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Grant Proposal

Polar Ocean Mixing by Internal Tsunamis (POLOMINTS)

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Abstract

Mixing of the ocean around Antarctica is a key process that exerts influences over large scales and in multiple ways. By redistributing heat in the ocean, it exerts strong influences on the Antarctic Ice Sheet, with implications for sea level rise globally. Similarly, the redistribution of ocean heat affects the production of sea ice in winter and its melt in summer, with consequences for climate. Mixing also affects the distribution of nutrients in the ocean, with direct impacts on the marine ecosystem and biodiversity and with consequences for fisheries.

It was long thought that mixing of the seas close to Antarctica was predominantly caused by winds, tides and the loss of heat from the ocean especially in winter. However, we recently discovered that when glaciers calve in Antarctica, they can trigger underwater tsunamis. These are large (multi-metre) waves that move rapidly away from the coastline and when they break, they cause sudden bursts of very intense mixing. Simple calculations indicated that the net impact of these underwater tsunamis could be as strong as winds, and much more important than tides, in driving mixing. It was also argued that they are likely to be relevant everywhere that glaciers calve into the sea, including Greenland and across the Arctic. As our ocean and atmosphere continue to heat up, it is very possible that glacier calving will become more frequent and intensify, increasing further the impact of underwater tsunamis on large-scale climate, the cryosphere and ecosystems.

This is an exciting new avenue of scientific investigation and many key questions remain unanswered. We need to know how widespread and frequent the generation of underwater tsunamis is, how far they travel from the coastline before breaking, and how variable this is. We need to measure what impacts the extra mixing has on ocean temperature and nutrient concentrations, and to determine what this means for the cryosphere and ocean productivity. There is a pressing need to include the effects of underwater tsunamis in the computer models that are used for projecting future ocean climate and ecosystem conditions and to determine the feedbacks between climate change and the generation of more underwater tsunamis.

To answer these questions, our project will deploy innovative techniques for measuring the ocean and ice in close proximity to a calving glacier, including robotic underwater vehicles and remotely-piloted aircraft, and cutting-edge deep-learning techniques applied to satellite data. We will use advanced computer simulations to fully understand the causal mechanisms responsible for the creation and spread of the underwater tsunamis and their impacts on ocean climate and marine productivity. We will make our developments in computer simulation available to the whole community of users, for widespread uptake and future use.

This project will have significant benefits for academics seeking to predict the future of Antarctica and its impacts on the rest of the world, for Governments and intergovernmental agencies seeking to understand how best to respond to climate change, and for the curious general public wanting to learn more about the extremes of the planet and why they matter. The fieldwork will be especially photo- and video-genic and will lead to outstanding outreach and impact opportunities, and we will work with media agencies seeking to tell compelling stories about the extremes of the Earth.

Keywords

ocean mixing, glacier calving, internal waves, internal tsunamis, carbon, biogeochemistry

Motivation and context

Transformations of Antarctic shelf waters exert a global climatic influence (IPCC 2019). Heat from these waters drives the retreat of the marine-terminating glaciers and ice shelves that fringe Antarctica (Shepherd et al. 2004, Cook et al. 2016), impacting ice sheet stability and sea-level rise (The IMBIE team 2018, IPCC 2019). Dense water production on Antarctic shelves replenishes the lower limb of the global oceanic overturning circulation, significantly influencing global climate (Orsi et al. 2001). Antarctic shelf waters are typically highly productive due to the injection of micronutrients from glaciers and sediments (Boyd and Ellwood 2010), with both surface glacial melt and subglacial plumes subsidising primary production (Forsch et al. 2021). Vertical mixing of deeper waters replete in macronutrients supports the food web locally and facilitates drawdown of carbon from the atmosphere (Buesseler et al. 2010, Schofield et al. 2010, Barnes et al. 2018).

The conventional paradigm has long held that ocean mixing around Antarctica is driven predominantly by winds, tides, and buoyancy forcing. However, it was recently observed that glacier calving can trigger internal tsunami waves, the breaking of which drives bursts of vigorous vertical mixing that strongly homogenise the upper ocean (Meredith et al. 2022; Fig. 1). Based on energy budget calculations and satellite-determined calving frequencies, it was argued that these internal tsunamis could be at least comparable to winds, and much more important than tides, in driving regional mixing. Further, it was argued that they could be relevant across wide areas where marine-terminating glaciers calve, including Greenland and across the Arctic, impacting large-scale ocean productivity, carbon cycling and the marine ecosystem. Calving could become more frequent as ocean and atmosphere temperatures continue to rise (Luckman et al. 2015, Todd et al. 2019); exacerbated by larger ice blocks calving as grounding lines retreat, this would likely lead to strengthened internal tsunamigenesis and mixing. This could have significant implications for how future polar shelf seas support their ecosystems and regulate climate.

The discovery of calving-induced internal tsunamis and their role in mixing was serendipitous, with only a single event observed for a few days. Important questions remain concerning the type and scale of calving most effective in triggering such tsunamis, how widespread they are, how far they propagate, their dependence on oceanographic conditions and fjordic geometries, their climatic, biogeochemical and ecological impacts, and their likely evolution in a warming world. At present, it is unclear even whether this process represents a positive or negative feedback on glacier stability under different conditions of ocean stratification. A systematic, process-orientated project is now needed to answer these questions and to determine how this newly-discovered source of ocean mixing can be represented in regional and large-scale ocean models.

