute for Water Research, NOAA OAR Laboratories (U.S. Department of Commerce), Florida State University, University of Alberta, University of Bristol, University Centre in Svalbard (UNIS), South Atlantic Environmental Research Institute.

Concept and approach

Global marine productivity and ocean carbon (C) storage are strongly influenced by nutrient cycling and ecosystem processes at the Poles (Moore et al. 2013, Fig. 1). By handling and processing different chemical elements in distinct ways, polar ocean ecosystems are a key source of nutrients such as nitrogen (N) and phosphorus (P) to the rest of the world's oceans (Sarmiento et al. 2004). The Arctic exports an excess of P relative to N, equivalent to ~ 90% of the net phosphate flux to the Atlantic at 47°N (Torres-Valdés et al. 2013), fuelling 16% of North Atlantic N-fixation (Yamamoto-Kawai et al. 2006). The Southern Ocean is a major source of N and P in thermocline waters globally (Sarmiento et al. 2004). Interruption of polar nutrient export, for instance, through nutrient trapping, could decrease global primary productivity and fisheries by around a quarter over multi-century timescales (Moore et al. 2018). Polar oceans are also significant sites of organic C sequestration particularly mediated by animals (Fan et al. 2020). Arctic and Southern Ocean ecosystems are both subject to sea-ice, low temperatures and a highly seasonal light environment. Their food-webs are also similar in that zooplankton are adapted to exploit short, intense periods of productivity by amassing large lipid energy stores to overwinter at depth (overwintering dormancy known as 'diapause', Wassmann et al. (2006), Murphy et al. (2016)). These shared features have a distinct impact on elemental cycling which sets polar ecosystems apart from those in other latitudes. Through ocean warming, shifts in ocean circulation and sea-ice loss, climate change is already altering many processes affecting elemental cycling at the Poles, placing an urgency to understand both the mechanisms driving this cycling and the global implications.

At an ocean basin scale, the ratio (stoichiometry) of C:N:P in the oceans (canonically 106:16:1; the "Redfield ratio", Redfield (1934)) is consistent within both organisms and the chemical environment. Maintenance of such tight stoichiometric relationships indicates feedbacks stabilising elemental content against external perturbations (Deutsch and Weber 2012). However, important latitudinal variations from the Redfield ratio have been measured (Martiny et al. 2013) and modelled (Matsumoto et al. 2020) and results have indicated that ratios within the polar regions are anomalous. These anomalies arise from the diverse sources of nutrients to the polar oceans - glaciers, rivers, sea-ice and oceans - and how they are subsequently processed by polar organisms (e.g. through nutrient uptake, remineralisation, denitrification and lipid formation). These delivery routes and processing of elements within the polar oceans are vulnerable to the rapid climatic changes being experienced by these regions.



- Elemental inputs to polar ecosystems and their sensitivities to climate change
- Influence of ecosystem processes on elemental balance and movement of C to depth
- Balance of elements leaving the poles, impacting global fish stocks and C cycling

Figure 1. doi

BIOPOLE will examine how global marine productivity and ocean carbon storage are influenced by nutrient cycling and ecosystem processes at the Poles.

Predicting the consequences of climate change on polar elemental cycling and subsequent global impacts on C storage and fish stocks requires resolving:

1. **the sources of elemental inputs that have most influence on the polar chemical environment**,
2. **the ways in which this environment is modified by polar ecosystem processes and**
3. **the balance of elements leaving the Poles and their global influence .**

This leads to three questions:

Q1: What physical, chemical and biological processes modify elemental balance *en route* from source to polar ocean ecosystem and what are their sensitivities to climate change? An intensified hydrological cycle under climate change will fundamentally alter the transport and transformation of fresh water and elements into polar oceans (Wrona et al. 2016). We can distinguish between sources of elements through advances in the use of biologically inactive provenance tracers (Paffrath et al. 2021). Each elemental source has distinct environmental dependencies, while the influence they have on the receiving ocean ecosystem depends on the local nutrient balance (Hodson et al. 2015). Additionally, the moderation of elements *en route* to the polar oceans (e.g. through coastal ecosystems), depends upon source chemistries and is sensitive to climate change. We therefore require a comprehensive assessment of the elemental sources from land, ice and other oceans, a better understanding of how these elements are transformed during passage to ocean ecosystems and identification of how major sources feed key oceanic locations.

Q2: What is the influence of ecosystem processes on elemental balance and movement of C to depth in the polar oceans and how may these change in the future? Our understanding of how ocean biology responds to and influences stoichiometry and carbon transport in the polar regions is in its infancy, with little consensus on the relative importance of the range of processes involved. Ecosystem processes particular to the polar regions deserve closest attention. For instance, the generation of excess P in the Arctic subsequently exported to the Atlantic highlights processes that denitrify water passing through the Arctic. Additionally, the separation of C from N and P during lipid production by pelagic organisms is a distinguishing feature of polar environments. These same lipid-rich organisms are also responsible for driving the 'lipid pump', an understudied component of the biological carbon pump which is prevalent in both polar regions (Record et al. 2018, Boyd et al. 2019) and potentially a major conduit for C sequestration (Jónasdóttir et al. 2015). Although the potential stoichiometric consequences of lipid production are large, they are yet to be fully quantified, as is the implication of stoichiometry on the efficiency of nutrient transfer between trophic levels. Moreover, the dynamics and the magnitude of the lipid pump in the Southern Ocean are poorly resolved due to a lack of targeted, empirical observations.

