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# Oceanography, biogeochemical cycles, and biodiversity in the Central Arctic Ocean: current state of knowledge and directions for future research as part of the Tara Polaris expeditions

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# Abstract

Climatic changes in the physical environment modulate biogeochemical cycles, biodiversity, and trophic interactions in the Central Arctic Ocean (CAO). Physical processes and sea-ice conditions are highly seasonal in the CAO and dependent on interactions that occur throughout the evolution of the upper ocean–sea ice–lower atmosphere system. Understanding these seasonal interactions is critical to comprehending and predicting the long-term trends as the CAO moves towards ice-free summers and to informing future policy decisions at the core of ongoing discussions concerning the CAO Fisheries agreement, e.g., at the Arctic Council and International Council for Exploration of the Sea working group on the CAO. Here, we review current knowledge of the physical environment, biogeochemical cycles, and biodiversity in the waters of the CAO, identify emerging research questions, and introduce the science plan for the first Tara Polaris drift onboard the *Tara Polar Station* to advance knowledge and address these questions. Despite increased observational programs in the CAO over the past years, e.g., the Nansen and Amundsen Basin Observational System (NABOS) and Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC), extensive knowledge gaps remain in relation to ocean stratification, sea ice and lightscape, nitrogen fixation and nutrient fluxes, carbon export and transfer, sympagic-pelagic coupling, aerosol production, contaminant transport and transformation, chronobiology, and fish distribution. Further knowledge on overall CAO biodiversity, ecosystem functionality and interannual variability is also critically needed. We describe a way forward to address these knowledge gaps using ice-tethered and profiling instruments coupled with multi-omics, culturing, and imagery approaches deployed from *Tara Polar Station* during the first of ten Tara Polaris drifts designed to facilitate detection of interannual variability and change over time.

# 1. Introduction and state of the art

Water mass properties, currents, and sea ice shape habitats in the Central Arctic Ocean (CAO). Environmental drivers govern the functioning of the entire ecosystem, including biogeochemical cycles, biodiversity, and transport of matter and energy across trophic networks. The physical environment also drives the capacity for adaptation or replacement of organisms living in the water column (pelagic) or at the ice-water interface (sympagic; Galand et al., 2009; Salazar et al., 2019). A better understanding of the interactions between ocean physical conditions, biogeochemical cycles, and biology is thus essential to model and forecast the future CAO. Physical processes and sea-ice conditions are highly seasonal and dependent on upper ocean–sea ice–lower atmosphere interactions that occur during ice formation, thinning, and ice melt (Brandon et al., 2010; Sumata et al., 2023). Increased sea-ice fragmentation and open leads in winter can increase heat loss and $CO_2$ exchange compared to previous conditions when the sea-ice lid better insulated the water underneath (Ericson et al., 2023; Boutin et al., 2024). Understanding the time scales and full range of physical and environmental interactions is particularly critical to comprehending and predicting long-term trends as the CAO moves towards ice-free summers and shorter winters with more dynamic sea-ice conditions (Jahn et al., 2024).

Knowledge about the pelagic ecosystem of the CAO remains scarce. In the context of rapid climate change and loss of habitats, there is a pressing need for coordinated interdisciplinary and comprehensive data collections collated over complete annual cycles (Pelt et al., 2017; Rabe et al., 2022). Several large programs, including the Nansen and Amundsen Basin Observational System (NABOS), the Norwegian N-ICE2015 and Nansen Legacy expeditions, and the

Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) (Granskog et al., 2018; Pnyushkov and Polyakov, 2022; Kohlbach et al., 2025), have increased knowledge on the Eurasian side of the CAO. However, the high regional and natural variability combined with ongoing climate change calls for continued observations, especially outside the better observed summer seasons. Here, we review our current understanding of the pelagic ecosystem of the CAO. We further introduce novel research questions to be addressed in future programs, which include the Tara Polaris I expedition, the first of ten planned consecutive transarctic drifts over the coming 20 years (Babin et al., n.d.). We focus on how physical oceanic conditions and sea ice affect biogeochemical cycles and pelagic ecosystems in the CAO, and vice versa. While essential sampling activities required to monitor marine ecosystems at high latitudes are described briefly, we emphasise novel approaches and questions that remain mostly unexplored yet are likely to advance our understanding of the pelagic ecosystem in the region.