We propose an interdisciplinary project combining intensive dedicated observational campaigns, data mining, Earth Observation (EO) studies, deep-learning techniques and innovative modelling to meet this requirement. Using these techniques, we will address a key overarching goal, which is ***to determine the key mechanisms of internal tsunamigenesis across a wide range of temporal/spatial scales of glacier calving and ocean conditions and to quantify its impact on mixing, heat and nutrient redistribution, marine productivity and carbon cycling.***

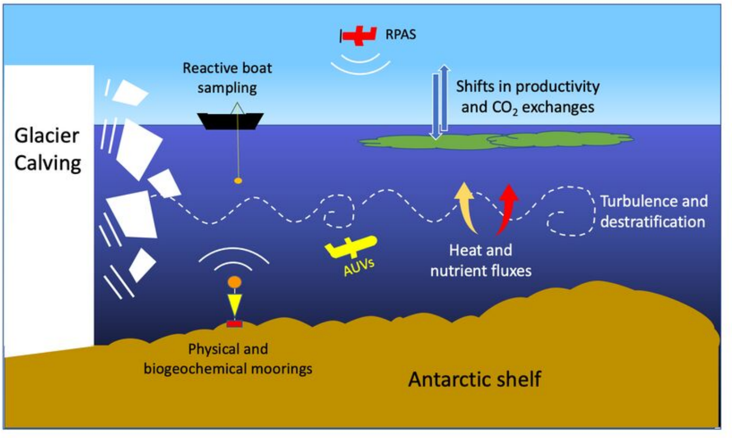


Figure 1. doi

Schematic of calving-induced internal tsunami generation and breaking, with impacts on mixing, heat and nutrient fluxes, and exchanges of carbon dioxide. Some elements of our planned observational campaign are marked.

This is a very recent and exciting new avenue of interdisciplinary science. The single observation of internal tsunamigenesis by glacier calving made thus far has already generated a high-profile paper and significant media interest and there is now very strong potential for rapid progress. The science we propose here will greatly advance our understanding of, and ability to predict, ocean transformations in regions crucial for climate change, cryosphere loss and ecosystems change. By delivering this science, POLOMINTS will produce three key outputs:-

1. Detailed mechanistic understanding of the forms/sizes of calving and fjord/shelf geometries most effective at generating internal tsunamis, enabling *advances in understanding of ice/ocean interactions in climatically-, biogeochemically- and ecologically-important regions.*
2. An assessment of the regional impacts of ocean mixing from internal tsunamis on the distributions and exchanges of ocean heat, nutrients and carbon, and how this may change in future, enabling *policy-relevant assessments of the implications for climate, the cryosphere and ecology.*
3. Knowledge of how to represent vigorous and episodic internal tsunami-driven mixing in ocean models, thus *improving model capability in relation to one of the most poorly-understood components of the Earth system.*

Justification for a Large Grant approach

Large, multidisciplinary challenges require large multidisciplinary projects. The impacts of internal tsunamis on climate and marine productivity will depend on complex interactions between the cryosphere, ocean, biosphere and atmosphere. Determination of these requires multidisciplinary analyses of a wide range of *in situ*, autonomous and remotely-sensed data, along with sophisticated model analyses and deep-learning techniques. Collaborative work across a large team of specialists is needed to ensure that the model configurations are suitably informed by diverse data and remote-sensing outputs and that fieldwork execution and data interpretation are informed by the modelling. A single integrated project is needed to achieve our objectives, and is beyond the resource scope of smaller funding schemes.

Beneficiaries

The POLOMINTS outputs will directly benefit a range of academic and wider stakeholders. They will be of significant benefit to scientists seeking enhanced knowledge of ice/ocean interactions in climatically-, biogeochemically- and ecologically-important regions, including some of the most rapidly-changing in the world. We will improve model skill in one of the most poorly-understood components of the Earth system, representing an important pathway to improve our capability for robust future projections. This will include transferring our model parameterisation back to the trunk of the Nucleus for European Modelling of the Ocean (NEMO), which is widely used nationally and internationally for simulations and projections of the ocean, climate and ecosystem. Our project will enable improved contributions to policy-relevant assessments of the role of the polar regions in climate, the cryosphere and ecology, thus helping to improve decision-making concerning mitigation of, and adaptation to, climate change. We anticipate disseminating key findings via UN and Intergovernmental assessments, including the Intergovernmental Panel for Climate Change (IPCC) and the Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services (IPBES). Potential implications relevant to ecosystems conservation and fisheries policy will be disseminated to the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). In addition, we will engage with UK policy stakeholders via the All-Party Parliamentary Groups (APPGs) for the Ocean and for Polar Regions, via the annual “State of the Polar Regions” reports for the Foreign, Commonwealth and Development Office, and so on. We will also engage with communications specialists, popular science communicators and documentary makers, many of whom have already shown great interest in this research given its dramatic and videogenic nature; by so doing, we will seek to convey the importance and excitement of what we do to the curious public.

