Connecting the Arctic Ocean


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NERC-BMBF Changing Arctic Ocean – Summary Report

Changing Arctic Ocean

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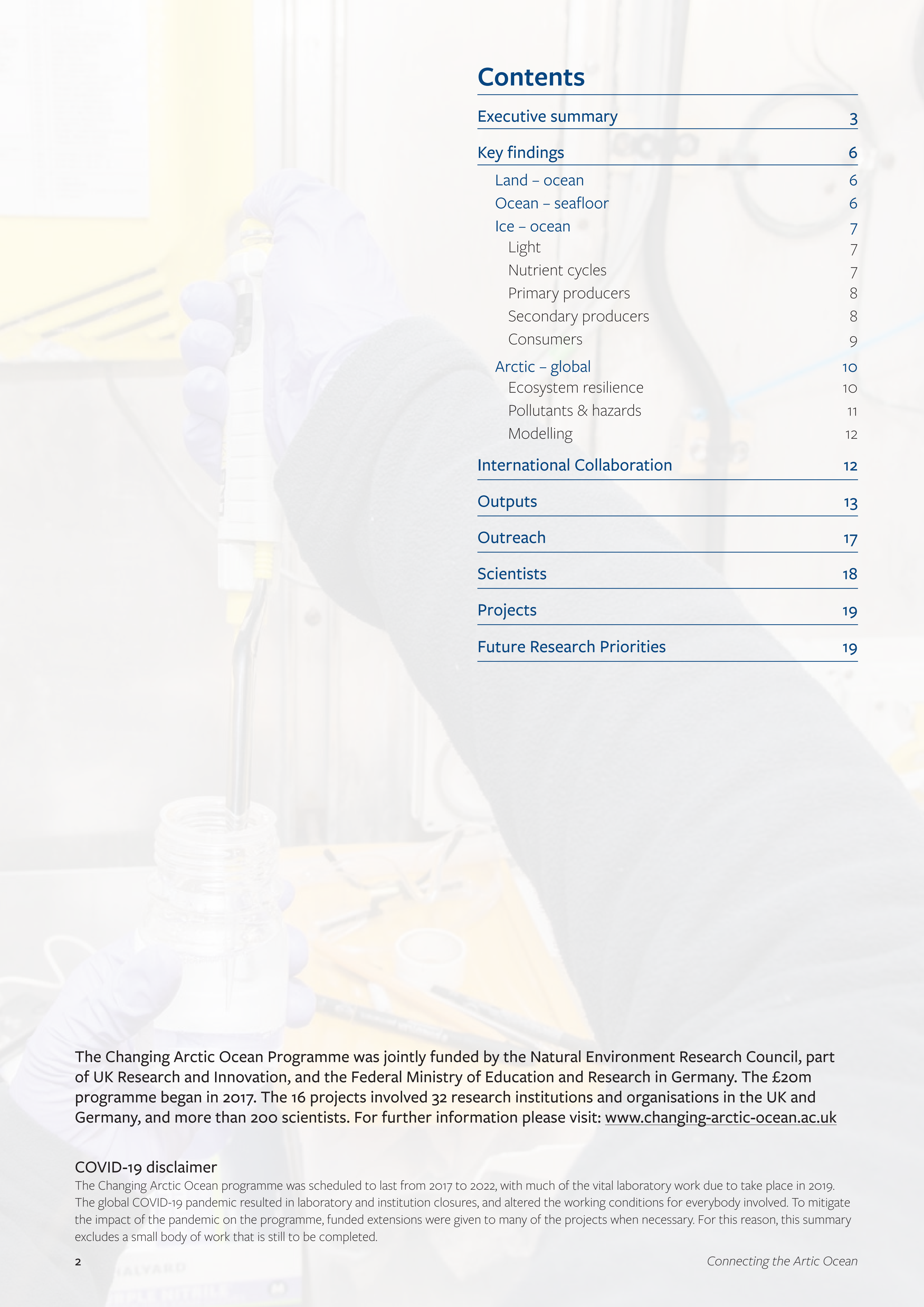

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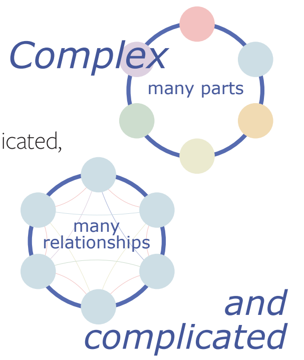
The Changing Arctic Ocean Programme was jointly funded by the Natural Environment Research Council, part of UK Research and Innovation, and the Federal Ministry of Education and Research in Germany. The £20m programme began in 2017. The 16 projects involved 32 research institutions and organisations in the UK and Germany, and more than 200 scientists. For further information please visit: www.changing-arctic-ocean.ac.uk

COVID-19 disclaimer

The Changing Arctic Ocean programme was scheduled to last from 2017 to 2022, with much of the vital laboratory work due to take place in 2019. The global COVID-19 pandemic resulted in laboratory and institution closures, and altered the working conditions for everybody involved. To mitigate the impact of the pandemic on the programme, funded extensions were given to many of the projects when necessary. For this reason, this summary excludes a small body of work that is still to be completed.

Executive summary

Warming in parts of the Arctic is now 2.3 °C or higher above “pre-industrial” levels, and we are witnessing monumental alteration to the ecosystems, biology and biogeochemistry of the Arctic Ocean and its adjacent permafrost region. This rapid change in the Arctic is expected to become more pronounced and to have serious consequences in the near future on the global environment and economy, with direct impacts on the European climate, migratory species and industries. The impacts of climate change on the vast and multiple interacting Arctic systems are inherently complex, but can be broadly summarised as an increase in mean air temperature causing enhanced connectivity between land, oceanic, and global systems and the subsequent loss of sea ice cover. This will ultimately result in the emergence of a new physical and ecological state which the Changing Arctic Ocean (CAO) programme begins to quantify and understand. The consequences of warming and its subsequent effects upon the physical and biological processes within the Arctic Ocean are complex and complicated, and therefore have to be addressed through interdisciplinary and international collaboration. The Changing Arctic Ocean programme provided this platform, bringing together a multidisciplinary team of over 200 scientists.



As Arctic landscapes warm, previously frozen grounds - known as permafrost, are beginning to contribute greater amounts of materials to large Arctic rivers, and in turn coastal Arctic Ocean waters. The intensification of freshwater runoff from land enhances the supply of permafrost and other terrestrial carbon pools, and is altering the amount and type of materials delivered to the Arctic coastal zone. Research as part of this programme has found that these changes may have profound consequences for the balance of greenhouse gas emissions from coastal Arctic Ocean waters, by altering the rates at which carbon can be broken down by oceanic microorganisms and the physical environment. We show that in some areas of the Arctic Ocean, terrestrial inputs may reduce the growth of phytoplankton by reducing light penetration or changing the structure of the base of the food chain. Coastal permafrost erosion, due to wave action and exacerbated by greater sea ice retreat, adds additional carbon to the system which can then be converted to methane by bacteria – a more potent greenhouse gas. With the open season increasing under future change, total greenhouse gas emissions will increase too.