Q3: How may C sequestration by polar ocean organisms and the export of nutrients change in the future and what impacts will this have on global ocean fish stocks and C cycling? Research programmes already underway are studying the stoichiometry of waters leaving the Southern Ocean, but there is much greater uncertainty in the Arctic, where a small number of observations suggest export of excess P, but observations at key exit gateways are sparse. Common to both Poles is further uncertainty over how nutrient export will change and the impact of this on global fish biomass, with one model predicting a significant decrease by 2300 (Moore et al. 2013). The longer-term fate of biological transport of C to depth by lipid-rich organisms (the "lipid pump", Jónasdóttir et al. (2015)) also remains undetermined. Improved predictive capacity requires global modelling, but this remains untried.

Workplan

BIOPOLE will answer these three questions through three matching scientific Work Packages (WPs). Throughout this section, we refer to programme Tools (described in detail in the following section), which are the scientific techniques or infrastructure used to deliver the scientific objectives of each WP. The combination of the Work Packages and Tools provide an approach that is both comprehensive and integrated.

WP1: Nutrient inputs and freshwater processes To address Q1, WP1 will assess the source signatures of major inputs from land, sea-ice and oceans and provide information on the key transformation processes that determine their eventual inputs to open-ocean ecosystems. This information will be used alongside satellite and historical data (both observational and modelled) and projected changes in inputs, to gain insight into future impacts on supply to marine ecosystems.

We will first determine how nutrients and their associated isotopic signatures vary across the major source types (i.e. glaciers, rivers, ocean currents, sea ice), from their origins to the point where they enter the polar marine environment. This will be achieved through a combination of field sampling (Tool *Source-sampling*) and analytical chemistry (Tool *Biogeochemical analyses*). Field-sampling will be carried out at both Poles and will involve both:

1. intensive month-long campaigns at sites that provide type-examples of processes happening at larger scales throughout the polar regions and
2. sampling using the infrastructure and capabilities of collaborators providing data across a wider geographical range of major source types (Tool *Source-sampling*).

We will next investigate the dominant processes that modify isotopic signatures, nutrient forms and lability between sources and the receiving marine ecosystem (Tool *Source-sampling*). Physico-chemical (e.g. sorption/desorption, particle aggregation) and biological (e.g. microbial production/consumption) processes will be measured to determine their influence on the behaviour of organic and inorganic constituents (Tool *Biogeochemical analyses*). For areas experiencing high particulate nutrient loads (e.g. P and Fe; from glacial meltwater run-off), we will identify conditions promoting nutrient sorption-desorption from suspended sediments utilising mixing experiments under variable salinity and redox conditions representing freshwater-coastal water extremes. We will quantify freshwater microbial and photolytic production/consumption of dissolved organic matter and other nutrient pools utilising field- and laboratory-based incubation assays, producing estimates of nutrient uptake into local autotrophic communities. Empirical and mechanistic descriptions of these processes will be incorporated into chemical equilibrium models and simple dynamic models to assess their sensitivity to climate change. This will include assessment of the behaviour of key nutrients from high inorganic particulate fluxes (e.g. glacial melt sources) under varying conditions of freshwater influx (e.g. ± snowmelt) and coastal water chemistry, plus interactions between dissolved nutrients and humic substances from other sources (e.g. rivers or sea ice).

Tracer signatures of sources will be used to examine the polar nutrient balance, combining with related work in WP2 and WP3. Conservative and semi-conservative/ hybrid tracers that discriminate different freshwater inputs will be measured (Tool *Cruises*) and used in multi-parameter mass balance calculations to quantify the composition of each ocean sample in terms of river run-off (including breakdown to individual inputs from specific rivers), sea-ice melt, glacial melt and oceanic source waters (e.g. Paffrath et al. (2021)). The contributions of each source signature to the waters sampled will be used to deduce the effect of biological/non-conservative behaviour, for example, along headwater-coastal-marine transects. This will be further supported by trajectory tracking (Tool *Lagrangian modelling*), compared to and validated with observational datasets on nutrients and hydrography and cryospheric elements (sea ice drift, thickness, glacial discharge) to elucidate the key pathways and processes whereby mixing and physical/biological transformations are effected (e.g. by time-varying wind-driven advection and mixing, sea ice interactions, tidal processes and changing stratification). The role of ocean dynamics (especially mixed layer processes and the role of sea ice and strong wind events) will be incorporated through a combination of ship-based campaigns (Tool *Cruises*), autonomous measurement programmes (Tool *Gliders* and Tool *Moorings*) and fine-resolution models (Tool *Regional modelling*).

To understand the temporal context of the field campaigns and to generate understanding of variability and climatic sensitivity, we will interpret the BIOPOLE data alongside satellite and historical records. Many fundamental tracers (salinity, oxygen isotopes, macronutrients etc.) have multi-year or multi-decade datasets that enable the sensitivity of combined inputs to known climatic variability to be established. Model output will be examined to determine historical climatic conditions (multi-decade hindcasts) and future conditions under different climate scenarios, using a hierarchy of models up to Earth System models (UKESM1) (Tool *Regional modelling*, Tool *Global modelling*).

WP2: Biological processes and ecosystem function To address **Q2**, WP2 will concentrate on ecosystem processes that are particular to the polar regions (Record et al. 2018, Boyd et al. 2019). Fieldwork will be conducted alongside data-mining, laboratory analyses and modelling to substantiate how these processes modify elemental inputs before their export from the polar regions.