## 1.1. Physical environment

### 1.1.1 Water masses and circulation

The CAO comprises the deep Amerasian (Canada and Makarov) and Eurasian (Nansen and Amundsen) basins. Being surrounded by continents, the CAO has limited connectivity with subarctic basins and the world ocean. Still, the inflow of saltier Atlantic deepwater and fresher Pacific surface waters through the gateways on the Atlantic and Pacific side are important drivers of deep-water circulation and characteristic layering in the Arctic Ocean (Polyakov et al., 2024). The Arctic Ocean receives more than 10% of the global freshwater runoff and, consequently, is the world’s freshest ocean, although a large portion of the freshwater is retained on the shelves (Aagaard and Carmack, 1989; McClelland et al., 2012). In polar regions, salinity is the primary source of stratification and the depth of the brackish surface mixed layer (SML) varies seasonally and regionally, with the Eurasian Basin having a deeper SML (approximately 20 m in summer and 70 m to >100 m in winter) than the Amerasian Basin (approximately 8 m in summer and 30 m in winter; Peralta-Ferriz and Woodgate, 2015). The uniformly cold layer below the Eurasian Basin SML increases in salinity with depth, forming a halocline atop the warmer and saltier Atlantic Water (Figure 1A). In the Amerasian Basin, Pacific Waters entering via the Bering Strait form an intermediate layer between the Arctic SML and the warmer deep Atlantic Water layer (Figure 1A, B). In summer, solar radiation warms the SML to above-freezing temperatures leading to sea-ice melt which, together with river runoff, freshens the SML, enhances surface stratification and restricts vertical mixing across the SML (Maykut and McPhee, 1995; Jackson et al., 2010; Smith et al., 2023). As a result, the Arctic SML serves as a heat reservoir, with its dynamics controlling heat distribution and exchanges between the ocean, sea ice, and atmosphere (Maykut and McPhee, 1995; McPhee et al., 2003; Perovich et al., 2014). Yet, there are uncertainties related to the direction and magnitude of air–sea exchange along the transpolar drift (Loose et al., 2024).

The upper ocean stratification is dynamic and continuously changing across seasons (e.g., Solomon et al., 2021). Over the past decade, the positioning of the Atlantic Water layer has become shallower and the heat exchange with the SML has increased, resulting in regionally warmer surface waters and increased sea-ice melt (Polyakov et al., 2012; Ingvaldsen et al., 2021; Schultz et al., 2024). This feature was first observed along the Eurasian slopes but was also recently detected in the Amerasian Basin (Polyakov et al., 2025a).