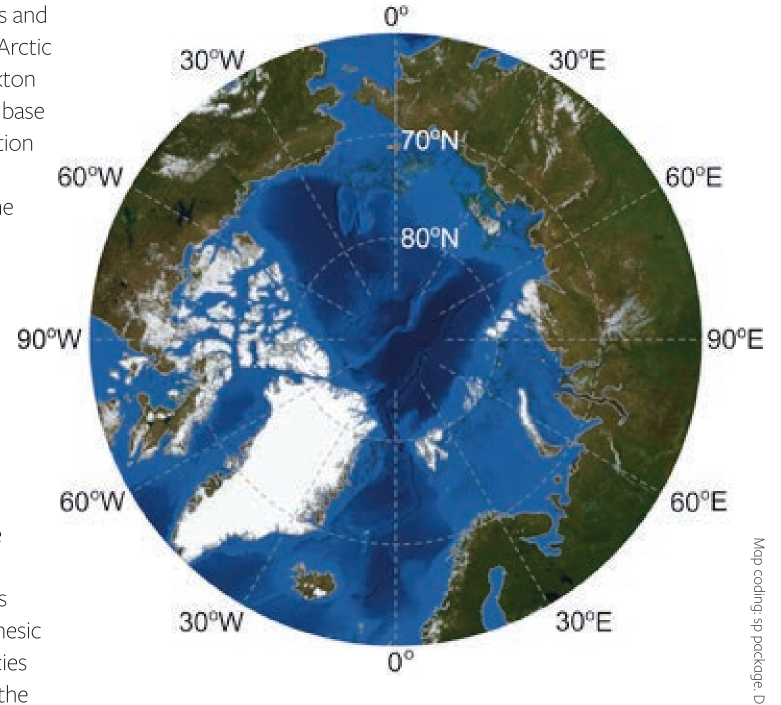
Ice retreat in the ocean increases light availability in terms of timing and quantity, and reduces habitat for species associated with the ice (e.g. polar bears, pinnipeds, and microorganisms). While primary production is predicted to increase by 5% annually due to this light increase and nutrient availability, the associated primary producer species shifts may increase the concentrations of toxic diatoms, for example *Pseudo-nitzschia spp.*, many types of which produce a potent neurotoxin that passes through the food web via planktivorous fish to the marine mammals and seabirds, and can lead to Amnesic Shellfish Poisoning if consumed by humans. However, the species shifts do not seem to negatively impact the vital next stage of the food web – copepods. Copepods are an important food source to commercial fish such as herring and mackerel.

Fish populations are sensitive to both the direct and the indirect effects of sea ice retreat and warming. CAO found that maintaining harvest of demersal fish while reducing harvesting of planktivorous fish as a strategy would alleviate some of the effects of ice loss and warming on higher food web levels.

The connections between the Arctic realms do not end in the Arctic – they have global reach. Our actions across the globe affect the Arctic in return. Atlantification – the shift in Arctic water properties to be more like the Atlantic - was demonstrated in the Eastern Arctic and explained by upper-ocean stratification from heat fluxes, atmospheric forcing, and related feedbacks. Coupled with the emerging shift in oceanic connectivity, there will be changes in the Arctic species and increased probability of the Pacific species invading, ultimately leading to the changes in Large Marine Ecosystems provinces.

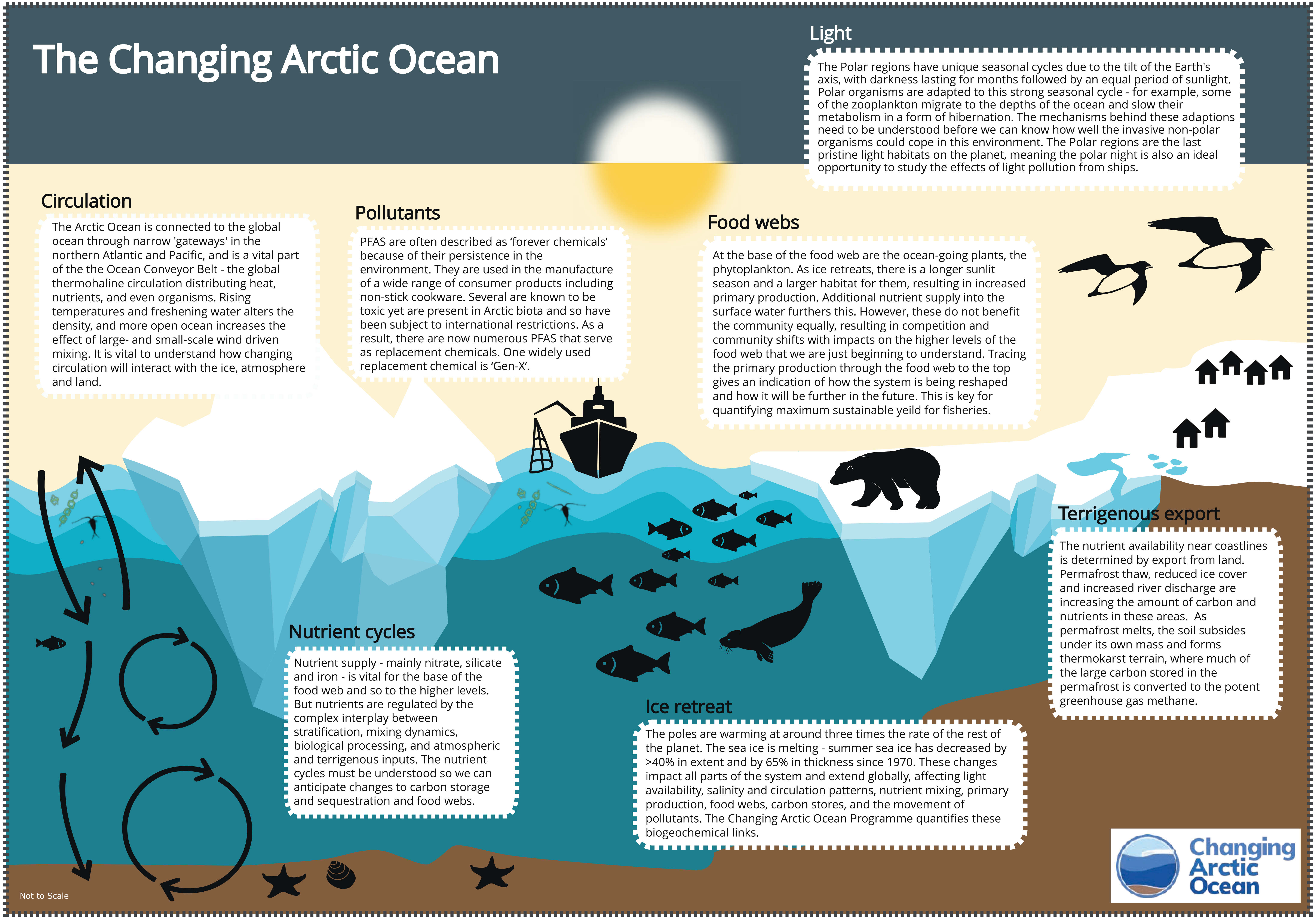
Global pollutants have reached the Arctic. Poly and perfluorinated alkylated substances ‘forever chemicals’ have been found in high concentrations due to past and ongoing atmospheric deposition. For some contaminants, concentrations in the ice-brine were higher than the beneath ice seawater; evidence of an enrichment process during ice growth. With the increasing prevalence of first year ice and the greater quantity of mobile brine channels that it contains, there is a high likelihood of ‘pulse releases’ during periods of thaw.

