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Blue Carbon on Polar and Subpolar Seabeds

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Abstract

When marine organisms eat and grow they capture and store carbon, termed blue carbon. Polar seas have extreme light climates and sea temperatures. Their continental shelves have amongst the most intense phytoplankton (algal) blooms. This carbon drawdown, storage and burial by biodiversity is a quantifiable 'ecosystem service'. Most of that carbon sinks to be recycled by microbes, but some enters a wider food web of zooplankton and their predators or diverse seabed life. How much carbon becomes stored long term or buried to become genuinely sequestered varies with a wide range of factors, e.g. geography, history, substratum etc. The Arctic and Antarctic are dynamic and in a phase of rapid but contrasting, complex physical change and marine organismal carbon capture and storage is altering in response. For example, an ice shelf calving a 5000 km^2 iceberg actually results in 10^6 tons of additional blue carbon per year. Polar blue carbon increases have resulted from new and longer climate-forced, phytoplankton blooms driven by sea ice losses and ice shelf collapses. Polar blue carbon gains with sea ice losses are probably the largest natural negative feedback against climate change. Here the current status, variability and future of polar blue carbon is considered.

Keywords: blue carbon, polar oceans, benthos, carbon immobilization, negative feedback

1. Introduction

Blue carbon is carbon captured and held within marine organisms. It is considered as one type of 'ecosystem service' that biodiversity provides, and thus is part of the value of biodiversity, often termed 'natural capital'. Typically blue carbon evaluations mainly consider habitats such as kelp forests, sea grass beds, salt marshes and mangrove swamps. These are global organismal powerhouses of carbon turnover and support huge biomasses of varied animal life [1]. These

environments are all characterized by rapid growth (high carbon capture) and high biomass (high carbon storage) but over relatively small, coastal areas that are dwindling with anthropogenic land use pressures. Of these environments, only kelp forests are represented in the polar and subpolar regions (**Figure** 1**a**), and even these are scarce because of regular iceberg scouring in shallow waters. Thus blue carbon ecosystem services have to date been little considered in the Arctic and Antarctic, although on land it was realized that a warming Arctic could lead to increased Taiga forest carbon capture and storage. However the magnitude of any negative feedback (mitigation) on climate change is complicated by change in permafrost gas release, reduced albedo because of altered snow cover and less than expected forest growth gains [2]. Nevertheless warming-induced Arctic vegetation expansion represents a rare, and significant, increasing source of carbon capture and thus negative feedback on climate change (this is because of Taiga forest carbon capture is increasing with regional warming, which reduces the greenhouse gas Carbon Dioxide). Antarctica has no forests and > 1% is ice free for the very limited plant biodiversity present, although this is likely to increases with snow and ice retreats.

There are very considerable, if intensely seasonal, phytoplankton (micro-algae) blooms around Arctic and Antarctic coasts and on the underside of seasonal sea ice (the ocean surfaces freeze in winter) [3]. The composition of these blooms vary in time and space but are mainly tiny algae called diatoms, which can be eaten by animals in the food web. On death the vast majority of this huge summer primary productivity sinks through the water column where it is recycled by microbes (mainly bacteria) or eventually reaches the seabed, where most is again recycled, but by seabed microbes. This is called the microbial loop and is responsible for most

Figure 1. High latitude benthic biomass and blue carbon. Macro algae at South Georgia (a), benthic fauna in the shallows of Antarctic, Adelaide Island (b) and Arctic Tromsø (b), and at deeper continental shelf depths around Kerguelen.

polar blue carbon and energy cycling, but little is known about how much of this carbon is ultimately buried and thus genuinely sequestered. Even though only a small proportion of this productivity is consumed by animals, this still supports the largest abundances of animals on Earth, the copepod and euphausiid shrimps (krill). Their biomass, their feces [4] and in turn that of their predators (seabirds, seals and whales), become significant agents of carbon storage and turnover. As with primary productivity though, to be sequestered, the carbon accumulated in water column animals must sink to considerable depths and avoid microbial recycling on route or once it arrives at the seabed and be quickly buried. Recent work on the marine primary consumers (often called herbivores) amongst the zooplankton has shown that their vertical migrations, coupled with considerable lipid storage is a major factor in transferring carbon to the seabed [5]. Furthermore passing through the guts of zooplankton, such as krill, changes iron chemically to make it more bio-available, thus promoting and sustaining the very phytoplankton blooms on which they feed [6]. As a result the increased phytoplankton bloom fixes more CO2 and becomes another system feedback.

Although life in the water column in polar oceans is extremely numerous, it is not rich or diverse, compared with the seabed, and crucially is a long way in time and space for the site of ultimate carbon sequestration – the seabed. The vast majority of known polar species are benthic (seabed dwelling) as adults and many for their entire life-cycles [7]. Living on the seabed, especially as most of it is soft sediment (muds and clays), gives considerable potential for benthos to deliver carbon burial and sequestration. One of the primary factors hindering this pathway is seabed disturbance, unburying and reworking carbon in dead organisms. Storms can do this in the shallows and bioturbation (e.g. burrowing activity) across depths, but in the polar regions icebergs and diving mammals (e.g. walrus) can be major reducers of carbon sequestration. However a big factor is human disturbance of the seabed, such as harvesting by trawling. Most of the world's continental shelf seabed, including the Arctic, is territorial water of varying countries, which has valuable harvestable resources, such as food. In contrast the continental shelf around Antarctica is not owned, and the limited fishing which does occur is strongly regulated by the Committee for Conservation of Antarctic Marine Living Resources (CCAMLR). This governance, and as a result benthic harvesting impact, difference between the polar regions must have very significant influences on the magnitude of carbon buried and sequestered.

This chapter investigates blue carbon on high latitude seabeds (see **Figure 1**). Such a consideration starts by focusing on how and why it varies, between organism types, spatially, historically and with specific environmental factors. How blue carbon capture and storage is now changing in response to rapid, recent, regional physical change, such as 'global climate change' and stratospheric ozone losses. This is important given that parts of the polar regions are amongst the most rapidly and profoundly changing areas on Earth. An attempt is then made to evaluate the importance of polar blue carbon to the Earth system, with its respect to its action as a negative feedback on climate change. Lastly the likely future of polar blue carbon is considered and how this might be better monitored, for example by initiatives such as the Southern Ocean Observing System (SOOS). The polar oceans are key sinks for anthropogenic production of CO_2 and the sensitivity of their carbon cycles to physical change is poorly known and understood [9]. Blue carbon, in contrast to that stored dissolved in polar oceans storage is undoubtedly very much smaller, but increasing and with high genuine sequestration potential, and perhaps its quantification could lead to understanding some of the current unexplained variability in global model projections.

2. Environmental influences on the distribution and magnitude of benthic blue carbon around polar seabeds

Sediment cores taken by geological scientists around the polar regions have shown very considerable patchiness in the both the amount and proportion of carbonate ($CaCO_3$) in polar sediments [8]. Benthic biological work over the last century has similarly demonstrated a huge variety in the carbon stocks held in biota on the seabed [10]. The source of these is the dissolved carbon (dioxide) in water masses and huge, but intensely seasonal productivity by phytoplankton and dependent consumers, such as copepods and euphausiid crustaceans. The variability in the blue carbon component, despite being complex in both time and space, is predictable on some scales, but knowledge levels are also very patchy. The interface of the water column and the underlying sediments, the seabed, is a very dynamic environment for carbon [11]. Primary productivity, fecal pellets and dead organisms rain down to the seabed where they are mainly broken down by the 'microbial loop', thus recycling much of the carbon from near surface waters.