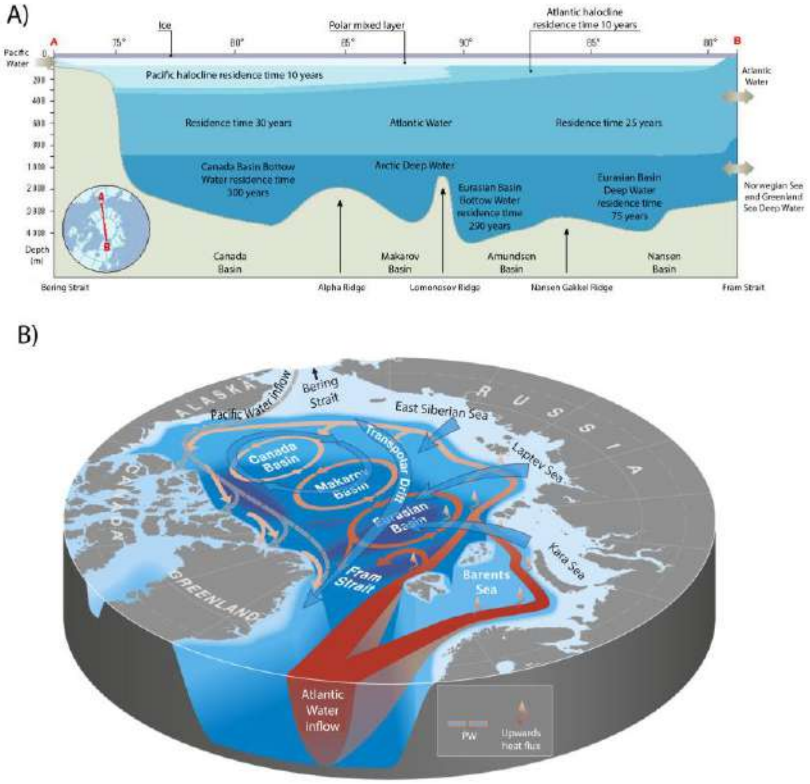

**Figure 1**. **Water masses and major currents in the Central Arctic Ocean**. A) Stratification of water masses across the basins (reproduced from the Arctic Monitoring and Assessment Programme; AMAP, 1998); residence times are approximate. B) Circulation of the surface water (blue), intermediate Pacific Water (PW, dashed pink/blue arrows), and warmer Atlantic Water (AW, red and solid orange, where the transition from red to orange indicates upward heat flux; reproduced from Carmack et al., 2015).

The first evidence of strong Atlantic Water warming — up to 1°C — was observed in 1990 when a warm pulse entered the Nansen Basin (Quadfasel et al., 1991). This pulse travelled through the ocean interior, reaching the Makarov Basin by 1993 and the Canada Basin by 2000 (Carmack et al., 1995; Morison et al., 1998; Shimada et al., 2004). A second, even warmer pulse (approximately 0.2°C warmer) entered through Fram Strait in 1999 (Schauer et al., 2004) and reached the eastern Eurasian Basin by 2004 (e.g., Polyakov et al., 2005). Since 2007–2008, the thermodynamic state of the ocean interior has remained relatively stable, with no significant changes over the following decade (Polyakov et al., 2020a).

During the 2010s–2020s, observations revealed unprecedented yet contrasting changes in stratification across the two major Arctic Ocean basins. On the Amerasian side, enhanced freshening and deepening of the surface freshwater layer, driven by sea-ice melt, redirection of Siberian river runoff into the Beaufort Gyre, and the intensification of the Arctic High and associated wind-driven upper ocean convergence, have strengthened stratification. This strengthening has led to a more pronounced separation between surface and deep ocean layers (e.g., Yamamoto-Kawai et al., 2009; Proshutinsky et al., 2009; Morison et al., 2012; Polyakov et al., 2017).

In contrast, in the Eurasian Basin, increased air–sea interactions and weakened stratification have resulted in the shoaling of the Atlantic Water layer and intensified current shear, altering the seasonal cycle of Atlantic Water temperature and vertical heat flux (e.g., Polyakov et al., 2020b). Specifically, the seasonal temperature range of the Atlantic Water layer in the eastern Eurasian Basin increased from 0.2–0.3°C in 2004–2007 to over 1°C in 2013–2015 (Polyakov et al., 2017). Significant shoaling of the Atlantic Water upper boundary, from depths greater than 160 m in 2002 to about 65 m in 2023, along with the loss of the permanent halocline layer, has enhanced upper ocean ventilation and wintertime entrainment of oceanic heat toward the sea ice. For instance, inferred divergent Atlantic Water heat fluxes of approximately 18 W $m^{-2}$ during 2021–2023 exceeded those recorded by moorings in the 2010s. As a result, the equivalent losses in sea-ice thickness due to reduced winter ice formation increased from approximately 0.4 m in the early 2010s to 0.7–1.0 m in recent years (Polyakov et al., 2025a).