The programme developed and deployed innovative robotic technology which can provide a long-term presence in the Arctic Ocean to monitor physical and biological parameters year-round, and has applications beyond the Arctic. The breadth and depth of the Changing Arctic Ocean programme has provided the ideal platform to begin to understand the consequences of climate change in the Arctic Ocean, and would not have been possible without the creativity and determination of the scientists and a great degree of international collaboration.



Map coding: sp package Data: NASA

The Changing Arctic Ocean



Light

The Polar regions have unique seasonal cycles due to the tilt of the Earth's axis, with darkness lasting for months followed by an equal period of sunlight. Polar organisms are adapted to this strong seasonal cycle - for example, some of the zooplankton migrate to the depths of the ocean and slow their metabolism in a form of hibernation. The mechanisms behind these adaptions need to be understood before we can know how well the invasive non-polar organisms could cope in this environment. The Polar regions are the last pristine light habitats on the planet, meaning the polar night is also an ideal opportunity to study the effects of light pollution from ships.

Circulation

The Arctic Ocean is connected to the global ocean through narrow 'gateways' in the northern Atlantic and Pacific, and is a vital part of the the Ocean Conveyor Belt - the global thermohaline circulation distributing heat, nutrients, and even organisms. Rising temperatures and freshening water alters the density, and more open ocean increases the effect of large- and small-scale wind driven mixing. It is vital to understand how changing circulation will interact with the ice, atmosphere and land.

Pollutants

PFAS are often described as ‘forever chemicals’ because of their persistence in the environment. They are used in the manufacture of a wide range of consumer products including non-stick cookware. Several are known to be toxic yet are present in Arctic biota and so have been subject to international restrictions. As a result, there are now numerous PFAS that serve as replacement chemicals. One widely used replacement chemical is ‘Gen-X’.

Food webs

At the base of the food web are the ocean-going plants, the phytoplankton. As ice retreats, there is a longer sunlit season and a larger habitat for them, resulting in increased primary production. Additional nutrient supply into the surface water furthers this. However, these do not benefit the community equally, resulting in competition and community shifts with impacts on the higher levels of the food web that we are just beginning to understand. Tracing the primary production through the food web to the top gives an indication of how the system is being reshaped and how it will be further in the future. This is key for quantifying maximum sustainable yeild for fisheries.

Nutrient cycles

Nutrient supply - mainly nitrate, silicate and iron - is vital for the base of the food web and so to the higher levels. But nutrients are regulated by the complex interplay between stratification, mixing dynamics, biological processing, and atmospheric and terrigenous inputs. The nutrient cycles must be understood so we can anticipate changes to carbon storage and sequestration and food webs.

Ice retreat

The poles are warming at around three times the rate of the rest of the planet. The sea ice is melting - summer sea ice has decreased by >40% in extent and by 65% in thickness since 1970. These changes impact all parts of the system and extend globally, affecting light availability, salinity and circulation patterns, nutrient mixing, primary production, food webs, carbon stores, and the movement of pollutants. The Changing Arctic Ocean Programme quantifies these biogeochemical links.

Terrigenous export

The nutrient availability near coastlines is determined by export from land. Permafrost thaw, reduced ice cover and increased river discharge are increasing the amount of carbon and nutrients in these areas. As permafrost melts, the soil subsides under its own mass and forms thermokarst terrain, where much of the large carbon stored in the permafrost is converted to the potent greenhouse gas methane.

Changing Arctic Ocean

Key findings

Land – ocean

Permafrost is defined as ground that remains constantly frozen for at least two years. It makes up a globally significant yet susceptible store of carbon. Increasing Arctic temperatures are causing terrestrial permafrost stocks to thaw, and enhanced coastal erosion is releasing substantial amounts of carbon and nitrogen to rivers and ocean. The Changing Arctic Ocean programme (CAO) has found that in future, permafrost thaw and increased freshwater run-off from land will not only increase the amount of dissolved organic carbon entering the ocean. **CAO found that not only the concentration of dissolved organic carbon increased, but the degradability of that carbon increased too, meaning that some shelves such as the East Siberian shelf waters will become CO_2 sources to the atmosphere, irrespective of changes in nutrients and light**[1]. This has implications for the growth of the primary producers and rates of microbial degradation and ultimately air-sea greenhouse gas emissions from coastal waters.

Similarly, organic matter sequestered in Arctic thermokarst lagoons – a terrain type formed as permafrost thaws – are likely to thaw much faster in the future, meaning that more of this organic carbon will enter the ocean and then become a CO_2 source to the atmosphere. **Other greenhouse gases emissions are changing: coastal nearshore regions emit methane throughout the open water period and are susceptible to increasing under future change with a longer open season**.

Subsea and coastal permafrost – permafrost on continental shelves that have seen prolonged sea-level rise over the last 10,000 years and so are now submerged – are governed by different degradation processes and so have different impacts on biogeochemical cycles. CAO quantified coastal permafrost erosion due to sea ice retreat and waves. The carbon flux due to this erosion can be converted to methane by bacteria, contributing to greenhouse gas flux. Research showed that seasonal sea ice retreat beyond the Siberian shelf slopes created favourable conditions for off-shelf water cascading - a specific buoyancy-driven current – which, along with Atlantic water upwelling and tidal shelf mixing, increases transport off the shelves by around 50%. Overall, we showed that for the Arctic ecosystem model projections, it is vital to account for riverine and terrigenous nutrient fluxes in biogeochemistry.

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Ocean – seafloor

The amount of organic matter that arrives at the seafloor and remains there has global implications for the amount of carbon dioxide (CO_2) permanently removed from the atmosphere. New research shows that an association of this organic matter with iron increases the preservation and burial efficiency of carbon in the Barents Sea for thousands of years[2]. Additionally, the strong seasonal contrasts in the Arctic means the seafloor communities – both larger animals and microbes - are adapted to a pulse of organic input in summer and then a reduction in the polar winter. The large animals inhabiting the seafloor, as well as the microbial ecosystems, seem to be well-adapted to strong seasonal organic matter export to the sea floor. Indeed, we find a clear separation in community composition at the polar front that marks a transition in the type and amount of bioturbation activity, and associated nutrient concentrations, sufficient to distinguish a southern high from a northern low[3]. Fresh food is consumed quickly. However, the presence of Atlantic water and earlier sea ice melt change the degradation of organic matter and can strengthen seafloor nutrient recycling rates - which may increase productivity. This can also lead to quite significant carbonate dissolution in the sediments, negatively affecting both carbon burial and the preservation of materials that can be used for inferring past climate conditions. There is some evidence for anaerobic metabolic strategies present, for example, denitrification, which may reduce the productivity by enhancing nutrient limitation. Experiments have revealed animal activity is moderated by seasonal variations in sea ice extent that influence food supply to the seafloor, and emphasize the rapidity with which an entire region could experience a functional transformation[3]. Furthermore, spatial variations in food quality and quantity, associated with the sea ice margin, are likely to affect the energy allocation available for reproduction for many species, and could result in decadal-scale recruitment failure in long-lived species.

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Regardless, these benthic fluxes are insignificant when compared to the fluxes of water masses. When water masses meet, they form a turbulent near-bottom layer. Where the Atlantic water intersects with the continental slope in the Arctic, heat fluxes between the water masses are significantly increased. Two common benthic organisms seemed resilient increases in both CO_2 and temperature.