Timeliness

The generation of internal tsunamis by glacier calving is a very recent and exciting discovery, and this is the first opportunity to mobilise a large, multidisciplinary project to investigate it with the specialist equipment and capability required. The urgency for such a project derives from the rapidly-changing nature of the polar environments, which include some of the regions most impacted by climatic warming anywhere in the world. Antarctica is potentially passing a tipping point to a “new normal”, with cryosphere and ocean changes key to this transition (Siegert et al. 2023). Important changes to mixing from internal tsunamis are likely already occurring and their current net impact and future role are completely unknown. Policy requirements specify the need for improved information on polar changes and global consequences (IPCC 2019, IPCC 2023); this requires that suitable understanding and model improvements are progressed rapidly.

Research Environment

We have selected Ryder Bay at the Antarctic Peninsula as the dedicated field campaign site (Fig. 2). This research environment is the ideal site to conduct our fieldwork: Sheldon Glacier terminates here and calves with a range of frequencies and magnitudes such that internal tsunamis will be generated several times across the two-year campaign (Fig. 3). The bathymetry in the Bay is well characterised and it is the location of the Rothera Time Series (RaTS) which provides year-round physical and biogeochemical ocean observations that will supplement POLOMINTS. Furthermore, it is very close to the scientific infrastructure and capability at Rothera Research Station required for the ambitious measurement programme. The boating facilities at Rothera will support reactive human sampling following calving events and will enable deployment and recovery of underwater robotic platforms (see Tools and Techniques below for full list). Rothera has capabilities to support the deployment and recovery of fixed-wing Remotely-Piloted Aircraft Systems (RPAS), putting Sheldon Glacier within easy reach of airborne scanning sensors. The Bonner Laboratory will be used for processing of seawater samples requiring immediate analysis; other samples will be returned to the UK for analysis in participating laboratories here. UK-based facilities for delivering the project include institutes and departments with extensive track records and capabilities for the science proposed, including biogeochemical laboratories, Earth Observation data processing suites, logistical support for preparing field campaigns and advanced computing facilities for numerical simulations and processing of large-volume datasets.

Programme Structure

Three science work packages (WPs; Table 1) will interconnect to deliver POLOMINTS, with a fourth WP ensuring delivery of all its elements, cross-linkages within and outside the project and provision of key results to external stakeholders. Each science WP will draw on a set of Tools and Techniques (T1-T10) outlined below.

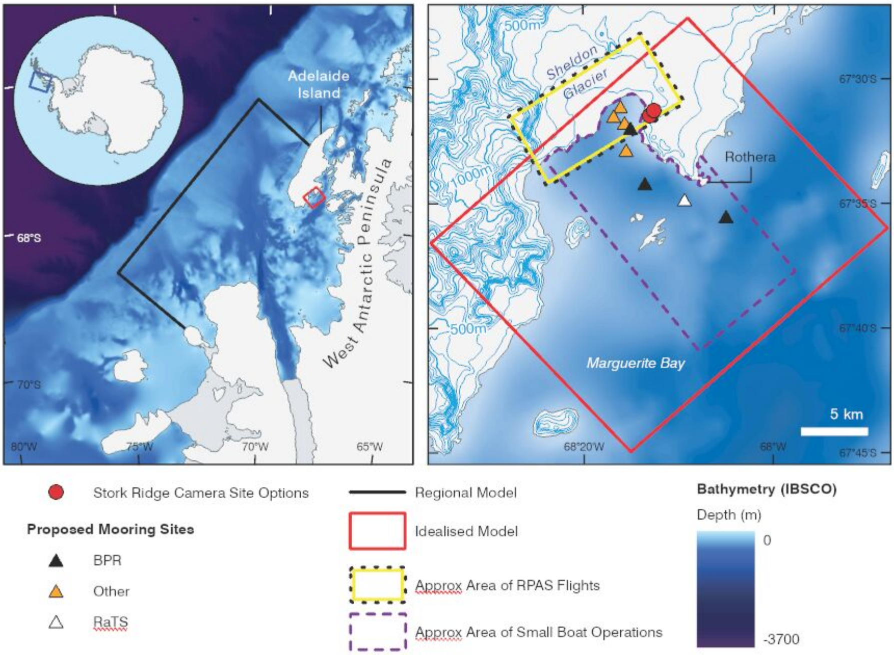


Figure 2. doi

(Left panel) Locations of regional (black) and idealised (red) model domains at the West Antarctic Peninsula. (Right panel) Positions for fixed cameras and ocean instrumentation (symbols), plus coverage of boating/underwater robotic vehicle operations (purple) and remotely-piloted aircraft system flights (yellow).

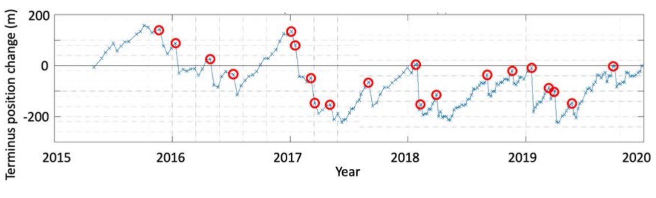


Figure 3. doi

Position change of the Sheldon Glacier terminus during 2015-2020, from satellite-derived Synthetic Aperture Radar (SAR). Red symbols indicate calving events of the magnitude observed previously to trigger internal tsunamigenesis (Courtesy Benjamin Wallis, Leeds University).