Identifying the cause of excess P exported from the Arctic will focus on the role of pelagic denitrification, as well as the coupled responses of lower trophic levels. Although it is known that benthic denitrification on the Chukchi Sea shelf contributes to the low N:P supplied to the Atlantic (Chang and Devol 2009), further denitrification may be taking place in the water column (Zeng et al. 2017). It is imperative that we determine the significance of this in space and time if we are to understand how the flux of excess P may vary into the future. We will determine vertical profiles of N:P for particulates and conduct isotope pairing experiments to quantify denitrification rates throughout the water column (Tool *Cruises*). Gene sequence analysis of these samples will identify the organisms responsible for driving denitrification and other signatures associated with N cycling within the pelagic biota. Tool *Moorings* will additionally collect water for N:P and molecular analysis throughout the year. Controlled factorial laboratory and at-sea experiments will examine how warming and nutrient supply affect microplankton cell size, metabolic physiology, biomass stoichiometry and community composition (García-Martín et al. 2014).

For the polar lipid pump, we will determine its impact on polar stoichiometry and identify processes that control the pump's efficiency, supporting the quantification of this flux in WP3. Our approach will combine archived-data syntheses and ecological niche modelling (Freer et al. 2020), calibrated and validated through spatially and seasonally extensive field sampling. Having already been used to good effect in the Arctic Ocean, we will apply this to the Southern Ocean where the larger area and greater extent of deep water suggests the lipid pump to be substantially larger (Record et al. 2018). Field sampling (Tool *Cruises*, Tool *Gliders*) will focus around areas of high productivity, such as above ridges and within the Marginal Ice Zone, where the accumulation of lipids by organisms driving the lipid pump, such as Calanoid copepods, pteropods and euphausiids, is likely to be high. Combining field data with niche- and trajectory modelling allows a seasonal circumpolar assessment of the abundance and distribution of zooplankton contributing to the lipid pump.

Major unknowns in representing the lipid pump in global models are controls on overwintering depth and timing of seasonal descent. Using vertically-resolved sampling methods (Tool *Cruises*), we will examine how the total amount of lipid and the composition of their lipid classes and fatty acids therein relate to the seawater density (≈ depth) and set neutral buoyancy depths. Enzyme assays and incubation experiments will measure diapause respiration rates. Moored acoustic instruments, current meters and sediment traps (Tool *Moorings*) will be deployed to determine when lipid rich organisms make their deep seasonal migrations and to assess the export of particulate organic C from the productive zones. This deep phase is also when interactions with the benthos are most likely to occur. We will resolve the importance of this poorly-studied bentho-pelagic interaction, both in how it may augment estimates of C sequestration and how it influences benthic community distribution, productivity and biodiversity. Additionally, modelling (Tool *Lagrangian modelling*) will be employed to investigate the role of current flows around steep benthic topology in facilitating such bentho-pelagic interactions. The stoichiometric consequences of deep overwintering by zooplankton will be investigated through a coupled life-cycle and food-web model incorporating the effect of prey stoichiometry which will be used to provide information for global modelling of the lipid pump in WP3.

Observations on copepod physiology will also be essential for parameterising any quantification of carbon transport via the lipid pump. To obtain these, seasonally and vertically resolved sampling (Tool *Cruises*) will enable bioassays of copepod respiration, elemental analysis, lipid classification and lipid sac volume. Lastly, a major knowledge gap is the extent of mortality during diapause, particularly via predation by benthic organisms. We aim to resolve the importance of these bentho-pelagic interactions, both in how it may augment estimates of carbon sequestration and how it influences benthic community distribution, productivity and biodiversity. An Individual Based Model coupled with a regional ocean model will track the distribution of diapausing individuals in the South Scotia Sea (Tool *Lagrangian modelling*) to investigate the role of current flows around steep benthic topology in facilitating such bentho-pelagic interactions. Locations identified as having bentho-pelagic interactions will be targeted for benthic sampling

(Tools *Cruises*) for lipid, isotope and elemental analysis. Benthic species commonly encountered will provide the basis for subsequent Species Distribution Models (Tools *Ecological Modelling*) to scale up estimates of potential interaction hotspots.

The outputs listed above will contribute to, or feed directly into, WP3 efforts to quantify the lipid pump and its export of carbon within global models.

WP3: Understanding implications To address **Q3**, WP3 will carry out further focused field sampling and a range of modelling approaches to track and quantify elemental pathways out of the Poles. Jointly with WP1 and WP2, it will then synthesise results to determine the global consequences of non-Redfield processes at the Poles for global C sequestration, nutrient supply and fish stocks.

The global significance of the lipid pump depends on how much C is transferred to depth and how long it remains out of contact with the atmosphere. We will use two complementary approaches to assess this. The first will use data from WP2 on zooplankton abundance, distribution, diapause depth and C respiration during diapause to empirically estimate the lipid pump C flux in the Southern Ocean. Maps for the abundance and depth of diapausing zooplankton from WP2 will then be combined with Lagrangian tracking (Tool *Lagrangian modelling*) to determine how long C released during diapause remains away from the surface and, hence, atmosphere and its potential interaction with benthos. The second approach will modify the NEMO-MEDUSA model (Tool *Global modelling*) to impose seasonal migration on zooplankton with characteristics (e.g. depth, timing, rate of respiration) taken from data and physiological modelling in WP2. For both approaches, we will explore the sensitivity to the depth and duration of diapause and to the rate of C respiration at depth. The second approach forms the basis for subsequent development of a lipid pump parameterisation for UKESM1, should the flux prove globally significant.