Ice – ocean

Light

The Changing Arctic Ocean programme has developed high resolution data on the light climate at high latitudes and modelled the progression of light through sea ice into the water[4]. Using a new modelling approach the team were, for the first time, able to map the under-ice light field across the entire Arctic Ocean based on satellite data[4]. Work is ongoing to use these new techniques to predict the under-ice light field in the future up to 2100, by integrating output from the latest climate predictions.

Previously, our understanding of the functioning of the Arctic marine ecosystem has been overwhelmingly based on compact multi-year ice, whereas the majority of the ice is now in its first year and in a decaying state[5]. The transition to a first-year ice cover may increase the light transmission to the surface ocean by 200%. Through a combination of cutting-edge observations and modelling CAO has better quantified light penetration through sea ice and its impact on the ecosystem.

Light drives primary production in the Arctic, thus a change in the seasonality of light will affect algae phenology and time of production with effects that will propagate along the entire marine food-web[6]. Seasonal changes to the light conditions control the depth that zooplankton inhabit and its seasonal migration in the water column, possibly as an adaptation to avoid visual predation. Increased light may increase the vulnerability of zooplankton to visual predation. Autonomous measurements by CAO's robotic platforms have enabled the first in-depth study of the impact the diminishing under-ice light field (that occurs during the transition from polar-day to polar night) has on the migration of zooplankton and high latitudes i.e. near the North Pole. **This innovative robotic technology used can provide a long-term presence in the Arctic Ocean to monitor physical and biological parameters year-round, and has applications beyond the Arctic**.

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Nutrient cycles

Nutrients are as essential as light in regulating the primary production in the Arctic. Nutrients are supplied from subsurface water masses of Atlantic or Pacific origin to the sunlit zone by vertical mixing, as well as regional upwelling, with each of these processes being controlled by sea ice dynamics[7–9]. The change to a more Atlantic ice-free dynamic is likely to increase nutrient availability and the duration of seasonal drawdown of nutrients in Arctic shelf regions. Under ice-free or ice-dominated conditions the seasonal dynamics of nitrate were similar, but nitrate supply to the surface was greater under ice-free conditions and drawdown was slower. The extent to which this increased nutrient availability and longer drawdown periods will lead to increases in primary production will depend on changes in upper ocean mixing and stratification[10].

The role of ocean stratification in maintaining primary production was further investigated in the Fram Strait. Nutrient limitation was reduced where stratification was weak, allowing nutrients to reach surface waters and support productivity. In contrast, primary productivity was limited by nitrate availability in Polar surface waters where stratification was strong. Historical model simulations reveal that nutrient cycles in the Arctic have been changing over the past decades, with variability at pan-Arctic scales[11]. Nutrient dynamics are likely to be altered by loss of winter sea ice and atmospheric warming within the Arctic[12] with processes within the connected oceans of the Atlantic and Pacific, as well as deposition of anthropogenically-derived nitrogen also playing a role[11].

Through the use of automated gliders, the programme discovered previously unknown eddies – circular currents of water – that had previously been undetected by satellites due to their surface waters being warmed by surrounding water. This temperature masking means circulation has been underestimated, and suggests this could also be the case in other areas where circulation is assumed to be relatively simple. The Atlantic Water is one of the key pathways of nutrient rich water into the Arctic. These eddies measure 18.6 miles across and are created in the northern part of the Barents Sea as cooler and fresher water from the Arctic moves south and becomes trapped within the warmer and saltier water from the Atlantic. They could provide pockets of nutrients to create a spike of primary production.

Some nutrient availability is determined by microbial degradation processes. The Changing Arctic Ocean programme found evidence that microbial cycles are significantly different between seasons, with implications for the anticipated changes to the seasons [13]. Moreover, nutrient availability near the coast is determined by export from terrestrial regions. Over an annual cycle, deltaic regions can contribute as much as one quarter to water column nutrient budgets, with the potential to alter nearshore nutrient turnover.

Primary producers

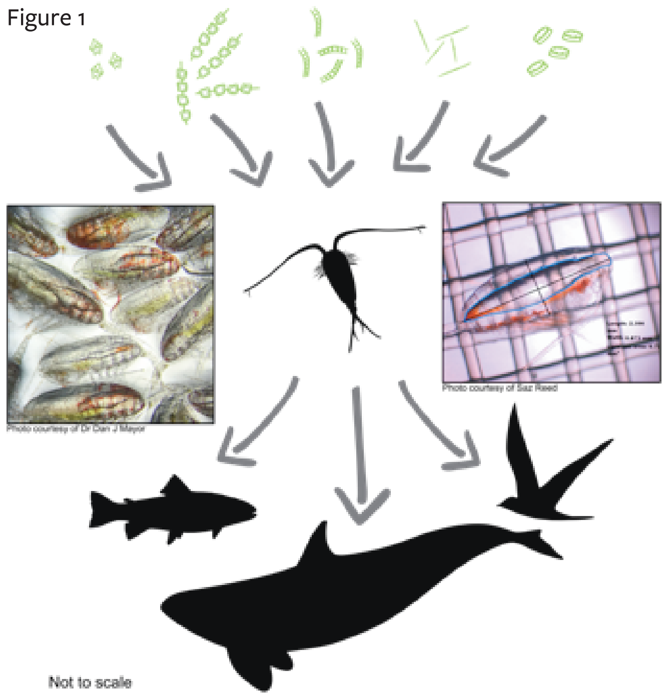
Primary production in the Arctic has been changing in response to both modifications within the Arctic Ocean related to sea ice loss, but also indirectly in response to changes in the transport of nutrients from the Atlantic and Pacific [14]. Arctic sea ice extent has decreased by around 50% in the last three decades. The Arctic is no longer a region dominated by thick multi-year ice, but is facing a regime controlled by thinner, fragmented, and more dynamic first year ice (e.g [15]). Ice retreat allows more wind- and wave- driven mixing and can bring nutrient fluxes into the mixed layer well after the spring bloom, allowing a late spike in primary production. Younger and thinner ice allows light to penetrate deeper into the ocean beneath and model simulations suggest that the under-ice primary production might happen earlier in the season [6]. The models suggest that in the Barents Sea, ice-free summers and the associated increase of light combined with oceanographic and biogeochemical changes will increase net primary productivity by 5% annually by 2040. However, whether this results in an increase in the amount of carbon drawn down to depths by these primary producers and their consumers is still highly uncertain, warranting intensified long-term observations [16].

Shifts towards younger sea ice may change the species compositions of the primary producers, and the Changing Arctic Ocean programme revealed that despite the anticipated increase in light with a shift from first-year to multiyear sea ice, changes to the algal community composition may limit the photosynthetic potential of the algal blooms in some areas [17]. This discovery is now being represented in biogeochemical models so that this complexity is not overlooked. The diatom-dominated sea ice algal bloom is not only changing in composition, but in timing and nutritional value too. **Species shifts may increase the concentrations of some toxic diatoms, for example *Pseudo-nitzschia spp.*, many types of which produce the potent neurotoxin, domoic acid** [18,19]. Domoic acid is transferred through trophic levels (levels of the food web) via planktivorous fish through to marine mammals and seabirds. Accumulation in any organism for human consumption could lead to Amnesic Shellfish Poisoning in humans which may cause vomiting, memory loss, coma or death.