Table 1.
Table of Work Packages and WP Leaders

#	Description	Leaders
WP1	Dynamics of internal tsunami generation	Inall (SAMS); Sheen (Exeter)
WP2	Physical and biogeochemical impacts	Carvalho (NOC); Brearley (BAS)
WP3	Large-scale relevance and future evolution	Young (BAS); Van Landeghem (Bangor)
WP4	Management, synthesis, dissemination, impact	Meredith, Hendry (BAS)

WP1: ***Dynamics of internal tsunami generation*** will answer the following key questions:

Q1) How does internal tsunami generation depend on calving magnitude and type (waterline, ice-fall, sheet collapse, stack topple, subaqueous, hybrid etc.)?

Q2) How do oceanographic conditions within fjords influence the characteristics of the internal tsunamis generated and how does this vary within and between seasons?

Q3) To what extent is fjord geometry a key influencer on the magnitude and nature of internal tsunamis generated?

Q4) How far do the internal waves generated propagate from the source, how does the internal wave energy decay, and what is the associated dissipation of turbulent kinetic energy?

To answer these questions, we will use fixed cameras (T5) and passive underwater acoustics (T3) to detect and quantify calving events, augmented with routine and reactive RPAS footage (T4), satellite remote sensing (T7) and active acoustic glacier scanning from small boats (T9). The internal wave response to these events will be classified in terms of vertical structure and spectral composition using moorings and continuously-present underwater glider datasets (T3, T2, T10). Internal wave characteristics will also be recovered from flight deviation analysis applied to underwater glider trajectories. Non-linearity, wave decay and dispersion will be determined from mooring data. Idealised modelling (T8) will be informed by observational data (including from data mining; T1) and used to determine how different modes of ice movement induce different modes of pycnocline response; these simulations will then be used to explore causal relationships across a wide range of parameter space. We will use the idealised modelling simulations and glider data to quantify the magnitude of internal wave energy at differing distances from the glacier front, its direction of speed and propagation and the dissipation of turbulent kinetic energy. The findings of WP1 will be used in other analyses (WP2) to determine the consequences of internal tsunamigenesis for vertical and horizontal water property fluxes. The final output of WP1 will be a set of functional relationships derived from observations and fine-resolution modelling that will provide algebraic expressions relating enhanced vertical mixing (in the form of spatio-temporal estimates of vertical eddy diffusivity) as a function of fjord geometry, stratification and calving type/size. These expressions will form the basis of a parameterisation to be employed in the regional and circum-Antarctic model simulations (WP2, WP3).

WP2: Impacts on ocean physics, biogeochemistry and phytoplankton ecology will answer the following key questions:-

Q1) What impact does internal tsunami-induced mixing have on the water column properties, specifically the stratification, mixed layer depth and heat fluxes?

Q2) How does the magnitude of this compare with other (known) generators of mixing, including near-inertial shear from winds and internal tides?

Q3) What are the biological and ecological implications of this mixing for ocean biogeochemistry (fluxes of nutrients into the photic zone) and phytoplankton ecology?

Q4) What are the implications for carbon sequestration into the deeper ocean, below the main thermocline?

To answer these questions, a combination of observational datasets collected during POLOMINTS (T2, T3, T6, T10) will be used alongside regular weekly water column profiling and sampling undertaken at the RaTS site (funded separately; Fig. 2). In addition, building on the outputs of WP1, a parameterisation of mixing from internal tsunamis will be developed and implemented in a regional oceanographic model (T8). Baseline data from non-calving periods will be collected, including leveraging RaTS, and complementary baseline model simulations will be conducted to understand the natural spatial and temporal patterns upon which tsunami-induced mixing is superposed. The strength and mechanisms of background mixing from other sources will be assessed using historical data, re-analysis and tidal products, local meteorological data collected routinely at Rothera, and our own observational data and regional modelling, following initial procedures established in Meredith et al. (2022). The impacts of tsunami-induced vertical heat redistribution on glacier stability will be examined using simple meltwater plume theory (e.g. Jackson et al. (2020)). The biogeochemical/ecological implications of mixing and impacts on nutrient and carbon fluxes will be assessed via quantification of upper-ocean nutrient stocks, and primary productivity determined through diel cycles in oxygen and modelled using bio-optical data. We will determine links between changes in water column properties (light and stratification) and nutrient stocks due to mixing impacts on phytoplankton growth rates and potential changes in community structure. Observational data will allow quantification of the effects of mixing on carbon export dynamics, inorganic and organic carbon cycling and ocean alkalinity.

WP3: ***Large-scale relevance and future evolution*** will use a combination of observations and modelling, informed by outputs from WP1 and WP2, to answer three key questions:-

Q1) How widespread is internal tsunamigenesis by glacier calving?

Q2) What are the large-scale impacts of tsunami-induced mixing on ocean productivity and drawdown of heat and carbon?

Q3) How might changes in calving characteristics modify these impacts in the future as the ocean and atmosphere continue to warm?