2.1. Carbonate in sediments

Remarkably it was not until 2012 that the first circum-southern polar data set of carbonate in sediments was compiled (from just over 200 sediments cores from Antarctica's shelf seas [8]). Low-Magnesium calcite is the dominant phase of sediment carbonate, but high-Magnesium calcite, pure calcite and aragonite are also present. The study found that the proportion of carbonate in sediments was typically low, but could be above 15% in some shallow Weddell and deep Amundsen and Bellingshausen shelf areas. The magnitude of values found was very patchy, but most of the highest values were close to the edge of shelf (termed 'shelf break'). Even at the shelf break in the same sea carbonate could vary an order of magnitude between adjacent sites, so clearly local factors are very important as well. Notably sediments in regions of high primary production (surface microalgae productivity) such as the West Antarctic Peninsula and Ross Sea were generally below 5% carbonate. The authors concluded that the evidence in their meta-analysis was that benthic animals were not significant contributors to sediment carbonate content. Their core and data spatial coverage, although sparse around East Antarctica (as most marine data sets are), seemingly represented the spectrum of most shelf environments. However the conclusions based on existing samples could be underestimating faunal contributions for several reasons. 1) Across depths, faunal biomass and production is typically highest in the shallows (top 100 m) which were not represented. 2) Across habitats, faunal biomass and production is typically highest in difficult to core situations, such as glacial moraines, sea mounts and steep surfaces. 3) Much faunal production close to shelf breaks may be bulldozed over the edge to cascade down steep continental slopes and canyons – these are heavily iceberg scoured environments (**Figure 2**). However most blue carbon, the totality of carbon captured by organisms, is not in the form of carbonate but organic carbon as tissue.

2.2. Carbon held by marine animals (blue carbon)

Carbon captured by, and stored in, benthic organisms varies (within a set amount of space) over several orders of magnitude. Standing stocks peak in the kelp forests of the subpolar shallows with many kilograms per m^2 but decreases to less than a few grams by continental
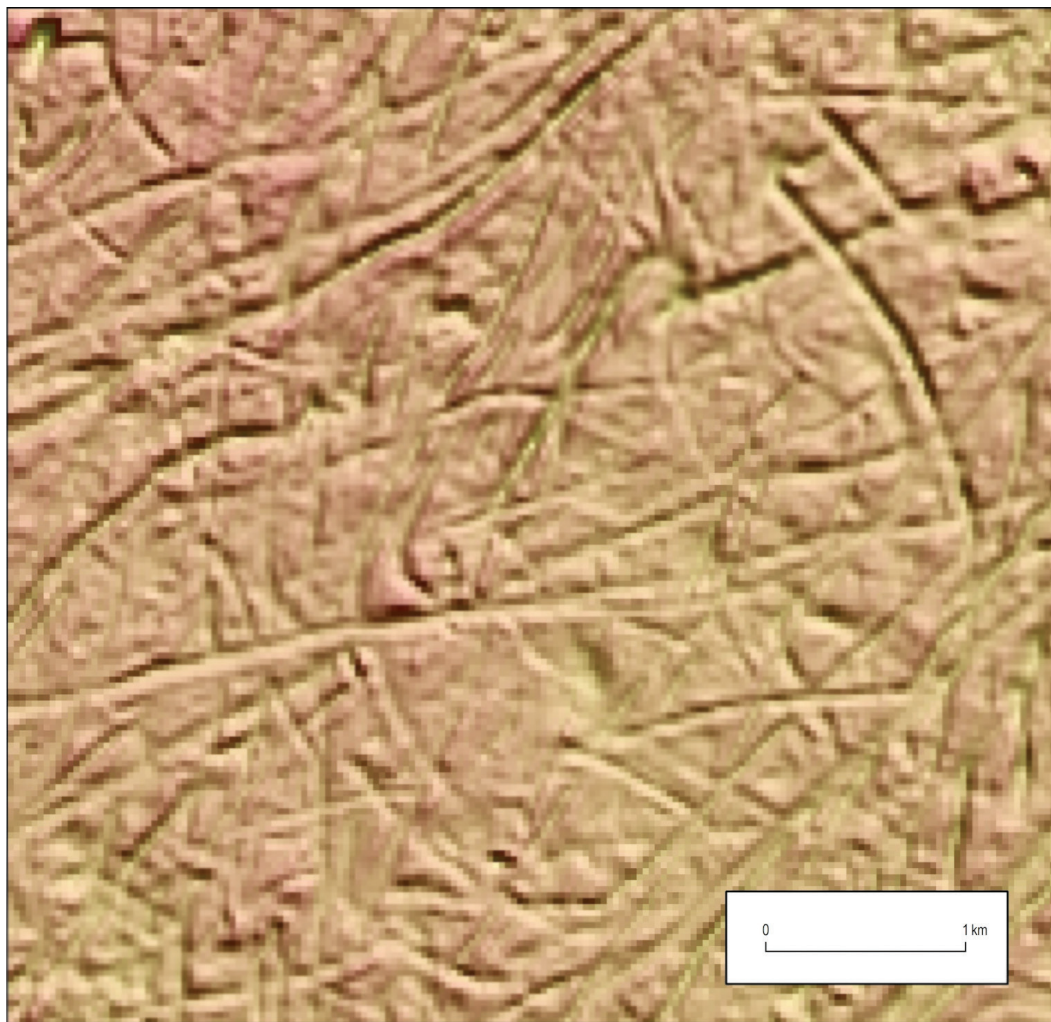
Figure 2. Iceberg scouring tracks recorded by the NERC-Conicyt ICEBERGS voyage of RRS James Clark Ross, Marguerite Bay, West Antarctic peninsula, 2017.

slope depths, on young or ice scoured surfaces, underneath Antarctic ice shelves or in other extreme environmental situations.

2.2.1. Organism identity

Some organism types are very much more important than others in terms of carbon and carbonate capture and storage. Some entire animal groups are poorly represented or absent altogether in the polar waters so clearly contribute little to carbon budgets. Typically variability in carbon contribution can be because of population and individual size (biomass), growth rates, ubiquity and the body structure and chemistry of different organisms. For example amongst the plankton the tiny foraminifera *Neogloboquadrina pachyderma* is both very abundant and ubiquitous around the Southern Ocean, and superabundant in sea ice, making it the single biggest carbonate producer [12]. A very different type and size of animal, the pelagic mollusk, pteropods (**Figure 3**) is next most important. As with foraminifers, around the Antarctica one species, *Limacina helicina*, dominates biomass [13]. Blue carbon captured and stored on the seabed by benthos is much less dominated by any one species or even any one type of animal. Sponges, echinoderms (such as sea stars and sea urchins), bryozoans (**Figure 1a**), polychaete worms (**Figure 1b**), molluscs

Figure 3. Pteropod shells are superabundant on the seabed around some Atlantic Ocean seamounts, here collected on a National Geographic Pristine Seas expedition in 2017.

(such as clams and snails), brachiopods (lampshells) are all typically important, and can each by dominant at particular sites but lots of other taxa can be important depending on the situation (environmental characteristics). Nevertheless organism identity can still qualify much information about the nature of blue carbon at a site, because of differences in the rate and timing of carbon capture, time to first reproduction and life span, chemical form of carbon stored (e.g. skeletal aragonite vs. calcite) vulnerability and other variables.