Secondary producers

Copepods are the small crustaceans that make up the majority of small zooplankton in the Arctic. They consume phytoplankton and transfer this carbon higher up the food web, **being particularly important for fish stocks such as capelin, polar cod, herring and mackerel. This 'waist belt' in the food web (see fig. 1) appears to be more resilient to the changing food environment than we expected** – a new theoretical model indicates that the reproduction of copepods is limited by the amount of food consumed, rather than its nutritional quality [20]. This advance provides opportunities to better predict how the productivity of important Arctic copepods will respond to future changes in their environment, and the wider ecosystem consequences.

Figure 1



Arctic zooplankton communities are dominated by just a few species of copepod from the genus *Calanus* (e.g. *Calanus finmarchicus, Calanus glacialis, Calanus hyperboreus*). Each of these has a different thermal niche, and depends upon the presence of sea ice to a different extent. These differences are what makes some of the species more vulnerable to climate change than others. For example, ocean warming, earlier sea ice retreat and increased productivity are simultaneously making Arctic latitudes increasingly favourable for the subarctic species, *C. finmarchicus* [21] and less so for the true Arctic species. Data collected over the last 60 years shows that environmental change in the Fram Strait has enabled *C. finmarchicus* to overwinter in this region and successfully spawn in the following year. The genetic code of this subarctic species has adapted to Arctic light conditions, with positive implications for future populations, their survival in the polar night and midnight sun, and therefore the commercial fish stocks that rely on them.

However, resilience to a different habitat and food environment does mean the copepods are resilient to all changes. The abundance of *Calanus* species was found to be sensitive to the influences of the climate on the ocean, specifically the mixed layer depth and nutrient concentrations [18] – things that will continue to change. In the Greenland and Labrador Seas, the timing of their peak suitability for *C. finmarchicus* is shifting towards an earlier season, linked to the ice loss and extended growing season. The copepod life cycle usually matches the food environment and includes a winter hibernation at depth – named diapause – which is thought to be linked to deep water temperatures. With warming of the deep ocean, copepods could shorten the length of their diapause by over 50 % [22], causing a mismatch between when they surface and when the food is available.

Consumers

Warming increases metabolic rates of ectothermic animals like fishes, but predicting whether warming will increase or decrease performance depends on the interaction between individual physiology and available resources. Different fish have different physiological responses to temperature change. CAO found evidence that species adapted to colder Arctic conditions express higher metabolic rates than their Atlantic counterparts when living in the same water masses. In the Barents Sea, all sampled fish species including commercially important cod, haddock and redfish and ecologically important polar cod, currently experience water temperatures below their field thermal optima. Under current ecosystem states, modest warming is likely to increase metabolic rates and production at least for adult life stages. This implies that cold adapted species have higher food requirements than warm adapted species, which may contribute to competitive replacement. Under-ice habitats are critical for many polar species. New ways to identify dependence on food from under ice habitats has been developed and used to identify the importance of ice-associated algae for consumers.

Long-term monitoring data on stomach contents of fish in the Barents Sea document changes in diet composition of e.g. cod, related to fluctuations in capelin abundance. However, the consequences of these diet fluctuations for food chain lengths – and hence the trophic efficiency of the ecosystem, have been unclear. CAO developed new methods for estimating tropic position based on carbon and nitrogen isotopic ratios. This approach depends on the progressive enrichment of ^{15}N and ^{13}C isotopes relative to ^{14}N and ^{12}C respectively, in animal body tissues with each step in the food web [23].

End-to-end food web modelling in CAO showed that changes in primary production in the Barents Sea between the 2010s and 2040s (assuming RCP8.5 emissions) are projected to propagate through the food web as a bottom-up effect on all trophic levels. However, these effects are complicated by the ice-dependencies of top-predators (see above) which generates a competing top-down effect on the food web with ice retreat. These top-down and bottom-up effects collide at mid-trophic levels with unexpected consequences for fisheries management. Maximum sustainable fisheries yield (i.e. productivity) of piscivorous and benthivoros demersal fish (cod, haddock) was projected to increase by the 2040s to 112% of 2010s levels. On the other hand, that of planktivorous fish (capelin, herring), was projected to decrease to 65% due partly to increased predation by demersal fish. Birds and mammals in the model were strongly sensitive to planktivorous fish abundance, meaning that the food web is expected to become more sensitive to fishing as upper trophic levels come under pressure from ice loss. **Maintaining harvest of demersal fish while reducing harvesting of planktivorous fish is a potential strategy for alleviating some of the effects of ice loss and warming on the food web**. These results indicate difficult trade-offs ahead, between harvesting and conservation of ecosystem structure and function. The societal implications of failing to include the entire ecosystem within fishery management could be particularly acute in the Arctic. Indigenous communities in these regions have subsisted on sustainable harvesting of marine fauna for generations, and the threat to their way of life already posed by climate change could be accentuated [24].

Long-term monitoring data on stomach contents of fish in the Barents Sea document changes in diet composition of e.g. cod, related to fluctuations in capelin abundance. However, the consequences of these diet fluctuations for food chain lengths – and hence the trophic efficiency of the ecosystem, have been unclear. CAO developed new methods for estimating tropic position based on carbon and nitrogen isotopic ratios. This approach depends on the progressive enrichment of 15N and 13C isotopes relative to ^{14}N and ^{12}C respectively, in animal body tissues with each step in the food web. However, interpretation of changes in these isotope ratios in a given species ($\delta^{15}N = {}^{15}N/{}^{14}N$, *et* $\delta^{13}C = {}^{13}C/{}^{12}C$) also depends on these ratios in the dissolved nutrients in the environment which are absorbed by primary produces – the so called 'isoscape'. CAO constructed the first nitrogen isoscape for the Arctic Ocean [11] using knowledge from in-situ observations [12,25] and provided the first carbon isoscape for the Arctic Ocean [26]. Using this new knowledge,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the trophic position of harp and ringed seals was estimated with consideration of pan-Arctic variation in the isoscape[27]. If the varying isoscape was ignored, harp and ringed seals would have been assigned the incorrect trophic position, with implications for contemporary and future food web studies and the Inuit communities that utilise seals. Over decadal timescales, it has been found that input of reactive nitrogen from the atmosphere to the ocean due to anthropogenic activity has contributed to the changing nutrient transport between the North Atlantic and Arctic[11], altering the nitrogen isoscape. This has ramifications for the decadal scale monitoring of ecosystem change in the Arctic[27,28]. There have also been detailed carbon, nitrogen and sulfur isoscapes mapped for pelagic and benthic fish communities in the Barents Sea.

Upper trophic level species in the Arctic (seabirds, pinnipeds, cetaceans and maritime mammals (polar bears, Arctic fox)) are dependent on sea ice in a variety of ways that are critical for their feeding efficiency and survival. Aquatic mammals are attracted to prey concentrations at the ice edge, but must avoid becoming trapped beneath ice. Bearded seals are able to maintain breathing holes in thin ice, while harp and ringed seals depend on ice to haul out, but also spend extensive periods in open water. Polar bears are notoriously dependent on ice as a platform on which to hunt for seals, though they are able to swim. CAO developed the first representations in an ecosystem model of the ice-dependencies of feeding efficiency and habitat for these high trophic levels, showing how seasonal migrations and ultimately population abundances depend on a trade-off between food and habitat. The models indicated that for pinnipeds and polar bears the loss of habitat has an overwhelming effect. The situation is less clear for seabirds. The distribution and abundance of Arctic Guillemots correlates with the sea surface temperature - both Arctic (Brunnich's) and Atlantic (common) Guillemots have experienced population declines, but the Arctic species at a higher rate. This means that it is not a simple replacement of Arctic birds with Atlantic birds as the oceans warm, although the role of competition between them is still unclear. The cold East Greenland current, East Iceland current and fjords provides cold water refugia that act to buffer the Arctic species from the effects of a regime shift, similar to the shift that caused warming and alteration of fish stocks in Iceland in the 1990's.