A significant portion of these changes is attributed to anomalous inflows from the Nordic seas, which is commonly referred to as Atlantification (Polyakov et al., 2017; 2020a; Ingvaldsen et al., 2021). This process, occurring in the Eurasian Basin of the Arctic Ocean, has led to weakened upper ocean stratification and enhanced release of Atlantic Water heat, accelerating sea-ice loss in the region (Polyakov et al., 2017; 2020b). The continued eastward progression of Atlantification into the Amerasian Basin is now having substantial impacts on the upper ocean, sea ice, and ecological components of the Arctic climate system (Polyakov et al., 2025a), with uncertain consequences for the broader marine food web.

### 1.1.2 Sea ice

Sea ice plays a critical role in the Arctic environment, acting as a regulator of air–ocean heat exchange and freshwater balance in the polar basins (e.g., Aagaard and Carmack, 1989). It reaches its maximum extent of approximately 14–15 million km² in March and declines to around 4–6 million km² by September. Sea-ice thickness varies significantly depending on location, season, and age, but historically it has ranged from 2 m to 3 m, with a substantial portion composed of multi-year ice that has survived at least one melt season (Janh et al., 2024). Sea-ice concentration remains high in the CAO, while it is more variable in the marginal ice zone. Due to its high reflectivity, sea ice exhibits a high albedo (approximately 0.6–0.8), playing a key role in the global energy balance and climate system through the sea ice–albedo feedback mechanism (Manabe and Stouffer, 1980). Major circulation patterns in the Arctic include the Beaufort Gyre and the Transpolar Drift (Figure 1B).

The rapid decline in the extent and volume of Arctic sea ice has become a prominent signal of global climate change. The extent of Arctic summer sea ice has decreased by nearly half compared to the 1970s. Since 2007, the annual minimum of sea-ice extent in September has been lower than in any previous year during the era of satellites (Stroeve and Notz, 2018). The ice cover is becoming thinner (Lindsay and Schweiger, 2015), younger (Kwok, 2018), and more mobile (Rampal et al., 2011). Results from the MOSAiC transpolar drift in 2019/20 confirmed a thinner sea-ice cover that grew faster, drifted faster, and melted faster compared to historical observations (Raphael et al., 2024). Such significant changes have not been observed since at least the Last Interglacial at around 130,000 years ago (Vermassen et al., 2023), and the likelihood of ice-free Septembers in the Arctic Ocean before 2050 is now high (Jahn et al., 2024), though daily ice-free conditions may occur before 2030 (Heuzé and Jahn, 2024). According to projections from intercomparisons of coupled models, the Arctic will likely become ice-free in summer by 2035 (Wang and Overland, 2012; Notz and Stroeve, 2016; Sigmond et al., 2018; Rantanen et al., 2022; AMAP, 2024). In addition to impacting habitats and ecosystems, sea-ice reduction favours anthropogenic activity in the high Arctic (Melia et al., 2016).

### 1.1.3 Seasonal cycle

Over the past decade, the seasonal cycles of sea ice concentration, shear, and current speed in the upper Arctic Ocean have also changed markedly. In particular, longer summers have led to earlier surface melt and later freeze-up. This has amplified the seasonal cycle of current speed and shear and produced a close coupling between upper ocean dynamics and sea ice conditions in the Siberian sector of the Arctic Ocean, as reflected by a strong negative correlation (*R* = –0.94) between the seasonal cycles of sea ice concentration and current shear from 2013 to 2023 (Polyakov et al., 2025b).

Currents in the Arctic halocline and SML are impacted significantly by the seasonal evolution of stratification. In the shallow (<20–30 m) summer SML, currents increase because strong stratification constrains wind energy from propagating into the deeper layers. Strong near-inertial currents that are generated when sea ice is reduced account for more than half of the summertime current speed and shear (e.g., Brenner et al., 2023; Polyakov et al., 2025b). In the winter, a thicker surface layer is created by deep upper ocean ventilation associated with Atlantification in the Siberian Arctic, which distributes wind energy to far deeper (>100 m) layers. Polyakov et al. (2025b) provided evidence of winter amplification in the average currents across the 100 m upper ocean layer in response to higher wintertime forcing. This winter amplification of currents and shear at depths is highly consistent with increasing seasonality and a general loss of double-diffusive staircases in the region over the 2004 to 2023 period (Lundberg and Polyakov, 2025). Consequently, stratification represents a physically significant link in the strong connection between the seasonal evolution of currents and sea-ice concentration.