2.2.2. Substratum type and profile as a factor

The nature of the seabed often shapes and is shaped by the energy of the environment and thus has a major role in structuring which organisms live there and the quality and quality

of their resources, such as food. For example very steep surfaces are nearly always bedrock and associated with high current flow whereas very gently sloping, flat seabeds are usually sediment and associated with lower flow. So-called infauna require soft sediments to burrow into or eat to extract microbes whereas hard surfaces are required by many anchored sessile organisms, such as kelp algae and encrusting animals. The spectrum from bed rock to muds and clays can all potentially hold high and low carbon standing stock biodiversity in the polar regions. Investigation of blue carbon by substratum type is often confounded by interaction with other variables, such as depth, geography, history and functional traits (e.g. feeding type). Nevertheless hard surfaces typically have high densities of rich biota, particularly those which are carbonaceous (bryozoans, brachiopods, corals, sponges and some molluscs). Stones which have been embedded in glacier ice, fall out on melting (termed drop-stones) to form blue carbon hotspots of suspension feeders on otherwise less diverse, sediment plains (**Figure 4a**) [14]. As a
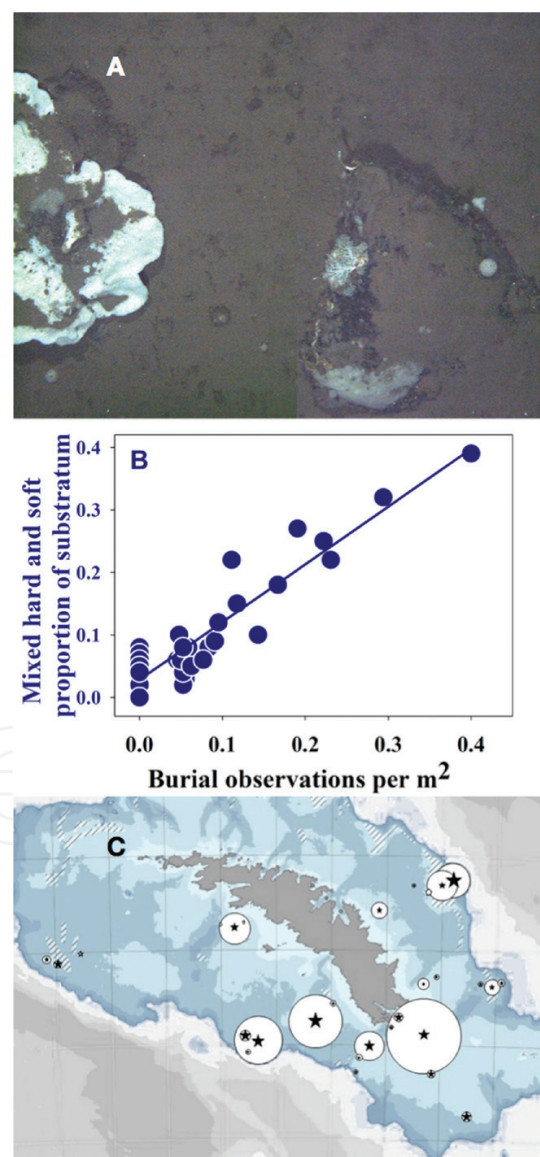

Figure 4. Blue carbon with substratum type and history. Drop-stones are blue carbon rich oases in the Arctic Barents Sea (A). Highest burial rates of zoobenthic carbon are associated with mixed substrata of boulders in sediments at South Georgia (B). Estimates of Carbon immobilization (circle size) and sequestration (star size) (C) [15].

result accumulation of blue carbon by zoobenthos is often most associated with hard surfaces such as boulder scree and glacial moraines [15]. The same work showed that hard surfaces facilitate immobilization of carbon, which is when organic carbon is held within tight matrices of skeleton, such as stony coral polyps (e.g. heavily skeletalized animals are much more likely to fossilize, thus sequestering carbon rather than it being broken down in the microbial loop). However burial conditions, which lead to sequestration are considerably stronger on sediments. Thus highest burial and sequestration rates are found at the interface of hard and soft substrata (**Figure 4b,c**). Such a combination is hard to investigate because it is a challenging environment to try and obtain cores from (e.g. the hard rocks break the plastic multi-cores and jam box core closing mechanisms).

2.2.3. Depth as a factor

Many physical and biological characteristics alter with depth so unsurprisingly it can correlate strongly with benthic carbon accumulation [4]. Increased depth away from the near-surface photic zone progressively separates fauna from their main food supply, phytoplankton, so it reduces growth, densities and biomass [1, 3, 10, 16]. The values of carbon accumulation, immobilization and sequestration can be an order of magnitude lower on the deep continental shelf than in the shallows (**Figure 5**). In deeper water blue carbon values are probably at least an order of magnitude lower again. Conversely to negative depth influences on blue carbon
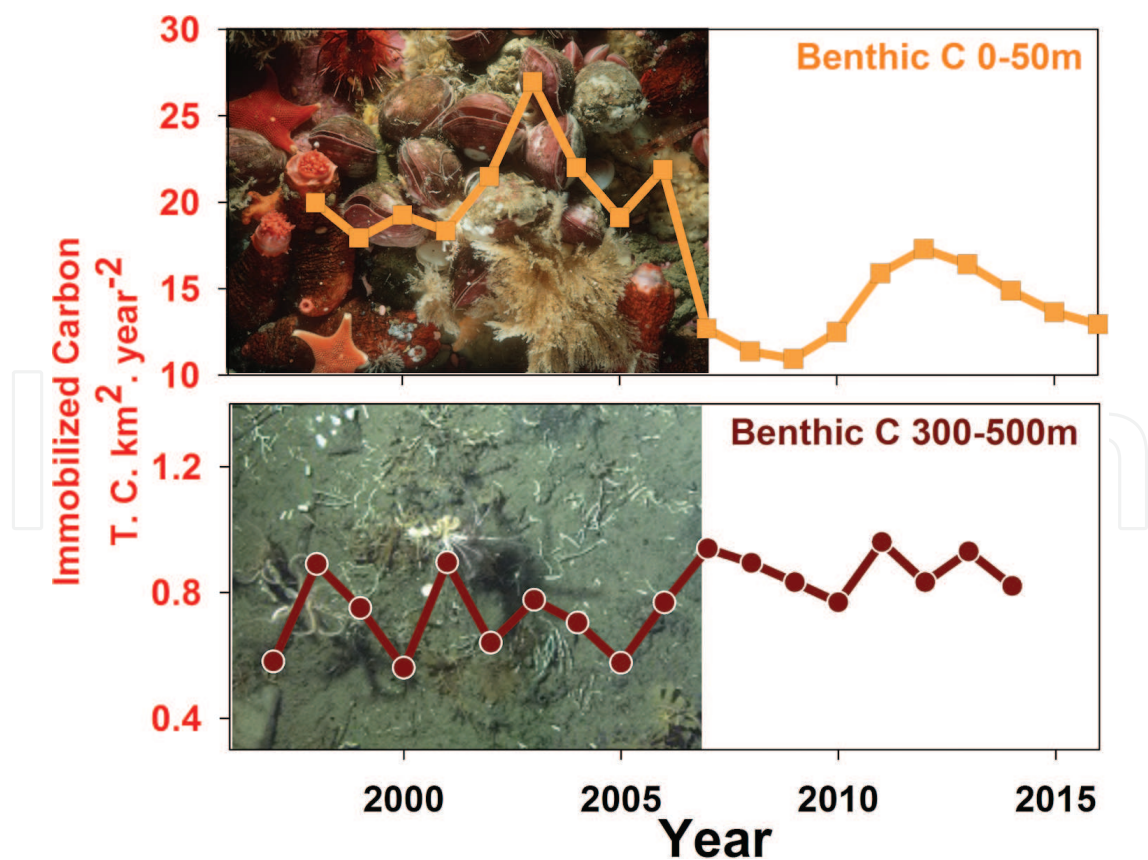