The quantity and stoichiometry of nutrients leaving the Poles both now and in the future is uncertain. The biogeochemistry of the Southern Ocean is already being addressed by other programmes. For the Arctic, WP3 will measure exiting nutrient concentrations throughout the year by adding water samplers to the Davis Strait mooring array (National Science Foundation, USA) and by collaborating with Alfred Wegener Institute (Germany) which monitors Fram Strait. Synthesising observations with data upstream at Chukchi Shelf (WP2) and sources of nutrients (WP1) will determine the dominant controls on excess P leaving the Arctic. To examine how the nutrient fluxes leaving the polar regions will change in time, WP3 will analyse Earth System Model (ESM) simulations exploring different 21st-century Shared Socioeconomic Pathways (SSPs) from CMIP6 (including UKESM1) run to 2300 (Tool *Global modelling*). ESM model output analysis will be augmented by tracking water trajectories (Tool *Lagrangian modelling*) to examine changes in dominant export routes. To identify which processes lead to these future changes, the same CMIP6 model output will be examined in a water mass framework which allows attribution to changes in circulation, an adjoint analysis will be carried out and an idealised model (Tool *Idealised model*) will be used to assess the impact of projected environmental changes (e.g. sea-ice concentration/extent, strength and latitude of maximum wind stress).

Determining how anticipated changes in polar regions affect global fish stocks requires two steps. First, the ESM model analysis will be extended to identify changes in the magnitude and geographical distribution of primary production globally (Tool *Global modelling*). Causal links to nutrient export from, or trapping within, the poles will be determined by examining nutrient concentrations and ratios on density surfaces extending from the Poles and outcropping in areas of greatest change, complemented by Lagrangian tracking (Tool *Lagrangian modelling*). Comparison of results across the ESM ensemble will provide a measure of uncertainty in predictions. Second, WP3 will assess how primary production translates into global fish biomass using UKESM1 and other ESMs to drive fish biomass models (Tool *Fish biomass modelling*). This dual approach will provide detailed projections of changes in global fish biomass from now to 2300 and quantify causal links to polar nutrient export.

Programme tools

To deliver the workplan, BIOPOLE will use a number of tools incorporating observational and modelling approaches (Fig. 2). These efforts cover both land- and oceanic domains in both polar regions (Fig. 3).

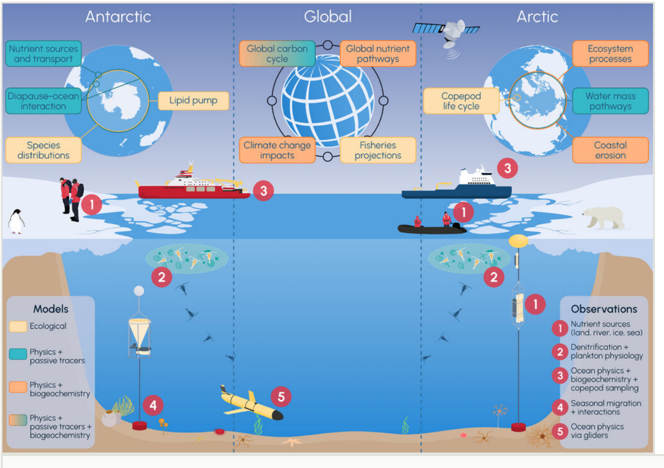


Figure 2. doi

BIOPOLE will deliver its objectives using a number of tools incorporating observational, analytical and modelling approaches. Models (upper level) will consider Antarctic, Arctic and Global domains covering physical, biogeochemical and ecological aspects. Observations (lower level) will take place in both the Arctic and Antarctic and consider ocean physics, nutrient sources, biochemical processes, animal behaviour and ecological interactions. BIOPOLE will use a variety of sampling platforms, including open-ocean research ships, autonomous vehicles, moored sensors and inshore sampling vessels. Modelling and observations will be synthesised to improve global level projections of climate change impacts on nutrient pathways, the carbon cycle and fisheries production.

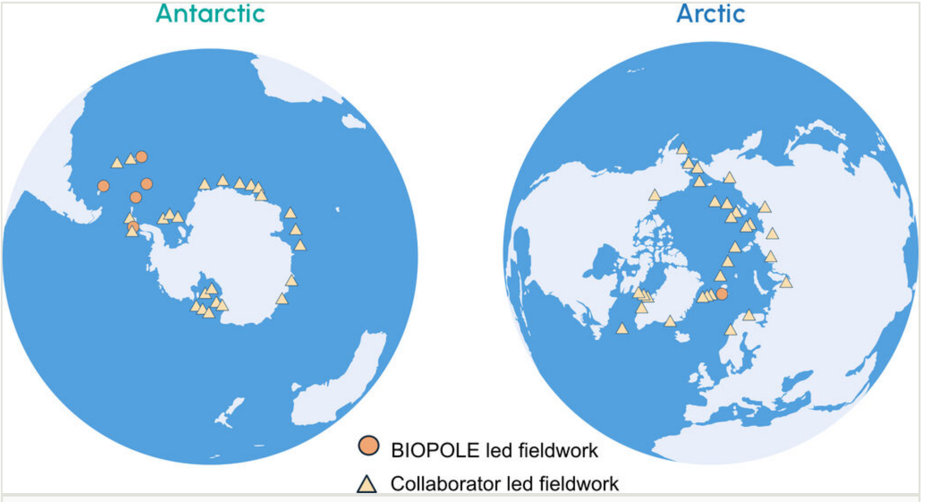


Figure 3. doi

BIOPOLE operates in both Poles simultaneously. In the Antarctic, it will lead a number of science expeditions while, in the Arctic, it will mainly use collaborator-led fieldwork.

Tool *Source sampling*: Collaborative virtual workshops will formalise the survey and analytical techniques before utilising remote field sites (e.g. Scotland, termed “Methods development land station”) to test deployment, survey and associated analytical procedures. Intensive field sampling will be carried out at sites (termed “Process land stations”) in both Arctic and Southern Ocean domains to perform transects from elemental source to the receiving marine systems to parameterise nutrient gradients and resolve any modification processes during passage. In the Arctic, BIOPOLE field teams will be deployed to survey replicates of all source types accessible via the International Science Station at Ny Ålesund (land, marine-terminating glaciers and sea ice) and the Tana River (large Arctic river). In the Southern Ocean, BIOPOLE field teams will be deployed to survey source sites accessible from South Georgia (Subantarctic land- and marine-terminating glaciers) and the Antarctic Peninsula (Antarctic marine-terminating glaciers, sea ice). BIOPOLE will also coordinate a distributed pan-polar campaign (termed “Broadcast land stations”) in collaboration with project partners to obtain measurements of major nutrient source types to provide information for our tracer analyses, using field sampling where necessary to augment existing long-term monitoring data.