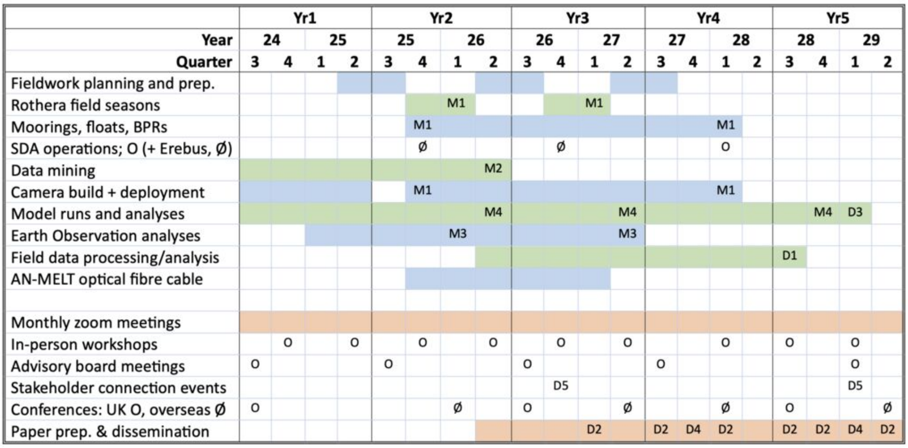
To address Q1, we will exploit Synthetic Aperture Radar data from the Sentinel-1 satellite (T7) combined with deep-learning methods to systematically map the circumpolar geographical extent and frequency of large glacier calving events for all of Antarctica. Concurrently, we will mine available oceanographic time series (T1) to ascertain the geographical extent of internal tsunamis associated with identified calving events and to reveal which calving magnitudes are likely to trigger internal tsunamis, with subsequent refinement of the satellite data analysis. The 8-year long satellite data record provides year-round measurement capability, enabling us to:

- characterise the amount of ocean mixing associated with different types of calving behaviour in different areas,
- measure how calving behaviour varies seasonally and interannually in different regions, and
- investigate how this might be linked to different sea ice and oceanographic environmental conditions.

To address Q2, we will use a numerical modelling approach, combining the tsunami extent and frequency quantified in Q1 together with the new parameterisation of mixing from internal tsunamis developed in WP1 and tested at a regional scale in WP2, to assess the impact of internal tsunamis on Southern Ocean heat and carbon drawdown and on large-scale productivity (T8). This will be achieved through incorporation of the new mechanism for oceanographic mixing in an existing high-resolution (1/12º) NEMO-Medusa model with circumpolar coverage. To address Q3, we will use the enhanced model to quantify the physical and biogeochemical effects of predicted future changes in calving frequency and magnitude, with different simulations conducted to represent an increase in calving as warming continues and glaciers retreat and a decrease in calving as glaciers retreat further to become land-terminating.

WP4. Management, synthesis, dissemination and impact. All investigators and Project Partners will participate in this WP, with the PI assuming overall responsibility for project delivery, risk management, dissemination and generation of impact. Operational responsibility for individual project components, including line management of PDRAs, will be devolved to the relevant Co-Investigators. All-hands meetings will be held monthly via videoconferencing and every six months in person to ensure effective progress towards our objectives, with the meeting location rotating between the investigators' institutions. We will invite an Advisory Board (composition to be agreed with NERC) to oversee the project progression and help ensure optimal delivery and impact.

Fig. 4: Key events/activities within POLOMINTS, with specific Milestones and Deliverables marked



	Yr1				Yr2				Yr3				Yr4				Yr5			
Year	24		25		25		26		26		27		27		28		28		29	
Quarter	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2
Fieldwork planning and prep.																				
Rothera field seasons							M1				M1									
Moorings, floats, BPRs						M1									M1					
SDA operations; O (+ Erebus, Ø)						Ø				Ø					O					
Data mining								M2												
Camera build + deployment						M1									M1					
Model runs and analyses								M4				M4						M4	D3	
Earth Observation analyses							M3					M3								
Field data processing/analysis																	D1			
AN-MELT optical fibre cable																				
Monthly zoom meetings																				
In-person workshops		o		o		o		o		o		o			o		o		o	
Advisory board meetings	o				o				o				o						o	
Stakeholder connection events										D5									D5	
Conferences: UK O, overseas Ø	o						Ø		o			Ø			Ø		o			Ø
Paper prep. & dissemination											D2		D2	D4	D2		D2	D2	D4	D2

Figure 4. doi

Key events/activities within POLOMINTS, with specific Milestones and Deliverables marked.

M1. Successful deployment of fixed observational array (Q4 25); completion of season 1 summer field campaign (Q1 26); summer 2 field campaign (Q1 27); recovery of fixed array (Q1 28).

M2. Collation of all mined datasets for truthing models and enabling historical tsunamigenesis to be investigated around Antarctica (Q2 26).

M3. EO datasets processed and deep-learning algorithm trained (Q1 26); processing of large-area datasets and inclusion in analyses (Q2 27).

M4. Idealised (Q2 26), regional (Q2 27) and circum-Antarctic (Q4 28) models successfully run, with new parameterisation included in latter two.