Figure 5. Zoobenthic blue carbon storage fluctuation with time and depth on the West Antarctic peninsula, modified from [4]. Note the apparent phase shift since 2006 coincident with low sea ice levels and high iceberg scouring levels.

accumulation, increased depth also reduces the probability and frequency of iceberg scouring on the seabed, thereby increasing the potential life span of benthos and burial chances. The effect of these confounding depth-correlates are complex biological responses to climate change with depth. For example, climate-forced reductions in sea ice, as is happening around the Arctic and parts of the West Antarctic, can reduce blue carbon in the shallows because of increased ice scour but increase it in deep water because of longer phytoplankton blooms [4]. Substratum type and profile, temperature and geographic factors also change with depth. An example of the latter is that benthos become more geographically separated in time and space (not just bathymetrically) from the origin point of their food because of water current velocities and directions.

2.2.4. Geography and history as factors

Most, though not all, shallows and shelf are associated with coast in the polar regions, just like elsewhere in the world. This drives an onshore-offshore gradient in polar blue carbon, but it is further exacerbated by most physical change (e.g. melt runoff, glacier retreat and ice shelf collapse) also being coast-associated. There is major temperature, sea ice duration and productivity variability associated with different regions around and between the polar seas, as is reflected in strongly contrasting biomass [10] and sediment carbonate values [8]. Within a distinct area the separation of different habitats and zoobenthic blue carbon performance can be geographically predictable factors, which also reflect regional history. A clear example of this can be seen in the continental shelf around the South Georgia archipelago. Blue carbon accumulation is highest on the glacial moraines, which are generally found close to the shelf break, the furthest extent of grounded ice in the Last Glacial Maximum [15]. However such moraines can also be found at the head of canyons and part way along some coastal fjords. The oldest sediments beyond these moraines have the highest sediment blue carbon values, whereas the sediments within these moraines (which were covered by grounded ice just 20 kya are blue carbon poor (**Figure 4c**). The highest blue carbon burial and estimated sequestration rates were at the interface of these moraines and sediments.

Zoobenthic blue carbon levels also reflect more recent historical and geographic factors, such as invasion of seabed following glacier retreat, ice shelf collapses and recovery from iceberg impacts. At South Georgia depressed blue carbon values have been measured nearly a decade after giant (thousands of square km in size) iceberg impact [17]. The same study showed there are distinct macrogeographic hotspots of giant iceberg grounding, but the same is true within regions, where shelf breaks are most likely to be impacted. The hotspots of smaller icebergs are more associated with retreating glaciers and longer periods of open water, such as the West Antarctic Peninsula [16, 17]. As with biodiversity succession, the seabed blue carbon within the shallowest hundred meters probably strongly reflects the duration of recovery since the last iceberg scour at any one location. The lowest continental shelf values of blue carbon are those underneath the thick floating ice shelves [18]. However collapse of these can lead to major new phytoplankton blooms and the highest blue carbon capture rates and benthic growth (blue carbon storage levels) [19]. Ice shelf collapses have been most associated with the Weddell and Bellingshausen seas, most recently the major breakout of the 6000 km^2 iceberg from Larsen C. Such events are very important in terms of blue carbon budgets and

dynamics, both in the water column [20] and the seabed [17]. As a result there is strong connectivity between temperature, ice changes and blue carbon.

2.2.5. Temperature as a factor

The polar regions, particularly the Southern Ocean, are typically the most thermally constant surface regions of our planet. Annual polar sea temperature variability is generally less than 4°C in the Southern hemisphere but more geographically variable around the Arctic. A major source of variability has been Milankovitch 41 and 101 kyr Earth orbital cycles but this has been overshadowed in the Arctic by rapid, recent, regional climate change. Temperature can theoretically influence blue carbon through influences of ocean chemistry, sea ice formation and duration and physical constraints on enzyme performance, effecting food processing, carbonate synthesis and biomass growth rates. Ashton et al. [21] recently attempted to manipulate polar seabed temperature, whilst leaving other factors unchanged. Their study at Rothera Research Station (WAP), which established a series of temperature controlled artificial substrata, found that temperature had a stronger and more complex influence on growth than expected. A 1°C increase led to a significant increase in blue carbon (but measured as growth increment) whereas responses to a 2°C increase resulted in increased variance of assemblages. The major surprise was the extent of the increased growth (approximately double), which far exceeded that predicted by calculations of a pure temperature effect. The experimental infrastructure has now been transferred to the Canadian Arctic station of Cambridge Bay to compare the response of raised temperature of northern to southern polar nearshore fauna.

2.2.6. Other factors (sedimentation and water chemistry)

Many environmental factors are likely to influence blue carbon capture and storage rates around polar seas but our knowledge and understanding of these is patchy. Amongst the best studied locations are King George Island (South Shetland Islands, Antarctic Peninsula) in the south and West Spitsbergen (Svalbard) in the North. Multinational, interdisciplinary efforts to study biotic interactions to a multitude of environmental parameters at such places are enabling scientists to examine which factors are most important, to which organism types and to which stages of the carbon pathway. In contrast to Ryder Bay, adjacent to Rothera Research Station, where ice scouring [16, 17] and temperature [21] seem to be most important to carbon storage, at Potter Cove, King George Island, sedimentation mainly dictates the composition and performance of benthos. Sahade et al.'s [22] monitoring of that cove since 1998 showed that amongst the many varying factors for benthic life close to a retreating glacier, it was sediment levels and tolerance to this which drove drastic shifts in organism type. However sedimentation is not only co-linked to other variability such as salinity and nutrients but also varies in several different aspects, such as particle density and particle size distributions.