Tool *Biogeochemical analyses*: Glacial and river water samples collected in the field will be analysed for total, particulate and dissolved macro- (i.e. N, P, Si, K, Ca, S, Mg) and micro-nutrients (e.g. Fe, B, Mn, Zn) and other metals (e.g. Ba) to characterise nutrient source signatures. Particulate and dissolved organic matter characterisation will be conducted using a range of techniques, including fluorescence analyses and FT-ICR MS. Local autotrophic community composition will be analysed using flow cytometry. We will utilise field and laboratory incubation facilities (e.g. floating chambers; lab-top replicated light/temperature incubators) to assess nutrient modification processes. The provenance of source signatures in marine samples will be examined using a suite of conservative and semi-conservative/hybrid tracers (e.g. salinity, oxygen isotopes, Ba, macronutrients, rare earth elements and Nd) and auxiliary parameters will be collected using in situ field probes (e.g. water temperature, salinity, dissolved oxygen, pH and conductivity).

Tool *Cruises*: Arctic oceanic sampling will measure the tracers of nutrient inputs and determine elemental balance across regions of the Arctic. We will sample particulate matter and water for investigating pelagic denitrification processes and zooplankton for life-history and biochemical analyses. We will obtain our own Arctic data using existing infrastructure of project partners through a combination of:

1. deployments of BIOPOLE instruments,
2. collection of samples for analysis by BIOPOLE teams and
3. participation of BIOPOLE staff on Science Partner and Science Collaborator research cruises.

We have targeted regions of greatest significance concerning the determination of elemental balance within the Arctic and have a secured network of opportunities with adequate redundancy. The Southern Ocean does not offer the same existing infrastructure possibilities; hence, oceanic sampling will be carried out through two visits by an ice-capable vessel to the Marginal Ice Zone around the Scotia Ridge, a site of high productivity and hypothesised high lipid pump activity. The first visit will capture the early season processes that prime conditions for high levels of primary productivity and lipid accumulation, analysed through taxonomic, biochemical and molecular techniques. The second visit, the following year, will be late season, after the seasonal descents of zooplankton. Measurements for determining ocean circulation and the tracing of nutrient sources (described above) will be made on both cruises. Autonomous instrumentation (Tool *Moorings* and Tool *Gliders*) will be deployed on the first visit and, for moorings, recovered on the second visit.

Tool *Gliders*: We will deploy autonomous underwater ocean gliders to conduct multi-month missions in key regions of the Southern Ocean. These will deliver data on ocean stratification and mixed layer depth. The gliders will resolve the upper 1 km, with previously unobtainable temporal resolution and penetrating further underneath the retreating ice edge than previously possible using new ice avoidance software.

Tool *Moorings*: In the Arctic, BIOPOLE will instrument moorings maintained by Science Partners to obtain a seasonal cycle of N:P in Arctic export fluxes through the Davis Strait, a major conduit to the Atlantic. We will conduct collaborative analyses on samples and data from Chukchi Sea and Siberian shelf moorings. In the Southern Ocean, we will deploy a deep-ocean mooring in the Weddell Sea to resolve the seasonality of the lipid pump at a site of major lipid production. The mooring will contain shallow and deep sediment traps to capture zooplankton during their seasonal descent and to compare this injected flux against the gravitational flux at the same site. The descent and re-ascent will be further resolved by multifrequency acoustics with sensors for temperature, salinity, current velocities and oxygen providing an environmental context. Additionally, existing moorings on the South Scotia Ridge will monitor the key export pathway of carbon enriched deep waters from the Weddell Sea to the global ocean. We will also maintain the existing mooring at Rothera to monitor outflows.

Tool *Global modelling*: BIOPOLE will make use of output from existing runs of the standalone NEMO-MEDUSA global biogeochemical model, as well as from the CMIP6 suite of ESMs, including the UK ESM, UKESM1, which includes NEMO-MEDUSA as its ocean component. NEMO-MEDUSA only runs exist at ¼° resolution both historical (forced using atmospheric data) and to 2100 (forced using UKESM1 atmospheric output). MEDUSA includes two size classes of zooplankton, the larger of which represents copepod-sized zooplankton which will be modified to quantify the lipid pump in WP3. Runs to 2300 from the CMIP6 suite of models will be analysed. Model output is available to 2300 from UKESM1 for SSP126, SSP585 and SSP534.

Tool *Lagrangian modelling*: The ARIAN, TRACMASS OceanParcels software (oceanparcels.org) allows existing model output to trace trajectories of water and its contents consistently with model conservation laws (van Sebille et al. 2018). NEMO-MEDUSA model ¼° runs will provide global coverage. In the Arctic, we aim to use the improved physical model being developed by CANARI, a sister project (https://canari.ac.uk), to refine our analyses. In the Southern Ocean, where global models often fail to capture deep water formation (potentially critical to sequestration of lipid pump C), output from a previously developed regional model will be used to track C on to water masses *en route* to exits from the Southern Ocean. The high resolution model of the South Scotia Ridge will also be run incorporating the hydrodynamics-based algorithm for Lagrangian studies, as well as particle behaviour simulating zooplankton seasonal vertical migration behaviour.