### 1.1.4 Optics and light field

The marine lightscape of the CAO is unique for two reasons: 1) seasonal variations in incident irradiance are extreme; and 2) the majority of incident photons do not reach the epipelagic zone (0–200 m) because sea ice and overlying snow are ubiquitous for most of the year. While variation in day length is constant from year to year at any latitude (Lund-Hansen et al., 2020), the effect of clouds, ice and snow is highly variable in space at scales of metres to tens of kilometres at any time of the year, as well as inter-annually (Katlein et al., 2019). Compared with other oceanic basins, the epipelagic zone of the CAO is thus often characterised by continuous darkness or twilight during the polar night, continuous illumination during the midnight sun period, and variable irradiance at small scales due to heterogeneous ice cover. Sea-ice features, such as leads and melt ponds, result in abrupt variations in submarine irradiance over as many as four orders of magnitude (Lei et al., 2010; Nicolaus et al., 2012; Arrigo et al., 2014). The optical properties in the water column are also influenced by coloured dissolved organic material from large rivers, mainly in Russia, and transported with the Transpolar Drift, which is reflected by a stronger impact in the Eastern Eurasian part of the CAO (Schulz et al., 2024, and references therein).

## 1.2 Biogeochemical fluxes

### 1.2.1 Nutrients and nitrogen

In addition to light, the nutrients nitrogen, phosphorus, iron, and silicon predominantly control primary production in the CAO, with nitrogen generally being the most limiting among the nutrients (e.g., Tremblay et al., 2015; von Friesen and Riemann, 2020). Primary production and upward vertical fluxes of nutrients and organic matter are more constrained in the CAO than in other sectors of the Arctic due to the strong water column stratification (e.g., Bluhm et al., 2015; Fernández-Méndez et al., 2015), which also impacts vertical carbon export (Randelhoff et al., 2020). In winter, as seawater freezes, salt is rejected and reduces stratification in the SML and the halocline (e.g., Rudels, 1989). While lateral nutrient input from rivers is high on Arctic shelves, entrainment of saline and nutrient-rich deeper waters plays a crucial role in nutrient supply to the surface in the highly stratified basins of the CAO, where winter mixing is absent, to sustain production when light becomes available in spring (Fernández-Méndez et al., 2015; Tremblay et al., 2015; Randelhoff et al., 2020). The increased contact between the deeper nutrient-rich Atlantic water and the surface layers in the regions impacted by Atlantification is known to facilitate increased nutrient supply in periods of increased mixing (Randelhoff et al., 2018; Schultz et al., 2024). A longer ice-free period also increases the possibility for wind mixing and resupply of nutrients at the surface (Randelhoff and Sundfjord, 2018). However, how the ongoing changes in CAO sea-ice cover will impact stratification and, ultimately, nutrient replenishment, still remains poorly understood.

In nitrogen-limited systems, nitrogen fixation by microorganisms results in the conversion of $N_2$ to ammonia and nitrate, which is then available to algae and can contribute significantly to nitrogen supply (e.g., von Friesen and Riemann, 2020). This process was assumed to be rare in the Arctic Ocean due to the absence of cyanobacteria; however, non-cyanobacterial diazotrophs are present in the Arctic. Nitrogen fixation by free-living bacteria or bacteria-microalgae symbiosis has been documented and quantified for Arctic shelves (Sipler et al., 2017; Harding et al., 2018), but rarely for the deeper basins of the CAO. There, the first studies suggest that this process is an underestimated contribution to nutrient supply for primary production, especially in actively melting sea-ice regions, and supported by dissolved organic carbon from phytoplankton as carbon source for the arctic diazotrophs (von Friesen and Riemann, 2020; von Friesen et al., 2025). River water transported with the Transpolar Drift can maintain relatively elevated concentrations of other nutrients, such as dissolved iron, in the Amundsen and Markov basins, and hence support nitrogen fixation (Klunder et al., 2012). In general, a trend toward less sea ice and a longer productive season could increase the importance of nutrient-regenerative microbial food webs in a stratified Arctic Ocean (Ardyna et al., 2011; Kohlbach et al., 2023).