Arctic – global

The connections between the Arctic realms do not end in the Arctic – they have global reach. And our actions globally affect the Arctic in return. The CAO found evidence of global human impact on the Arctic for the past 60 years, not only 30 as previously thought, a find that utilised both biogeochemical models of the food web and plankton distributions.

Atlantification in the Arctic is a shift in water properties to become more like the Atlantic. Organism movements correspond with these changes to allow them to stay within their thermal niche. Atlantification was demonstrated in the Eastern Arctic and explained by upper-ocean stratification from heat fluxes, atmospheric forcing, and related feedbacks. A new Arctic state is emerging, and it may not be reversed. Evidence showed that, coupled with the emerging shift in oceanic connectivity, there will be changes in the Arctic species and increased probability of the Pacific species invading, ultimately leading to the changes in Large Marine Ecosystems provinces. The potential changes may lead to the Pacific species traveling faster in the ocean currents and surviving the winter cycle, then emerging on the Atlantic side of the Arctic Ocean, thus invading not only Arctic but also the North Atlantic marine provinces[29].

Ecosystem resilience

All organisms do not change their distributions in relation to the temperature, and all immigrant species are not adapting to the Arctic life in a uniform way. Expression of climate forcing at the benthos (here, approx. 300 m water depth) is not temporally or spatially homogeneous and leads to context-specific changes in species behaviour and related levels of ecosystem functioning 3. Some species have declined over 50%, and others have been lost to the movement north whilst trying to remain within the same temperature. Different fish have different physiological responses to temperature change. CAO research found evidence that species adapted to colder Arctic conditions express higher metabolic rates than their Atlantic counterparts when living in the same water masses. Similarly, cold adapted populations of Atlantic cod express higher metabolic rates then warm adapted populations at the same water temperatures. This implies that cold adapted species have higher food requirements than warm adapted species, which may contribute to competitive replacement. Predictions of species' responses to climate change must also factor changes in latitudinal distributions of populations as well as species.


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Ocean circulation and ecosystems

There is a wealth of research about the impact of polar warming on the global conveyor belt, the thousand-year long system of currents driven by thermohaline circulation. However, there was a gap in the knowledge of detailed circulation across the Arctic and pathways of the Atlantic and Pacific nutrients into and within the Arctic Ocean, and therefore uncertainty in knowing how changes in the global conveyor belt can impact Arctic ecosystems in the future. The intrusion of the warm and nutrient-rich Atlantic and Pacific waters in the Central Arctic ocean created favourable conditions for non-Arctic species to propagate into the ocean. The data on ocean hydrography and marine biogeochemistry collected during the Arctic cruises and collaboration ones (including MOSAiC - Multidisciplinary drifting Observatory for the Study of Arctic Climate and GEOTRACES Programmes) allowed development of the novel pan-Arctic synthesis of the observational archives as a part of Unified Database for Arctic and Subarctic Hydrography (UDASH) and led to a unique opportunity for the joint analysis of the data and high-resolution ocean-ecosystem models to established variability of nutrient pathways and emerging processes controlling biogeochemical tracers[30–33].

Heat is lost to the atmosphere from the Bering Strait in Autumn, but a significant fraction of warm salty water dives beneath and extends into the Beaufort Gyre. The subduction of this water further increases the heat content of the deeper gyre, and this combined lateral stirring, and upward vertical mixing explains the pattern of accelerating sea ice melt spreading out from the Pacific inflow that has been observed in recent decades[34].

New methods have been developed to determine the potential predictability of the ocean currents. These methods, combined with Artificial Intelligence and Machine Learning techniques, allow us to assess predictability barriers in the short- and medium-term model projections[35,36]. New developments of the remote sensing technologies are instrumental to obtain details on sea ice and surface ocean dynamics to understand variability in the basin-wide connectivity in the Arctic Ocean[37,38].

Data and models showed that biogeochemical connectivity between the Arctic and the global oceans is changing: in 2000-2005 there was a connection between the Arctic Siberian shelves and the central Arctic Ocean but almost no direct connection of the Siberian shelves to the North Atlantic; in contrast, in 2006-2010 there was no direct connection of the Arctic Siberian shelves with the central Arctic but direct connectivity to the North Atlantic; and post 2011 the Arctic shelves–central Arctic connectivity re-emerges, with cessation of connectivity to the North Atlantic. Models predict in future there will be shorter transit times from the Northern Pacific to North Atlantic, a weakening or complete disappearance of oceanic and ice connectivity between the Arctic Siberian shelves and North Atlantic and increased Atlantic inflow in the Arctic[36].

Pollutants & hazards

Poly and perfluorinated alkylated substances (PFAS), often described as 'forever chemicals' because of their persistence in the environment, are used in the manufacture of a wide range of consumer products including non-stick cookware, waterproof clothing, dental floss, carpets and food packaging. Several perfluoroalkyl acids like perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) are known to be toxic, are present in Arctic biota and have been subject to international restrictions. Due to these restrictions, there are now numerous PFAS that serve as replacement chemicals. One widely used replacement chemical is 'Gen-X' or hexafluoropropylene oxide-dimer acid (HFPO-DA), a high production volume chemical, which the CAO measured at relatively high concentrations in the surface waters of the Fram Strait. This demonstrates that this chemical is subject to long-range environmental transport and is sufficiently persistent to reach the Arctic. The total concentration of PFAS was significantly enriched in the cold, low-salinity surface water exiting the Arctic through the Fram Strait compared to warmer, high salinity water from the North Atlantic entering the Arctic. **This indicates that past and ongoing atmospheric deposition is a major source of these chemicals to the high Arctic, more so than oceanic transport into the Arctic with surface currents**.

Interactions between seawater and sea ice of persistent organic pollutants, like PFAS, were investigated in both laboratory and field experiments. Detailed field studies on the Barents Sea ice floes, for example, revealed unique processing of PFAS contaminants in the ice system, particularly their accumulation in the ice-rafted snowpack and surface snow-ice layers. This work demonstrated that meltwater release during periods of thaw can result in extremely high PFAS concentrations in the beneath-ice seawater (depth of 0.5 m), with concentrations akin to those observed in coastal areas of the North Sea. Unlike some pesticides, melt-pond water plays a relatively minor role in PFAS transfer to seawater. For some contaminants, concentrations in the ice-brine were higher than the beneath ice seawater; evidence of an enrichment process during ice growth. This has implications of pollutant dynamics in young, single season ice; the dominant ice type across large parts of the Arctic Ocean. **First year ice contains more mobile brine which interacts with the overlying snowpack and can also concentrate pollutants, meaning there may be greater focusing of pollutants within ice in the future, with the likelihood of 'pulse releases' during periods of thaw**. Chemical pollutants like PFAAs are present in Arctic biota, although pathways and seasonal fluctuations in exposure, particularly in marine systems, are not fully resolved. Deleterious effects of PFAS exposure has been reported for higher trophic level organisms such as Polar Bear and several bird species. In contrast, adverse effects of PFAS on selected benthic microbial communities was not detected during sediment incubation studies. Pelagic polar bears had higher pollutant loads than coastal bears because they feed on a higher proportion of marine and higher trophic level prey; they have higher energy requirements and higher prey consumption; they forage in the marginal ice zones; and they feed on prey located closer to pollutant emission sources and transport pathways. The presence of these pollutants in the Arctic has unknown implications for fisheries, but this highlights the need for global efforts to reduce their use.