D1. All new datasets processed, quality controlled and passed to data centres for archiving and dissemination (Q3 28).

D2. Key publications on: (i) historical evidence for calving-induced tsunamigenesis, based on data mining and EO; (ii) dynamics and dependencies of calving-induced tsunamigenesis; (iii) impacts of breaking internal tsunamis on ocean mixing, heat, nutrient and carbon fluxes; (iv) large-area impacts on physical and biogeochemical ocean dynamics; (v) future changes in tsunamigenesis and impacts under different idealised climate scenarios; (vi) overarching paper drawing key findings together, targeted at a high-profile journal. Numerous other papers are anticipated throughout the course of the project.

D3. Model configurations made publicly-available and new parameterisation passed to developers for inclusion in NEMO trunk (Q1 29).

D4. Briefing papers written for Government, APPGs and intergovernmental agencies on relevance of new findings to climate, ecosystem and resource management policy (Q4 27; Q1 29).

D5. Stakeholder connection events with media, academics and policymakers (Q4 26; Q1 29).

WP4 will oversee dissemination activities, ensuring suitable representation at key meetings and conferences and tracking production and delivery of outputs. It will ensure the delivery of new scientific evidence in accessible form to intergovernmental assessment bodies concerned with climate and biodiversity (IPCC, IPBES) to make it available to policymakers. We will work with marine biologists in BAS and beyond to determine the key implications of the science for conservation and fisheries policy; WP4 will ensure accessible material is input to CCAMLR accordingly. We will pro-actively engage with a wide stakeholder community in the UK, including Government and Parliament; this will be achieved via our connections with the All-Party Parliamentary Groups (APPGs) on the Ocean and on the Polar Regions and through the production and dissemination of briefing notes. Our fieldwork will be extremely photo- and video-genic, and we will work with the press offices of the partner institutes to connect with different media interested in reporting the science as it happens, in addition to key new findings; we will use this route to inspire the curious public with the excitement of the science and Antarctica.

Project risks include those inherent in any marine/polar field-based campaigns. The risk of equipment failure/loss in the field will be mitigated by using multiple platforms with overlapping capabilities and by incorporating pre-existing data where possible. The risk of the fieldwork schedule being moved due to operational reasons will be mitigated by the capability to deploy field personnel and equipment by different routes (air, sea) and by leveraging collaborations to help with deployment where practicable. Our heavy use of autonomous technology reduces dependency on large research vessels for many of the techniques to be used. The risk of Ryder Bay being covered in sea ice during key periods is diminishing due to climate change, but cannot be assumed negligible especially in winter; use of the permanently-staffed Rothera Research Station as the launching site for our fieldwork will ensure that the work can be undertaken whenever conditions allow. Having two summer field seasons is not only scientifically important, it will enable lessons to be learned from the first season and methods to be refined. Risks with laboratory/office-based aspects of the programme are low, with tested equipment and procedures to be used. The project requires cutting-edge model development, but the team includes experienced developers and has the MIT general circulation model (MITgcm) and NEMO communities to draw upon for support. With suitable mitigation in place, the chance of successful delivery of POLOMINTS is very high.

Tools and Techniques

T1. Data mining. Given that the existence of calving-induced internal tsunamis is a very recent discovery (Meredith et al. 2022), it seems very likely that their signatures are present in existing observational datasets, but were not recognised at the time of their collection. To gain baseline information on the spatial extent of these tsunamis, we will examine existing data holdings, with particular focus on ocean moorings data that have the necessary high temporal resolution. Analyses will include identification of apparent impulsive changes in velocity, shear and/or properties at fixed depth that are not readily explicable by other causal factors such as storms. Linking of these data to remotely-sensed imagery (T7) will enable positive attribution of *in situ* ocean changes to glacier calving events. Diverse data banks will be interrogated, including the US National Centers for Environmental Information, the British Oceanographic Data Centre and others, and we will use networks of collaborators and Project Partners to access as-yet-undeposited data.

T2. Autonomous Underwater Vehicles (AUVs). Four underwater gliders will be deployed (Fig. 2), carrying sensors for the measurement of conductivity-temperature-depth (CTD), chlorophyll, optical backscatter, dissolved oxygen and photosynthetically-active radiation. A Rockland microstructure package for quantifying the turbulent kinetic energy dissipation rate will also be used. Intensive four-month long deployments will occur over the two summer seasons, with wintertime data collected as sea ice permits using a rechargeable glider based at Rothera. The gliders will be deployed at different distances from the glacier front to elucidate the distance and magnitude of internal wave propagation and its biogeochemical effects and will be piloted adaptively in both “virtual mooring” and “section” modes. The continuous glider observations will be augmented at the times of calving events by short (~ 1 day) deployments of the micro-AUV Ecosub, which will run short sections to/from and parallel to the front of Sheldon Glacier, measuring temperature, salinity, chlorophyll, dissolved oxygen and pH. When combined with the small-boat based measurements (T6) and in combination with the moorings (T3), this will fully elucidate the near-field physical and biogeochemical impacts of the individual internal tsunami events.