### 1.2.2 Carbon

As in other oceans, the estimates of vertical fluxes in the basins of the CAO reveal a deficit in the quantified organic carbon production and export compared to benthic needs (Wiedmann et al., 2020) and call for improved insight into the different steps involved in carbon cycling. In general, the processes behind the sources and formation of particulate and dissolved organic carbon as well as retention and export of biogenic matter need to be studied in far greater detail across the CAO, especially during the winter (Roca-Martí et al., 2016; Rapp et al., 2018; Toullec et al., 2021). Specifically, while several global ocean studies have assessed planktonic interactions, including among bacteria and viruses, in the carbon cycle (Guidi et al., 2016), similar studies are lacking in the Arctic and during the polar night (Guidi et al., 2016; Gregory et al., 2019; Salazar et al., 2019).

The main source of organic carbon in the photic zone of the CAO is the photosynthetic fixation of inorganic carbon (primary production) by phytoplankton (Ardyna et al., 2024) and ice algae (Gradinger et al., 2024), and by chemolithoautotrophic archaea and bacteria during the arctic winter and in the deeper ocean layers (Alonso-Sáez et al., 2010; Royo-Llonch et al., 2021). Organic carbon supply and its partitioning between particulate and dissolved organic carbon is driven by changes in ice extent and conditions, and associated changes in productivity (Thomas et al., 1995; Jørgensen et al., 2015). For example, on Arctic shelves the input of sympagic biogenic matter to benthos is strongly correlated with the duration of the sea-ice period (Cautain et al., 2022). Particulate carbon export to depth in the deeper basins of the CAO, however, is less studied. Yet, studies from the Nansen Basin and along the shelf breaks showed that grazers significantly impact phytoplankton and the carbon flux composition, which is reflected in the high abundance of faecal pellets (Dybwad et al., 2021; 2022; Bodur et al., 2023).

Other carbon sources to the CAO include the cross-slope transport from adjacent seas and contribution of atmospheric carbon deposition (black carbon and organic carbon), which is still unquantified for the CAO (Schmale et al., 2025). Cross-slope transport not only impacts the transport of sediments, but also the export of particulate and dissolved organic carbon (Shen and Brenner, 2018; Krumpen et al., 2019). However, little is known about this carbon transport to the CAO in contrast to information available from the Chukchi Sea (Grebmeier and Harvey, 2005) and the Barents Sea (Lantuit et al., 2013; Rogge et al., 2023). The increased advection of Atlantic and Pacific water and organisms is expected to induce strong changes in the carbon flux dynamics of the CAO. Cross-slope and along-slope transports of organic matter may also be sensitive to changes in shelf-based dense water formation and stratification (Rogge et al., 2023). With thinner sea ice and faster sea-ice transport and melt, the deposition of ice-rafted sediment occurs closer to the shelves than in the past. In general, ice melting and potentially temperature changes are hypothesised to reduce the efficiency of the biological carbon pump in the CAO (von Appen et al., 2021; Bienhold et al., 2022). In addition to particulate organic carbon, changes in water column stratification and water masses impact the fluxes of dissolved organic carbon through modifications to the mixed layer and subduction pumps (Boyd et al., 2019).