Dimethyl sulphide (DMS) and carbon monoxide (CO) are potent greenhouse trace gases, and so their present and future dynamics need to be considered in the production of carbon budgets. CAO has demonstrated that ice melt will probably increase CO concentrations in the surface ocean, while increasing light availability and changes to the phytoplankton community will probably increase both CO and DMS. Changes in bacterial communities and ocean acidification will have unknown effects to both, and will need further study as it is likely that bacterial communities will show great changes with climate forcing.

Light is another pollutant relevant to the Arctic as the Polar regions are the last pristine light habitats on the planet, meaning the polar night is an ideal opportunity to study the effects of light pollution from ships. Research into the effects on net sampling biases in fish surveys is ongoing. Data show that normal working-light from a ship may disrupt fish and zooplankton behaviour down to at least 200m depth across an area of >0.125km^2 around the ship.

Changes in levels of pollutants links with the changes to ocean circulation, as their spread is affected. Contaminants from the land spread across the Arctic shelf seas and in the central Arctic Ocean, then into the North Atlantic and so can create substantial risk in contaminating the mid-latitude oceans. The spread of pollutants such as plastics should also be accounted for in ecosystem models so the socio-economic impacts can be considered.

Modelling

To model the Arctic Ocean system in a meaningful way necessitates an in-depth and quantified understanding of key aspects of the Arctic Ocean ecosystem and its biogeochemical cycles. The understanding of the Arctic Ocean gained from observational data contributes to the testing and development of numerical models. These models simulate how the Arctic Ocean will react to current and future change.

The 23 large-scale numerical models used in the programme are diverse in terms of the spatial and temporal scales they cover, the components of the marine system they are aiming to replicate, and the research questions they address. All are backed up by observational studies. For example, a model called FESOM was used to simulate light transmission through snow and sea ice, and CAO improved accuracy through the introduction of 15 categories of ice thickness instead of the previously used 7.

Given the strong connectivity of the Arctic with the adjacent Atlantic and Pacific basins there is a need to account for how global scale ocean dynamics drive Arctic change. Accounting for the transport of heat, carbon and nutrients into the Arctic from the Atlantic and Pacific requires global scale models as this connectivity contributes strongly to past and future trends 14. For this, the model used (NEMO ORCA0083-MEDUSA-2 forced with DFS/ERA reanalysis) included pan-Arctic and regional hydrography, nitrates-nitrites levels, primary production, sea ice mass balances and dynamics, surface ocean circulation including eddy and mesoscale structure dynamics, and cross-Arctic connectivity.

International Collaboration

CAO participated on 48 research cruises led by international collaborators across the world, worked with other research programmes (e.g. MOSAiC, GEOTRACES), and contributed to international initiatives (e.g. the Arctic Monitoring Assessment Programme).

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Outputs

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For an up-to-date list of publications, please see our website by scanning the QR code or following this link https://www.changing-arctic-ocean.ac.uk/science-outputs/publications/.

Outreach

Outreach is vital to ensure research has the necessary impact. CAO sought diverse audiences to share the exciting methodology and results with, including people of all ages and backgrounds. Here are some of the highlights.

- Scientists published a series of 19 articles in the youth-reviewed journal Frontiers for Young Minds, aimed at those aged 8-15 years. The special issue has already received over 100,000 views. View it here: https://bit.ly/cao-fym.
- CAO created 'Challenge Cards', a stat-based game of the Arctic organisms
- Many freely-available resources have been designed and distributed, including activity sheets and posters for children (below), GCSE and A-level resources, for teens and young adults, and infographics for the general public.
- Event appearances have also been numerous, with exhibitions such as 'Permafrost in Transition' that bring the Arctic closer to home. CAO researchers attended science, music, and culture festivals to showcase their work.
- Appearances in the news, on TV and on podcasts have been frequent. Investigators worked with experienced science journalists to produce a radio documentary for the BBC World Service "Discovery" programme. Collaboration with Interdependent Pictures created the documentary 'Into the Dark', and collaboration with Vox brought a series of films. See them here: https://bit.ly/cao-youtube.
- All were involved in school visits, social media promotions, or enjoyed giving talks to the public.