A new multi-year, multi-project investigation of the Atlantic sector of the Arctic, 'Changing Arctic Ocean', should elucidate the nature and dynamics of hyperboreal carbon pathways. Of these the Changing Arctic Ocean Seabed (ChAOS) project lead by Leeds University, UK is monitoring oceanography, geochemistry and biology at a latitudinal series of sites along the Barents Sea trough (**Figure 6**). Results from new initiatives like these should greatly increase our ability to estimate the value and variability of Arctic blue carbon ecosystem services [5, 9] and crucially how it is likely to respond to the very considerable, recent physical changes.
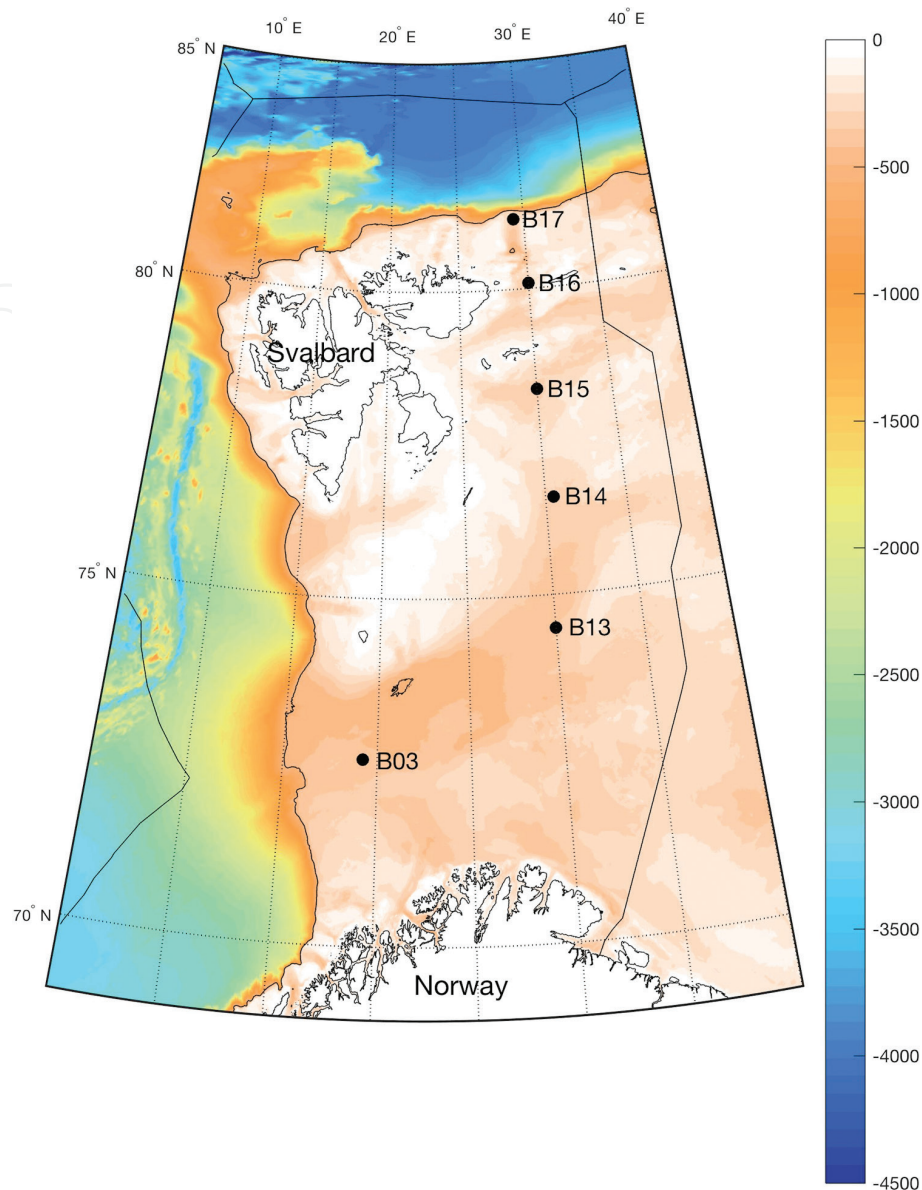
Figure 6. Continental shelf monitoring sites of the changing Arctic Ocean seabed (ChAOS) project, through the Barents Sea.

2.3. Seasonal and annual increment (growth)

Organisms incrementally capture and store carbon with distinct seasonal and annual variation (mainly caused by feeding reduction or cessation in winter). These temporal signals in carbon accumulation are externally visible in some organisms and observable in others by section (like tree rings) or through isotopic analyses. Thus one of the easiest approaches to measure carbon capture and storage on the seabed is to sequentially sample benthic growth to establish its variance. Because of the multitude of environmental factors influencing the magnitude of these (Section 2.2 above), simultaneous measurement of many local parameters needs to be made, in order to detect and understand any organismal performance trends. Growth (along with other processes, e.g. development) is typically considered to be slow in polar ectotherm organisms, in comparison with those at lower latitudes in the world [10]. However there is considerable variability in blue carbon captured in that organismal growth,

within and between regions, organisms, environments and time. Partitioning out the causes and effects of variability is key to meaningful estimates of blue carbon stocks and how they are likely to change. For example, young animals are likely to have higher specific growth rates (thus have high carbon capture but low storage values) whereas older animals would typically be larger but grow slower (and thus be associated with low carbon capture but high carbon storage values). Thus an event influencing population demographics (e.g. iceberg scour) could change carbon capture relative to storage rates, and this could alter depend on which season it occurred in.

Recent work in the Ross, Weddell and Bellingshausen seas have shown rapid growth rates, and changes in growth rates, are possible in polar organisms. Such blue carbon change has happened in response to wind-driven or ice shelf collapse promoted increased food avail-ability [18, 19, 23] respectively, or increase in temperature [21]. With carbon sinks, sources and flux values being so important to global climate as well as projecting trends and predicting future scenarios it is clear that quantification of blue carbon has an important role in this, and the polar regions are the most poorly known. Understanding biological response to polar change has become even more important since it has become apparent that amongst the most severe physical changes have been associated with these areas.

3. Changing blue carbon capture and storage rates in polar seas

Despite the relative constancy in many oceanographic parameters over geological time, the polar regions are quite dynamic in fluctuation between ice ages, the duration and rate of change to interglacial periods and within these, the position of the marginal sea ice zone, water masses and ice shelf extent. All of these can directly alter the biomass of organisms, their carbon capture and storage rates as well as direct carbon dioxide uptake and release by oceanic storage. Section 2 has highlighted that sediment carbonate levels [8] and organ-ism blue carbon capture and storage rates [10, 15] all vary considerably between and within regions. Measuring any change over time necessarily must have georeferenced baselines to measure against but most 'long term monitoring' programmes are relatively young. One of the most notable multidecadal data sets is that for zooplankton, focused on krill and salps. Analysis of this was one of the first to show change in polar ecosystems (krill reductions) in response to climate [24]. However these organisms are mobile and ice edge associated, which highlight both problems in measurement and interpretation – are the less krill in there survey areas because there are less overall or because they are somewhere-else? Crustacean zooplankton, such as Krill, are important to blue carbon capture and storage rates [5, 6] and may be important to sequestration rates as well [4].

We know little about blue carbon capture, storage and sequestration rates for the vast majority of the seabed, and there are a tiny number of sites which have been monitored regularly for more than a decade. Recently a series of ice shelf disintegrations along the Antarctic Peninsula and some elsewhere have been accompanied by major increases in primary [18] and second-ary [19] production. These new and increased stocks of seabed blue carbon there have been estimated to constitute ~7×10^5 tons of carbon per year equivalent to 10,000 hectares of tropical rainforest [19]. These ice shelf collapses have formed an increasing number of giant icebergs,

which have also increased carbon capture in the water column through ocean fertilization [20]. Duprat et al. [20] estimated the increases in water column blue carbon of a number of such icebergs. Those estimates were later built upon in terms of their total blue carbon impact (trade-offs of creating new sink areas and ocean fertilization versus scouring potential) to show a 5000 km^2 iceberg contributes a net positive of 10^6 tons of carbon per year [17]. Ice shelf losses, iceberg production and arctic forest increases [2] are not the only sources of blue carbon change around the polar regions.