Tool *Idealised modelling*: A model will be built using the MITgcm/BLING framework. Its simplified two-basin sector setup will enable it to be run to physical and biogeochemical equilibrium for numerous forcing experiments, while still capturing key circulation features including Weddell Gyre, bottom water formation, the Antarctic Circumpolar Current and North Atlantic deep convection.

Tool *Regional modelling*: A high-resolution regional application of NEMO encompassing key bathymetric features of the South Scotia Ridge in the Southern Ocean will be used to identify areas of sequestration and retention of marine biota and their associated biogeochemical elements. NEMO output will be coupled to an Individual Based Model to investigate the interaction between zooplankton behaviour and regional circulation including small-scale physical phenomena, for example, Taylor columns to determine the role of biophysical processes in influencing the local lipid pump.

Tool *Fish biomass modelling*: The Fisheries and Marine Ecosystem Model Intercomparison (FISH-MIP) community has compiled a suite of global models which use CMIP6 modelled phytoplankton and zooplankton to infer fish biomass. We will contribute to a FISH-MIP community statistical model by capturing the relationship between FISH-MIP fish biomass projections and the ESM forcing. The resulting model will be used to project fish biomass based on UKESM1 output for three contrasting scenarios.

Additionally, collaborative work will focus on directly forcing size-structured ecosystem models with UKESM1 outputs to 2300.

Tool *Ecological Modelling* : Species Distribution Models (SDMs) will be produced for the most abundant species of lipid-rich diapausing copepods in the Southern Ocean. These will incorporate a compilation of circumpolar, vertically and seasonally resolved abundance records, as well as high resolution biogeochemical and physical environmental variables. The result will be circumpolar predictions of copepod abundance and distribution during summer and winter periods. A set of SDMs for benthic species will be developed to identify locations of possible bentho-pelagic interactions. As a complement to correlative models, a mechanistic Individual Based Model will be developed for the Calaonoid copepod *Calanus finmarchicus*. This will aim to simulate the growth, development and reproduction of an individual copepod throughout its life cycle and to investigate the intrinsic and external factors that influence these.

Objectives and deliverables

BIOPOLE will integrate fieldwork campaigns and modelling in a coordinated approach between numerous UK science institutes and national and international partners covering ocean, biogeochemistry, ecosystems and climate research. This approach will enable BIOPOLE to address and deliver the following specific objectives:

1. To measure nutrients and their isotopic signatures at their various sources, determine how they are modified during their passage to the open ocean and parameterise their climate sensitivities;
2. To determine from isotopic signatures how nutrient inputs into the polar ocean combine to shape the contemporary nutrient balance in polar marine ecosystems;
3. To determine the climate sensitivities of key biotic processes affecting elemental balance in polar ecosystems;
4. To quantify the export of nutrients from the poles by making field measurements at key exit pathways;
5. To make the first circumpolar scale quantification of the lipid pump in the Southern Ocean;
6. To quantify the importance of bentho-pelagic interactions in sequestering lipid-based carbon in polar environments;
7. To examine how exported carbon is apportioned between different deep polar water masses and to parameterise its subsequent transport fate;
8. To use Earth System models to determine the influence of polar nutrient export on global primary productivity and fish stocks and to make long term projections on the future of these global processes;
9. To improve the skill of numerical models in simulating the influence of polar oceans on global productivity for inclusion in the IPCC process and policy development.

Data management and sharing of the products of research

BIOPOLE will ensure compliance with the FAIR data principles accoding to the following policy

https://www.ukri.org/about-us/nerc/our-policies-and-standards/nerc-data-policy/

which includes the preservation of valuable observational data, model code and model output. The UK Polar Data Centre are the lead designated Data Centre and will address queries regarding the policy and managment of BIOPOLE data.

Data will be preserved across the above-nominated NERC Data Centres, as part of the NERC Environmental Data Service. The Data Centres will hold the data under embargo up to two years from the end of data collection if requested – in line with NERC policy – to allow researchers to work-up their datasets and publish their findings. When released, data will be published under the UK Open Government Licence,

https://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/

unless agreed otherwise.

Impacts

Climate impacts: The principal objective of BIOPOLE is to quantify threats from climate change to polar ecosystem functioning, particularly their capacity to sequester carbon and to support ocean productivity and fish stocks. This objective will be achieved through a combination of field measurements and modelling studies to predict impacts of future changes to polar nutrient supply and ecosystem processes. This is an issue of global concern with impacts on many aspects of society, including our ability to extract food resources from the oceans sustainably and mitigating climate change through the biological drawdown of atmospheric CO_2 into the oceans.

Marine Protected Areas: Our work has a further regional benefit in identifying areas that are vital to global biogeochemical processes or that are highly sensitive to ongoing climatic change. This evidence is crucial in the designation of Marine Protected Areas and the ecosystem based management of living resources undertaken by CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources). BIOPOLE researchers have a prominent role in CCAMLR, enabling translation of BIOPOLE results to policy.

Novel technologies: BIOPOLE will deploy novel autonomous technologies with low energy and low emissions to obtain measurements in inaccessible regions and over longer timescales than could be achieved through cruise-based science alone. Our field testing and further development of these technologies will encourage uptake by wider user communities, improving our ability to study the oceans and lowering the need for carbon intensive means of field sampling.

Engagement

BIOPOLE is aware of the value of its science to indigenous polar populations. It will interact with other Arctic programmes and the Arctic Council to exchange knowledge with these communities.

BIOPOLE is a multifaceted project investigating many aspects of Earth System science. This presents a wealth of opportunities in which to engage and train young scientists. For instance, it will engage with summer school training and fellowship programmes to provide insights and experiences in biogeochemical and ecosystem science, including scientists from developing countries.