T3. Seabed-deployed instrumentation. Ocean moorings and bottom landers (Fig. 2) will be deployed to determine the changing physical/biogeochemical regimes in front of Sheldon Glacier and across Ryder Bay through two full annual cycles, including rapid perturbations to the ocean caused by internal tsunami propagation and breaking. Observations will include passive acoustic detection of glacier calving using hydrophones close to the front of Sheldon Glacier, with determination of calving mode/ magnitude conducted as per Głowacki and Deane (2020). Acoustic Doppler Current Profiler (ADCPs) will measure currents throughout the water column, from which internal wave kinetic energy and internal shear can be calculated. Sediment traps will be deployed on moorings to measure particle fluxes. To obtain profiles of the changing physical/biogeochemical structure of the full water column, we will deploy tethered profiling floats consisting of acoustic releases in syntactic foam collars attached to profiling floats fitted with CTD and biogeochemical (fluorometer/turbidity, dissolved oxygen, light) sensors. Between profiles, the floats will rest on the seabed, allowing near full-depth profiling without risking ice damage; ice-avoidance algorithms will also be used with profiling to the surface being aborted when ice is present. Profiling interval will be ~ 2-3 days over the 2-year deployment period. Three SBE26 high-precision bottom pressure recorders (BPRs) will be deployed at intervals from the glacier (Fig. 2). Internal waves of amplitude greater than ~ 3 m can be detected in such records (Moum and Nash 2008), thus internal tsunamis of expected magnitudes (up to ~ 20 m) will be identifiable (Meredith et al. 2022). Using these BPRs, we will be able to detect the magnitude and decay of the internal tsunamis as they propagate, which will feed into the estimation and modelling of the far-field internal wave effects.

T4. Airborne campaigns. During the summer field seasons, we will conduct regular flights with RPAS over the Sheldon Glacier front. These flights will use the BAS autonomous AgEagle eBee X fixed-wing aircraft with a SODA3D optical camera. We have an established photogrammetric workflow to derive surface elevation over ice- or snow-covered terrain. Differences between these derived surfaces will provide a measure of the magnitude of change above sea level and, hence, produce volumetric information on the size of calving events in addition to qualitative information on the locations across the glacier system where calving has occurred.

T5. Fixed-camera array. We will install four fixed cameras at two locations on Stork Ridge, overlooking the Sheldon Glacier front (Fig. 2). These cameras will be arranged to allow collection of regular (minimum twice daily during summer) stereo photography of the glacier front, allowing us to derive high-accuracy 3D models and calculate volume changes between calving events. The cameras will be linked to Rothera via a satellite communications link (Iridium Certus) to provide a live view of the glacier front and alert the local project team of calving events, enabling reactive sampling with small boats (T6) and retasking of autonomous underwater vehicles (T2).

T6. Reactive small boat sampling and laboratory analyses. When the Stork Ridge camera system (T5) identifies a calving event, the local team will deploy in rigid inflatable boats as soon as feasible, with immediate sampling being conducted as close to the glacier as is safe. During the rapid/reactive sampling, profiles of temperature, salinity, fluorescence, dissolved oxygen and turbulent fluxes will be obtained using a hand-deployable MSS90 microstructure sonde (Prandke and Stips 1998). The system is robust, portable and can be deployed by non-specialist field scientists, making it an ideal way to directly quantify vertical property fluxes (Inall et al. 2022) immediately after a calving event. CTD profiles will subsequently be conducted from the boat to determine the time evolution of the water column structure. These will include use of an RBRconcerto CTD with rapid data transfer to enable targeting of specific features in the water column (e.g. high turbidity layers, rapid changes in mixed layer depth) for discrete water sampling by Niskin bottle. Samples will be stored for further processing in the Bonner Laboratory at Rothera or for return to the UK, with the following variables determined: inorganic macronutrients, total alkalinity/dissolved inorganic carbon, pigments, stable oxygen isotopes, salinity and particulates (organic matter, lithogenic material etc.). These analyses will elucidate both the physical and biogeochemical responses to calving and internal tsunami breaking and will support glider bio-optical calibration.

T7. Deep learning applied to Synthetic Aperture Radar (SAR) imagery. We will apply deep-learning techniques (specifically convolutional neural networks) to satellite-derived SAR data to determine glacier front locations and calving events around Antarctica on unprecedented spatio-temporal scales. For the required training dataset, we will use a combination of publicly-available training datasets (Gourmelon et al. 2022) and manual annotation, bootstrapping and image augmentation. We will use neural network architectures and pre-trained models developed for the task of calving front delineation (e.g. Cheng et al. 2021, Baumhoer et al. 2023), adapting these for Antarctica using a bespoke dataset. For this, calving front locations in Sentinel-1 interferometric wide-swath SAR backscatter images will be manually delineated to represent realistic variation of calving fronts in Antarctica, with the images then tiled into patch images before random rigid transformations are applied to increase the volume of training data. The trained and fine-tuned neural network model will be used to produce calving measurements around the full Antarctic coastline for an 8-year period, with a temporal resolution of up to 6 days. For individual cases identified by data mining (T1) as being potentially internal tsunami-driven mixing, individual SAR images will be examined manually, with specific attention placed on glacier calving series at the field site (Fig. 2) to optimally interpret the new *in situ* data.

T8. Numerical Modelling. WPs 1-3 will draw on numerical simulations that span multiple scales, each with distinct capabilities and purposes.