Sea ice extent, particularly 'fast ice' (the freezing of the sea surface, anchored to land) has been one of the most drastic physical changes in the polar regions, particularly throughout the Arctic. Sea ice changes and primary production responses have been more complex around Antarctica [25], but crucially most sea ice losses have been over productive continental shelf whereas most of the sea ice gains have been over deeper slope and abyssal ocean depths [16]. Historical expedition zoobenthic collections and modern samples of longer lived animals with relevant information in skeletons has shown that blue carbon capture rates may have doubled over the last 25 years around West Antarctica [26]. The mechanism for this seems to be that reduced extent (in time and space) of sea ice leads to longer (but not necessarily larger biomass) phytoplankton blooms, resulting in longer meal times for primary consumers resulting in more carbon storage as growth (**Figure 7**). The total blue carbon increases driven by sea ice losses [17, 26] probably greatly exceed those caused by ice shelf collapse/giant iceberg formation [17–20]. However, from what we currently know, change in polar blue carbon is a complex of increases
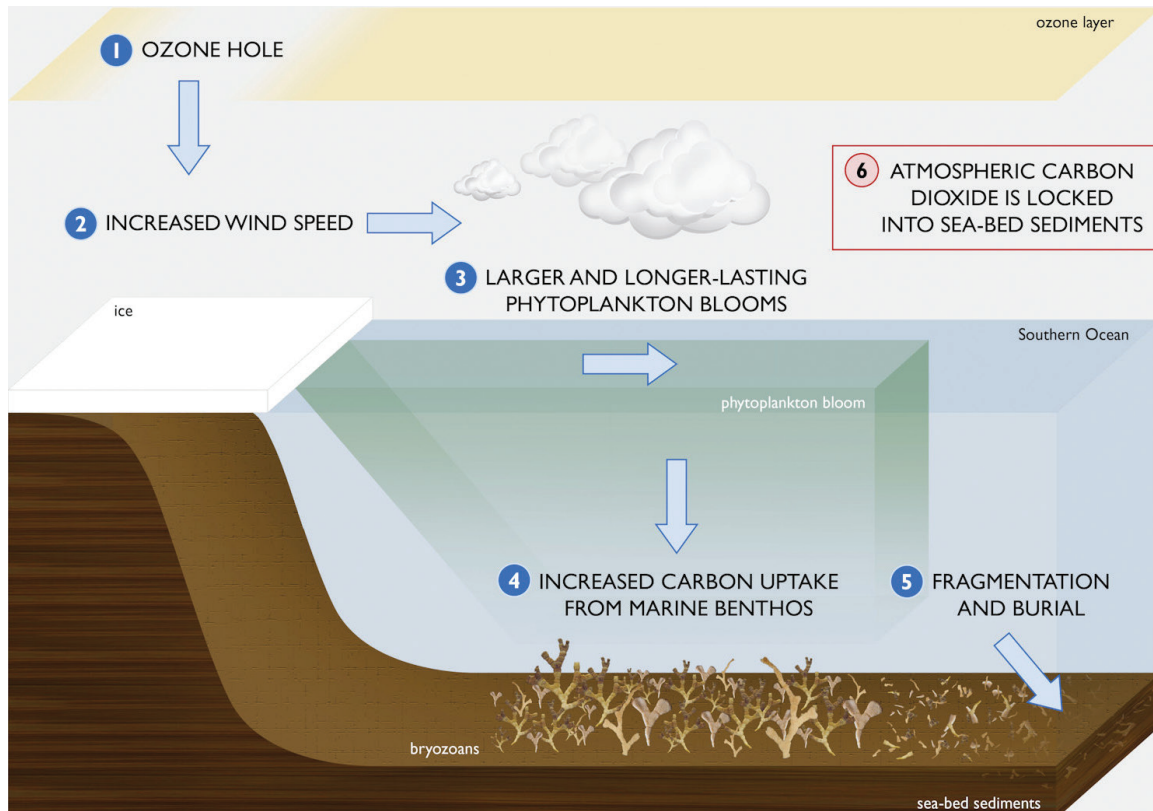

Figure 7. Schematic showing influence of ozone losses on phytoplankton carbon capture and zoobenthic carbon storage on polar seabeds.
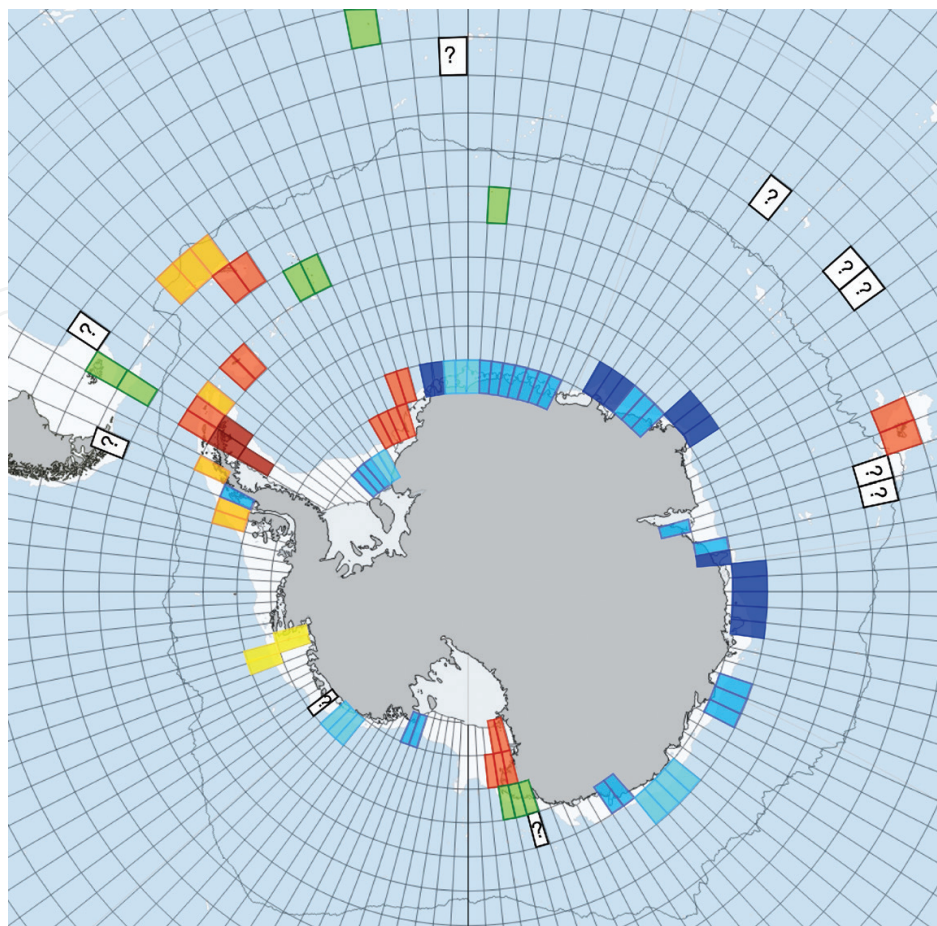
Figure 8. Trends in zoobenthic blue carbon accumulation around the Southern Ocean. The key to cell (3x3 degrees) colors are red (biggest increase) to blue (biggest decrease) [17]. Cells with question marks are samples awaiting analysis (from the Antarctic circumnavigation expedition and future British Antarctic survey scientific cruises.

and decreases (**Figure 8**). Around the Southern Ocean blue carbon increases are most associated with West Antarctic seas and decreases with the East Antarctic coasts [17] but the vast majority of all shelf carbon stocks and change is unknown. It seems likely that the biggest blue carbon changes are near coast caused by ice shelf collapse [18–20], iceberg scour [19] and glacier retreat driven sedimentation [22] but there could also be significant offshore change associated with a shifting seasonal sea ice margin [4, 24, 25]. Given the higher potential ectotherm growth performances at slightly higher sea temperatures [21] it also seems likely that the Arctic and subpolar regions are key areas to quantify blue carbon budgets for. Quantifying these becomes one of the key steps in estimating biotic feedbacks on climate change.