Polar research offers superb opportunities for wider public engagement and we will capitalise on existing and new opportunities to engage with UK, Arctic and international communities. This will include in-person presentations at local science festivals and schools. BIOPOLE will have a website (www.biopole.ac.uk), a social media presence (Instagram: @biopole_nerc_nc; BlueSky @biopole.bskyb.social; Facebook @BIOPOLE.NERC) and engage with the media via press releases.

Scientists within BIOPOLE are at the forefront of driving UK policy on diversity in UK Polar science through the Diversity in UK Polar Science Initiative. We will use BIOPOLE as a platform to advertise further the need for equality, diversity and inclusion (EDI) within the polar science community.

BIOPOLE will engage strongly with a number of schemes to improve EDI in polar research to celebrate existing diversity and to promote and enhance Antarctic science opportunities to under-represented groups, including women, people from ethnic minorities, BAME, LGBTQ+ communities and people with a disability.

We will involve members of the APECS (www.apecs.is) and IMECaN (http://imber.info/imecan-interdisciplinary-marine-early-career-network/) early career researcher (ECR) networks in open science meetings and, where possible, take on mentorships to assist young scientists through the early stages of their careers. We will also promote involvement of ECRs in the formal education and training programmes offered by Science Partners and Science Collaborators. An ECR member will be included within the Executive Board of BIOPOLE to ensure ECR representation in programme decision-making.

Programme management

An overarching and synthesising workpackage (WP4) will run alongside the three science WPs. An Executive Board (EB) will reinforce the integration of efforts across the science partners involving WP leads, institute leads and strategic leads (data management, Arctic fieldwork, observation-modelling integration, Early Career Researchers). The EB will meet monthly to ensure the smooth running of the programme and timely delivery of objectives. This process will be aided by a monitoring tracker system containing milestones and deliverables within each individual element of the programme with a schedule of delivery and identified interdependencies with other milestones and deliverables.

Fieldwork methodology will follow guidelines detailed in the open access BIOPOLE Cookbook (Hendry et al. 2025).

There will also be guidelines on:

1. Publication and authorship of data and manuscripts and
2. Science communications

Responsibilities and health and safety commitments during fieldwork will follow the guidelines of the research organisation (UKRI NERC). It will also adhere to UKRI policy on Equality, Diversity and Inclusion and Environmental Responsibility.

A panel of national and international experts covering the breadth of BIOPOLE's science will act as a Programme Advisory Board (PAB), which will meet twice a year over the course of the programme, at points chosen to be of greatest help in running the programme.

Risks will be managed in line with established UKRI NERC and institute methodologies. The PAB, Institute Directors and UK Research Institutes (UKRI) and the Natural Environment Research Council (NERC) will all be consulted if any major changes to the programme schedule are necessary.

Funding program

Natural Environment Research Council National Capability Multicentre Round 2 funding (grant no. NE/W004933/1)

Grant title

Biogeochemical processes and ecosystem function in changing polar systems and their global impacts (BIOPOLE)

Hosting institution

British Antarctic Survey

Ethics and security

BIOPOLE is subject to Responsible Research review by UKRI NERC and has acted to ensure that its research:

1. Has identified and minimised key environmental material risks/impacts associated with this project;
2. Will take actions to reduce the environmental harm associated with this specific project in terms of training, energy monitoring and efficiency considerations, renewable energy, deployment, innovation to minimise waste;
3. Will provide information that enhances and directly benefits the environment through improved understanding of climate and the development of new low carbon scientific techniques;
4. Has all required research sample collection and handling permits;
5. Adheres to accepted policy within the wider research organisation (UKRI) on Equality, Diversity and Inclusion.

Author contributions

GAT designed and wrote this research proposal in collaboration with EF, SLCG, NMJ, MJL, APM, DJM, AJSM, MPM, AS, BMS, PTH and EFY. All authors contributed to reviewing and editing this document.

Conflicts of interest

The authors have declared that no competing interests exist.

References

- Boyd P, Claustre H, Levy M, Siegel D, Weber T (2019) Multi-faceted particle pumps drive carbon sequestration in the ocean. Nature 568 (7752): 327-335. https://doi.org/10.1038/s41586-019-1098-2
- Chang B, Devol A (2009) Seasonal and spatial patterns of sedimentary denitrification rates in the Chukchi sea. Deep Sea Research Part II: Topical Studies in Oceanography 56 (17): 1339-1350. https://doi.org/10.1016/j.dsr2.2008.10.024
- Deutsch C, Weber T (2012) Nutrient Ratios as a Tracer and Driver of Ocean Biogeochemistry. Annual Review of Marine Science 4 (1): 113-141. https://doi.org/10.1146/annurev-marine-120709-142821
- Fan G, Han Z, Ma W, Chen S, Chai F, Mazloff M, Pan J, Zhang H (2020) Southern Ocean carbon export efficiency in relation to temperature and primary productivity. Scientific Reports 10 (1). https://doi.org/10.1038/s41598-020-70417-z
- Freer J, Tarling G, Collins M, Partridge J, Genner M (2020) Estimating circumpolar distributions of lanternfish using 2D and 3D ecological niche models. Marine Ecology Progress Series 647: 179-193. https://doi.org/10.3354/meps13384