- A fine-resolution (~ 50 m) idealised model of Ryder Bay (Fig. 2), constructed using the MITgcm and building on previous modelling of internal tsunamis (Meredith et al. 2022), will be used to investigate fundamental processes of their generation, propagation and breaking. Different methods to introduce calving-induced perturbations will be tested and optimised in relation to mined observations (WP1) and those from which the initial discovery/characterisation of internal tsunamis were made. We will then test the sensitivity of internal tsunami generation and propagation to different modes and sizes of calving events, different ocean stratifications and fjord geometries, and the impacts on energy dissipation and diffusivity will provide information for the development of a tsunami-driven mixing parameterisation for inclusion in the larger-scale ocean models. This parameterisation will be created using results from historical and satellite observations, including those from which internal tsunamigenesis was originally identified, with possible refinements following availability of bespoke field data (T1, T7, T2-6).
- The parameterisation of calving-induced mixing will be incorporated in a regional (Marguerite Bay; Fig. 2) very high resolution (~ 1 km) application of NEMO either additively as an enhanced background mixing coefficient or through modification of pre-existing NEMO mixing schemes. Comparisons with baseline (no tsunami) simulations will elucidate the regional-scale impact of the internal tsunamis on mixing, vertical and lateral heat fluxes and their seasonal and short-term

variabilities. Simulations with and without other forcings (winds, tides) will isolate the specific effects of the internal tsunamis. Initial simulations will consider solely the effects of the calving-induced mixing, with further simulations also addressing the role of additional freshwater pulses associated with calving events and their impacts on stratification.

- The parameterisation will be generalised for different grid resolutions and implemented within an existing high-resolution (1/12º) physical/biogeochemical NEMO-Medusa model with full circum-Antarctic coverage. Calving locations and the spectrum of their magnitudes derived from SAR and data mining (T1, T7) will be used in a 2-year simulation and compared with a baseline (no tsunami) simulation to elucidate the large-scale impacts on mixing and ventilation of water masses, biological productivity and heat and carbon fluxes. Further simulations will determine the oceanic responses to a doubling and a halving of calving frequency, representing the potential effects of accelerated calving upon climate-induced glacier retreat and an ultimate switch of some glaciers to become land-terminating.

T9. Glacier front mapping from Erebus workboat. During the period of mooring deployment from RRS *Sir David Attenborough* (SDA; T3), we will use the SDA's 10-m workboat Erebus to map the front of Sheldon Glacier with a MultiBeam Echosounder (MBES). This will capture the 3D shape of the ice front and the seabed underneath. Given that glacier mass loss due to large calving is affected by the interaction between ocean and ice front (heat transfer, subglacial water flux) and between ice and bed (friction and glacier stress field), the simultaneously-documented shape of the glacier front and adjacent seabed are fundamental variables when assessing the potential for large calving to occur and to impact ocean processes.

T10. Optical fibre cable. POLOMINTS will collaborate with the separately-funded AN-MELT project, which is deploying a 15-km optical fibre cable along the seafloor in Ryder Bay that overlaps with our field programme. Co-I Naveira Garabato is common to both projects and will facilitate this collaboration. This innovative technique combines acoustic and gravity wave noise interferometry techniques with distributed optical fibre dynamic strain sensing (e.g. Lindsey et al. (2019), Lucas and Pinkel (2022)) and will deliver a minimum 1-year time series of temperature and ocean velocity throughout the water column at expected spatial (horizontal and vertical) and temporal resolutions of O(10 m) and O(1 min). Whilst POLOMINTS is not reliant on AN-MELT for its successful delivery, this joint exercise will opportunistically enable us to both: (i) quantify the skill and limitations of the fibre optic sensing approach and (ii) enrich the interpretation of POLOMINTS observations by enhancing their spatial and temporal contexts.

Access to Facilities

This project will use a very small amount of ship time on SDA during resupply missions to Rothera and will use the SDA workboat Erebus in seasons 1 and 2 for glacier front mapping. Request is 1-2 days ship time per year, agreed with NERC as an acceptable level (see SMEs). Some moorings equipment has been requested from NMF via SME and confirmed available; all other equipment and platforms required will be provided by the participating institutes and departments. We will use facilities at Rothera Research Station (including boating and Bonner Laboratory facilities), confirmed available (see OSPQ). This project will use the national High-Performance Computing facilities ARCHER2 and JASMIN, which have been discussed and approved in principle by the relevant consortium lead.

Legacy

POLOMINTS will advance our understanding of how a remote and rapidly-changing region impacts the Earth System across large scales. In addition to the impacts detailed above (Beneficiaries and WP4), it will leave a legacy well beyond the 5-year timescale of the project. This will include:

1. key datasets from the data-sparse Southern Ocean, which will have value in perpetuity;
2. a new model scheme, passed to the NEMO trunk and available to all future users;
3. new methodologies for processing Earth Observation data to extract environmentally-critical time series;
4. new knowledge, passed to the academic, policymaker and the wider stakeholder communities, enabling improved decision-making in relation to this rapidly-changing environment and its large-scale impacts.

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Conflicts of interest

The authors have declared that no competing interests exist.

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