4. The importance of life on polar seabeds to carbon storage and feedbacks on climate change

The cold waters of polar oceans are the major marine sinks for atmospheric CO_2 but these are finite, likely diminishing and do not negatively feedback on global climate change. There is evidence to show that polar marine algal capture of CO_2 has increased with ice shelf loss

[18], sea ice loss [25] and iceberg production [20]. It also seems likely that polar macroalgal production could increase spatial and temporal extent with exposure of new habitats, sea ice reduction and increased light energy reaching the shallows. These negatively feedback (mitigate) on climate change through increased capture of CO_2 with increasing atmospheric of CO_2 content. Only very small proportions of this captured CO_2 are genuinely sequestered, depending on how much reaches the seabed and how much is recycled in the microbial loop and reworked following bioturbation. All natural carbon sequestration is via burial, mainly at the seabed, where zoobenthic assemblages (consumers) live. They are an important part of the negative feedback on climate, as new and longer availability of phytoplankton is converted into increased growth (organic carbon to tissues and inorganic carbon to skeletons). The feedback value is complicated to measure because it is dynamic in space and time but also because of simultaneous positives and negatives. For example ice shelf loss leads to more open water, a) reducing albedo, thus potential to absorb more heat; b) reduces buttressing of ice sheets, thus potential for this to accelerate coastwards, c) increasing potential for gas exchange, d) generating new phytoplankton blooms, e) opening new habitat for zoobenthos and f) generating giant icebergs with ocean fertilization potential [17–20]. Even the latter components themselves each contain contrasting feedbacks on climate, for example calving of an giant iceberg such as that to break off Larsen C in 2017 may scour and recycle 4×10^4 tCyr^{-1} of benthic carbon but algal capture and seabed zoobenthic storage of new carbon contributes a net positive of 10^6 tons of carbon per year [17]. The magnitude of this negative feedback is probably similar to that of Arctic Taiga expansion [2], although this too has also complicating factors such as increased heat absorption and less than expected growth gains.

Sea-ice loss areas exceed 1,000,000 km^2 whereas ice shelf losses approximate to ~30,000 km^2 see http://nsidc.org/) so biological responses to these are the largest measured natural negative feedback on climate change. These are dwarfed as an organic carbon store by tropical forests, but these are not increasing as a result of climate change and thus not a negative feedback (their genuine sequestration potential is also low, as burial rates of carbon are very small except for water logged swamp forests). The magnitude of polar blue carbon negative feedback from sea ice losses depends on whether the carbon is calculated from primary production, secondary production, immobilized carbon or sequestered carbon. The sequestration value is considered to be as low as two orders of magnitude different along the cascade from algal production to buried sequestered benthos (**Figure 9**). Scaling up from regional samples suggests that between 2002 and 2015 the zoobenthic blue carbon negative feedback averaged ~10^7 T C in production, 4.5×10^6 T C in immobilization or 1.6×10^6 tons C in terms of sequestration [16] along the West Antarctic Peninsula continental shelf alone. Scaled up to the whole Antarctic continental shelf area (4.4×10^6 km^2) the annual zoobenthic blue carbon feedback is estimated at 30-80×10^6 T C yr.$^{-1}$ but including outer Subantarctic continental shelves, such as the Kerguelen Plateau doubles this [17], equivalent to 1–2% of global anthropogenic output. It is clear this feedback is dynamic, polar blue carbon storage has demonstrably increased in coincidence with climate-forced sea ice changes, at least around West Antarctica [26]. Global climate change, ozone losses and other indirect (e.g. non indigenous species invasions) or direct (e.g. harvesting) anthropogenic pressures have the potential to have major impacts on marine biodiversity [27], and thus considerably increase or decrease polar blue carbon.
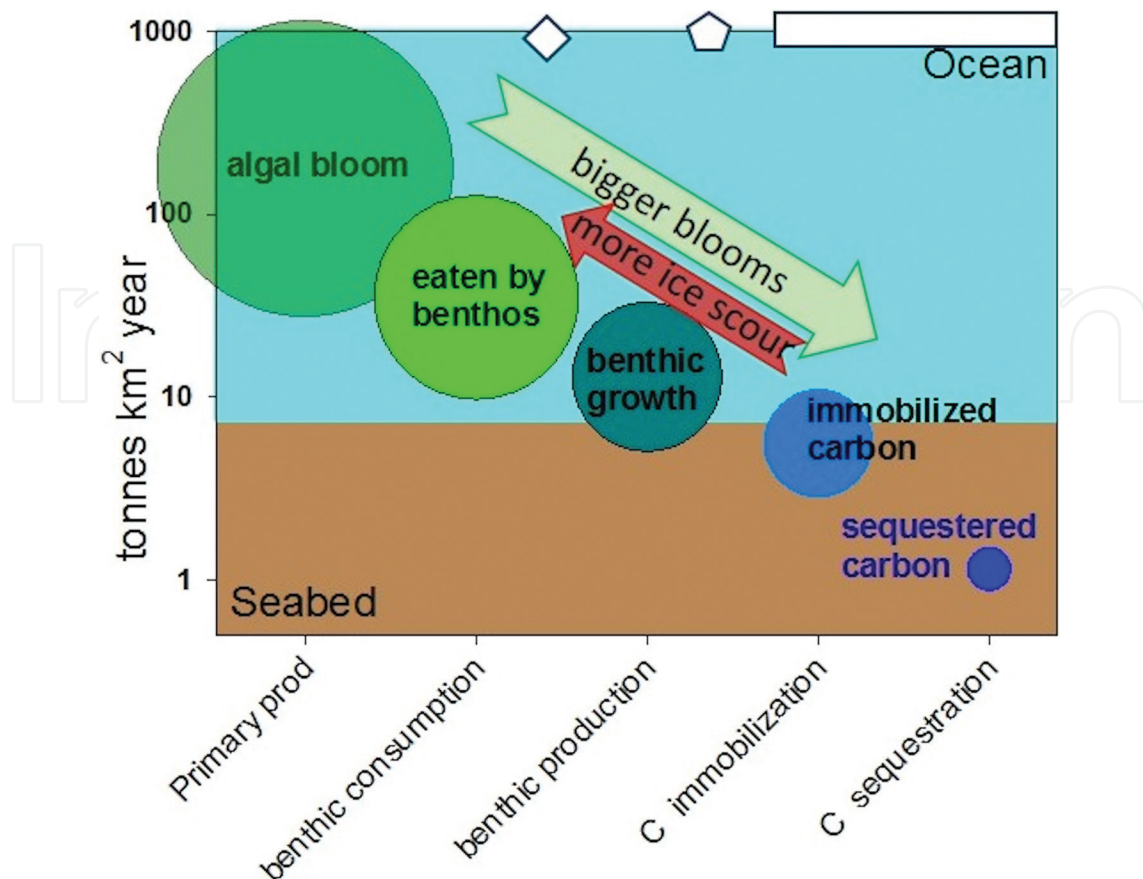
Figure 9. Cascade of blue carbon through trophic levels and states in polar waters, scaled to mean annual values. Data for the West Antarctic peninsula [16].