- García-Martín EE, Serret P, Leakey RJ (2014) Plankton community and bacterial metabolism in Arctic sea ice leads during summer 2010. Deep Sea Research Part I: Oceanographic Research Papers 92: 152-161. https://doi.org/10.1016/j.dsr.2014.06.007
- Hendry K, Manno C, Arrowsmith C, Bowes M, Callaghan N, Lofts S, McKenzie R, O'Brien A, Olszewska J, Pickard A, Spears B, Tye A, Woodward EMS, BIOPOLE (2025) BIOPOLE COOKBOOK: PARAMETERS AND ANALYSIS (Version 8). Zenodo. https://doi.org/10.5281/zenodo.15188897
- Hodson A, Nowak A, Christiansen H (2015) Glacial and periglacial floodplain sediments regulate hydrologic transfer of reactive iron to a high arctic fjord. Hydrological Processes 30 (8): 1219-1229. https://doi.org/10.1002/hyp.10701
- Jónasdóttir SH, Visser A, Richardson K, Heath M (2015) Seasonal copepod lipid pump promotes carbon sequestration in the deep North Atlantic. Proceedings of the National Academy of Sciences 112 (39): 12122-12126. https://doi.org/10.1073/pnas.1512110112
- Martiny A, Pham CA, Primeau F, Vrugt J, Moore JK, Levin S, Lomas M (2013) Strong latitudinal patterns in the elemental ratios of marine plankton and organic matter. Nature Geoscience 6 (4): 279-283. https://doi.org/10.1038/ngeo1757
- Matsumoto K, Tanioka T, Rickaby R (2020) Linkages Between Dynamic Phytoplankton C:N:P and the Ocean Carbon Cycle Under Climate Change. Oceanography 33 (2). https://doi.org/10.5670/oceanog.2020.203
- Moore CM, Mills MM, Arrigo KR, Berman-Frank I, Bopp L, Boyd PW, Galbraith ED, Geider RJ, Guieu C, Jaccard SL, Jickells TD, La Roche J, Lenton TM, Mahowald NM, Marañón E, Marinov I, Moore JK, Nakatsuka T, Oschlies A, Saito MA, Thingstad TF, Tsuda A, Ulloa O (2013) Processes and patterns of oceanic nutrient limitation. Nature Geoscience 6 (9): 701-710. https://doi.org/10.1038/ngeo1765
- Moore JK, Fu W, Primeau F, Britten G, Lindsay K, Long M, Doney S, Mahowald N, Hoffman F, Randerson J (2018) Sustained climate warming drives declining marine biological productivity. Science 359 (6380): 1139-1143. https://doi.org/10.1126/science.aao6379
- Murphy EJ, Cavanagh RD, Drinkwater KF, Grant SM, Heymans JJ, Hofmann EE, Hunt GL, Johnston NM (2016) Understanding the structure and functioning of polar pelagic ecosystems to predict the impacts of change. Proceedings of the Royal Society B: Biological Sciences 283 (1844). https://doi.org/10.1098/rspb.2016.1646
- Paffrath R, Laukert G, Bauch D, Rutgers van der Loeff M, Pahnke K (2021) Separating individual contributions of major Siberian rivers in the Transpolar Drift of the Arctic Ocean. Scientific Reports 11 (1). https://doi.org/10.1038/s41598-021-86948-y
- Record N, Ji R, Maps F, Varpe Ø, Runge J, Petrik C, Johns D (2018) Copepod diapause and the biogeography of the marine lipidscape. Journal of Biogeography 45 (10): 2238-2251. https://doi.org/10.1111/jbi.13414
- Redfield AC. (1934) On the proportions of organic derivatives in sea water and their relation to the composition of plankton. University Press of Liverpool 1.
- Sarmiento JL, Gruber N, Brzezinski MA, Dunne JP (2004) High-latitude controls of thermocline nutrients and low latitude biological productivity. Nature 427 (6969): 56-60. https://doi.org/10.1038/nature02127
- Torres-Valdés S, Tsubouchi T, Bacon S, Naveira-Garabato A, Sanders R, McLaughlin F, Petrie B, Kattner G, Azetsu-Scott K, Whitledge T (2013) Export of nutrients from the Arctic Ocean. Journal of Geophysical Research: Oceans 118 (4): 1625-1644. https://doi.org/10.1002/jgrc.20063

- van Sebille E, Griffies S, Abernathey R, Adams T, Berloff P, Biastoch A, Blanke B, Chassignet E, Cheng Y, Cotter C, Deleersnijder E, Döös K, Drake H, Drijfhout S, Gary S, Heemink A, Kjellsson J, Koszalka IM, Lange M, Lique C, MacGilchrist G, Marsh R, Mayorga Adame CG, McAdam R, Nencioli F, Paris C, Piggott M, Polton J, Rühs S, Shah SA, Thomas M, Wang J, Wolfram P, Zanna L, Zika J (2018) Lagrangian ocean analysis: Fundamentals and practices. Ocean Modelling 121: 49-75. https://doi.org/10.1016/j.ocemod.2017.11.008
- Wassmann P, Reigstad M, Haug T, Rudels B, Carroll M, Hop H, Gabrielsen GW, Falk-Petersen S, Denisenko S, Arashkevich E, Slagstad D, Pavlova O (2006) Food webs and carbon flux in the Barents Sea. Progress in Oceanography 71: 232-287. https://doi.org/10.1016/j.pocean.2006.10.003
- Wrona F, Johansson M, Culp J, Jenkins A, Mård J, Myers-Smith I, Prowse T, Vincent W, Wookey P (2016) Transitions in Arctic ecosystems: Ecological implications of a changing hydrological regime. Journal of Geophysical Research: Biogeosciences 121 (3): 650-674. https://doi.org/10.1002/2015jg003133
- Yamamoto-Kawai M, Carmack E, McLaughlin F (2006) Nitrogen balance and Arctic throughflow. Nature 443 (7107): 43-43. https://doi.org/10.1038/443043a
- Zeng J, Chen M, Zheng M, Hu W, Qiu Y (2017) A potential nitrogen sink discovered in the oxygenated Chukchi Shelf waters of the Arctic. Geochemical Transactions 18 (1). https://doi.org/10.1186/s12932-017-0043-2