Holly Jenkins

Holly Jenkins

Scientists

Dr Adam Reed	Postdoctoral researcher
Dr Aidan Hunter	Postdoctoral researcher
Professor Alessandro Tagliabue	Co-investigator
Professor Alexandre Anesio	Co-investigator
Dr Allyson Tessin	Post-doctoral researcher
Dr Andy Heath	Co-investigator
Professor Andrew Brierley	Co-investigator
Dr Andrew Rees	Co-lead investigator
Dr Andrew Yool	Co-investigator
Professor Dr Anja Engel	Co-lead investigator
Dr Anna Belcher	Postdoctoral researcher
Dr Anne Sophie Bonnet Lebrun	Postdoctoral researcher
Professor Anya Waite	Member Advisory Group
Dr Bart van Dongen	Co-investigator
Dr Ben Lincoln	Postdoctoral researcher
Dr Ben Ward	Co-investigator
Dr Benjamin Rabe	Co-lead investigator
Professor Dr Bettina Meyer	Co-lead investigator
Dr Birthe Zäncker	Postdoctoral researcher
Dr C.J. Mundy	Member Advisory Group
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Dr Camille de la Vega	Post-doctoral researcher
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Dr Chris Wilson	Co-investigator
Professor Dr Christian Haas	Co-investigator
Dr Christian Katlein	Postdoctoral researcher
Dr Christian März	Lead investigator
Professor Claire Mahaffey	Lead investigator
Dr Claudia Castellani	Co-investigator
Dr Clive Trueman	Co-investigator
Dr Colin Stedmon	Member Advisory Group
Professor Corinna Schrum	Member Advisory Group
Professor Crispin Halsall	Co-lead investigator
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Dr Dan Mayor	Co-investigator
Dr Darren Clark	Researcher
Dr David Barnes	Co-investigator
Dr David McKee	Co-investigator
Professor David Pond	Lead investigator
Professor David Thomas	Chair Advisory Group
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Dr Ekaterina Popova	Co-investigator
Dr Emily Venables	Technician
Dr Eva-Maria Nöthig	Co-investigator
Dr Fabian Große	Postdoctoral researcher
Dr Felipe Sales de Freitas	Postdoctoral researcher
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Dr Frank Kauker	Co-investigator
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Professor George Wolff	Co-investigator
Professor Geraint Tarling	Co-investigator
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Professor Tom Rippeth	Co-investigator
Dr Ute Daewel	Co-lead investigator
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Dr Yevgeny Aksenov	Co-lead investigator
Dr Yueng-Djern Lenn	Co-lead investigator
Dr Yuri Artioli	Co-investigator
Dr Zhiyong Xie	Co-investigator
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Alice Lowry	Affiliated PhD student
Anabel von Jackowski	PhD student
Andy Crabb	Film maker
Andrew Orkney	PhD student
Antonia Doncila	PhD student
Ben Barton	Affiliated PhD student
Bennet Juhls	Affiliated PhD student
Celeste Kellock	Technician
Charlotte Haugk	Affiliated MSc student
Chelsea McGowan-Yallop	Affiliated PhD student
Colin Abernethy	Technician
Colin Mettam	Technician
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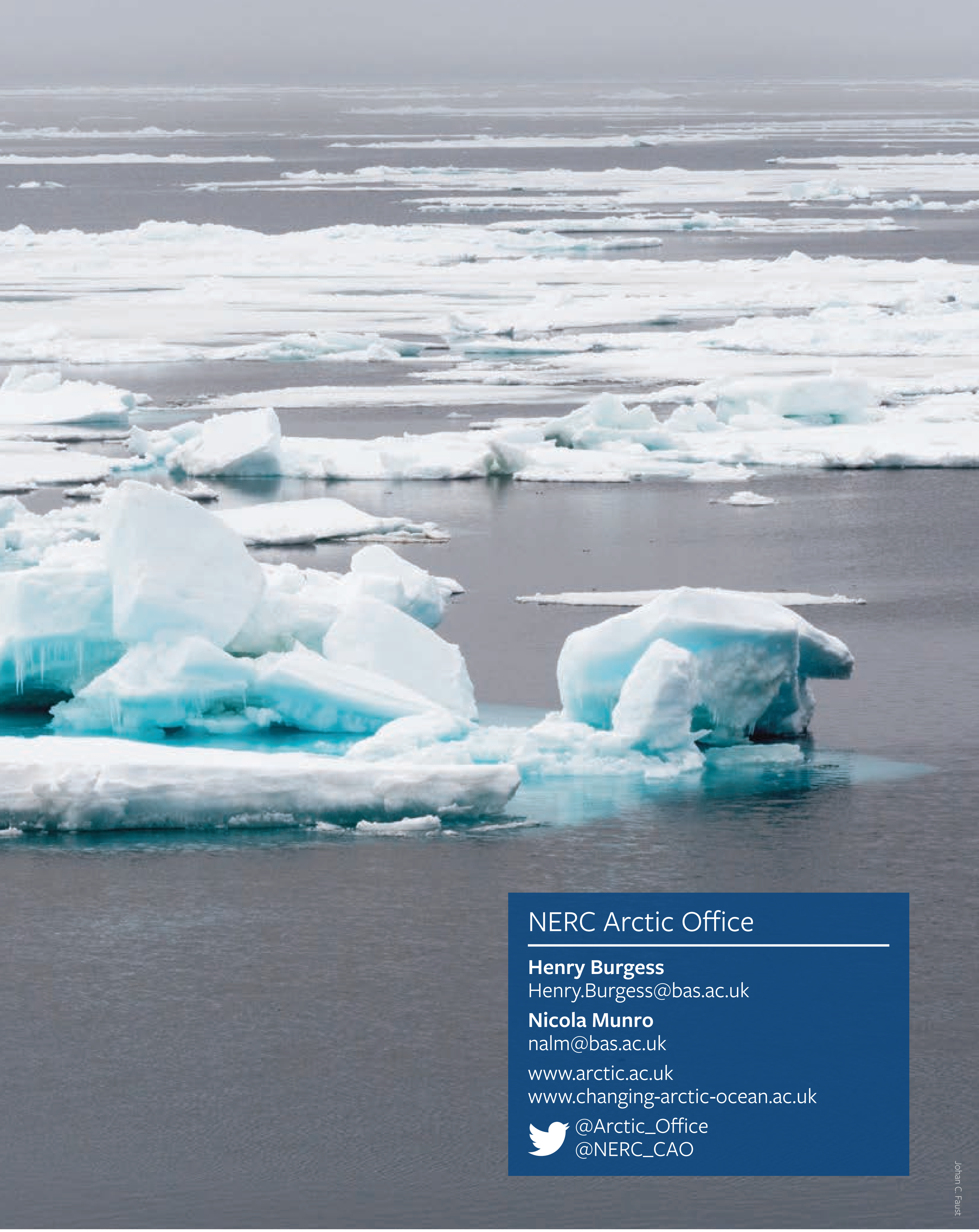
Projects

APEAR	Advective Pathways of nutrients and key Ecological substances in the ARctic
Arctic PRIZE	Arctic productivity in the seasonal ice zone
ARISE	Detecting changes in Arctic ecosystems
CACOON	Changing Arctic Carbon cycle in the coastal ocean nearshore
ChAOS	The Changing Arctic Ocean Seafloor
CHASE	Chronobiology of changing Arctic Sea Ecosystems
Coldfish	Potential benefits and risks of borealisation for fish stocks and ecosystems in a changing Arctic Ocean
DIAPOD	Mechanistic understanding of the role of diatoms in the success of the Arctic *Calanus* complex and implications for a warmer Arctic
Diatom Arctic	Diatom Autecological Responses with Changes To Ice Cover
Eco-Light	Ecosystem functions controlled by sea ice and light in a changing Arctic
EISPAC	Effects of ice stressors and pollutants on the Arctic marine cryosphere
LOMVIA	Linking Oceanography and Multi-specific, spatially-Variable Interactions of seabirds and their prey in the Arctic
Micro-ARC	Understanding the links between pelagic microbial ecosystems and organic matter cycling in the changing Arctic
MiMeMo	Microbes to Megafauna Modelling of Arctic Seas
PEANUTS	Primary productivity driven by escalating Arctic nutrient fluxes?
PETRA	Pathways and emissions of climate-relevant trace gases in a changing Arctic Ocean

Future Research Priorities

1. *Rethink the way research is funded, undertaken, and reported in this climate emergency and with the rapid changes evident across the Arctic.* The landscape is changing so fast that the methodology for science is not adequate to address the issues with the urgency required to halt some of the worst effects of climate change. There needs to be a more direct path between the original funded scientific enquiry, the science undertaken, and the reporting back to policymakers so it can be integrated into decision-making.
2. *Allow Indigenous communities to lead prioritisation of research questions, coproducing work targeted by urgency.* Arctic Ocean climate change is already happening and cannot be avoided, so adaptation must begin now and needs to have solid science underlying it. To do this, research must work with international partners on integrated and aligned action on observing strategies, data, education and technology, engaging scientists, Indigenous People/local knowledge holders and researchers and governments, the private sector, and other international organisations (e.g. NGOs).
3. *Value basic discovery and observational science, museum collections and historical archives and use this repository of information and perspectives to inform hypothesis driven investigation.* A cursory look at the literature cited by the contributors to this theme reveals that phenomenological observations are common and well-articulated, reflecting major investments in the recent past that stimulated much effort in establishing the basic science of the Arctic region. Emphasis is now needed to move beyond confirmatory observation and towards interrogation of system complexities, including unambiguous experimental demonstration of key mechanisms [39].
4. *Undertake diversification in the gathering of knowledge and evidence while adopting a holistic pan-Arctic view.* As this report highlights, the compartmentalisation of disciplines, seasons and study areas do not capture the interconnectivity between the realms and so bias the outcomes. [39].

This is by no means a comprehensive list, and more information can be found in this separate publication – 'Emerging Arctic research areas and approaches' on the Changing Arctic Ocean website.



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