5. The future of polar benthic blue carbon

Carbonates already in Antarctic shelf sediment surfaces could become part of the negative feedback if calcite undersaturation is reached on the Antarctic shelves [8]. Ocean acidification is one of the bigger unknowns for the future of polar benthic carbon, in terms of the cost of calcification for organisms, the potential for dissolution whilst alive and after death [28]. Probably the biggest unknown though is how sea temperature will change. There seem to be very different sea temperature trends between the polar regions, across depths and even within seas around the Southern Ocean [29]. The strongest climate-forced trends to date have been in ice extent change. Sea ice losses, glacier retreat and ice shelf collapse are expected to be sustained, although sea ice models are still in their infancy in terms of even recreating the complexity that has already occurred. Salinity changes can be strongly linked to sea ice changes [29] and is likely to remain very important in the Arctic in terms of surface stratification and stabilization impacts. Stratospheric ozone losses have driven seasonal increases in UV and wind strength, driving knock on influences on sea ice (e.g. maintaining open water areas). The impact of all these factors on polar blue carbon to date has been explored to various levels (Sections 3 and 4) such that for some areas summary trends can be erected (**Figure 8**). Because such trends have typically relied on scaling up by area and scaling from few taxa, and rarely accounted for all environmental factors, their main purpose is essentially hypothesis testing markers. Several new independent
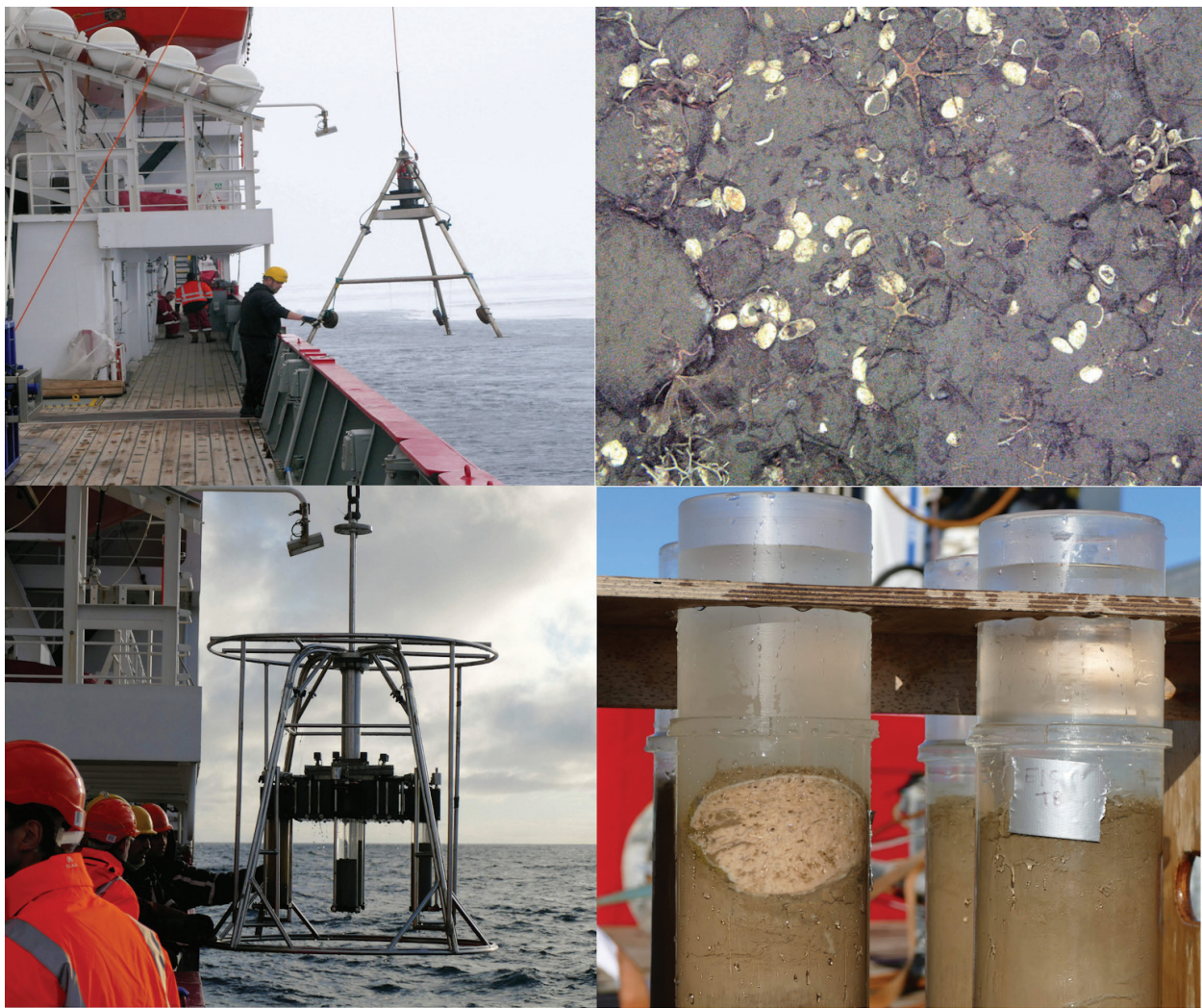
Figure 10. Apparatus used to estimate surface and sediment carbon and carbonate in polar shelf seas (here shown in the Arctic in 2017). The equipment are shelf underwater camera system (SUCS - above) and multicorer (MUC - below) and their collection products. Note the sponge bisected in one of the core tubes.

research programmes have been recently launched across polar seas to attempt to quantify and model polar carbon capture and storage, including the blue carbon component (**Figure 10**).

Current ideas on the direction of likely trends in polar blue carbon include a wide spectrum of near-future prospects [4, 9, 11, 27, 28]. Reasonable scientific scenarios have been put forward that we can expect drastic reductions in blue carbon storage under current climate projections. These are based on a (largely presumed) inability of polar biodiversity to tolerate lowered pH and increased temperature [9, 13, 27, 28]. This is partly due to the unprecedented level and pace (in recent geological time) of physical change and partly due to the limited options for migration to maintain climate envelope (stay within tolerable conditions). The moderate sea temperature rises expected over the next century could enhance carbon capture and storage [21], although scientific consensus is that more severe temperature rises are likely to reduce polar marine biodiversity performance [27]. However sustained sea ice and ice shelf losses seem likely to increase blue carbon capture and storage rates as to date, but possibly more widespread [16, 17, 26]. Processes by which this could be aided and enhanced, for example creation of artificial polar reefs, have even

been financially evaluated but are uneconomical at the current value of industrial carbon capture [30]. Patterns of blue carbon response to climate change are likely to differ strongly between the Arctic and Antarctic, because of their contrasting history and geography, human usage and disparity of current physical change. From current trends it seems most likely that moderate blue carbon increases will occur in Arctic and West Antarctic seas in the near future to be eventually replaced by more severe decreases when critically low pH and high temperatures begin to be reached. Predicting physical trends and blue carbon biological responses in East Antarctic seas is more difficult because of current variability and lack of sustained patterns. It seems intuitively likely that East Antarctic blue carbon patterns may ultimately follow those of other polar locations but with a considerable lag phase. Given the rarity of natural negative feedbacks on climate change and the importance of blue carbon as a current negative feedback, quantification and understanding of polar blue carbon change should be high as a scientific priority.

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Conflict of interest

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