The composition of the phytoplankton and ice algal community also plays a role in carbon export via aggregation, remineralization, and ballasting, altering carbon sequestration and the biological carbon pump (Lalande et al., 2014; Fadeev et al., 2021; Lalande and Dezutter, 2024). For instance, with climate change, small *Phaeocystis* algae are becoming increasingly abundant at the expense of larger diatoms (Assmy et al., 2017; Ardyna and Arrigo, 2020). This shift alters chemical composition of metabolites from phytoplankton blooms, subsequent particle composition, and thus export, because *Phaeocystis* can produce large mucilaginous aggregated colonies with sinking velocities that differ from dense packages of diatoms (Engel et al., 2017; Trudnowska et al., 2021). The export of *Phaeocystis* cells and derived material, however, may be less efficient and more dependent on downwelling or ballasting than diatoms, leading to reduced vertical carbon export (Reigstad and Wassmann, 2007; Wollenburg et al., 2018).

Ongoing changes in the composition of the organic carbon pool impact its quality as a substrate for heterotrophic and mixotrophic microbial communities, which in turn might determine its fate in the water column (exported versus remineralized). For instance, substantial amounts of extracellular polysaccharides (Krembs et al., 2011) and proteins (Brogi et al., 2018) are produced in situ in sea ice and may be released to the seawater during ice melt. The fate of carbon in the system will depend not only on dissolved and particulate organic matter composition, but also on the metabolic potential of the producing and degrading microorganisms (Digernes et al., 2025). Environmental forcing by temperature and nitrate availability, and the multiple interactions between the different microbial compartments, influence net fluxes. For example, viruses are predictive of ocean carbon fluxes (Guidi et al., 2016; Kaneko et al., 2021) and can influence dissolved (Kuhlisch et al., 2021) and particulate organic matter composition. Yet, how viruses influence recycling versus export of organic matter — the “shunt versus shuttle” paradigms (Wilhelm and Suttle, 1999; Sullivan et al., 2017; Vincent et al., 2021) — remains poorly quantified. This situation is partially due to our inability to quantify the fraction of cells that are actively being infected (Mruwat et al., 2020; Vincent and Vardi, 2023) and to correctly trace the fate of carbon into either dissolved or particulate pools.

At higher trophic levels, carbon and lipid transfer by zooplankton and fish relies on sources of carbon-dense fatty acids supplied by phytoplankton (Falk-Petersen et al., 2009). This often-overlooked biochemical link needs to be understood because it is tuned by water temperature, photosynthesis, and availability of nitrogen and phosphorus (Pittera et al., 2018; Holm et al., 2022). Ongoing increases in water temperature are assumed to activate the catabolism of these metabolites in phytoplankton early during the polar night, which may disrupt this key trophic resource (Schaub et al., 2017). Increased temperature is also expected to alter fatty acid quality, which is essential for the health of fish and mammals (Holm et al., 2022). Moreover, increased temperature may affect plankton community composition and therefore contribute to the modification of available metabolites across the food chain. Meta-lipidomic profiling allowing an evaluation of carbon fluxes through lipids from primary to secondary producers is therefore critically needed.

Ongoing changes in the CAO will affect not only the cycling of organic carbon. Rising atmospheric $CO_2$ concentrations and increased carbon uptake by the oceans lower calcium carbonate saturation states (mainly aragonite and calcite) and pH, with detrimental consequences for shell-forming marine organisms (Doney et al., 2009). Because of low saturation states of aragonite and calcite, the Arctic Ocean is considered the region most susceptible to acidification and associated ecosystem impacts (Fabry et al., 2009; Terhaar et al., 2020), including carbon export (Anglada-Ortiz et al., 2023). Observational studies have shown an increase in anthropogenic carbon and acidification in the Eurasian Basin (Ulfsbo et al., 2018; Ericson et al., 2023), and modelling studies have suggested that the mesopelagic CAO could store more anthropogenic carbon than anticipated (Terhaar et al., 2020). More accurate knowledge on both the physical oceanography and carbon uptake and export across the annual cycle is required to better forecast the levels and effects of acidification in the CAO.

### 1.2.3 Sea spray aerosols

Sea spray aerosols consisting of sea salt, dissolved and particulate organic matter, and microorganisms are produced by bubbles bursting on the sea surface due to wind stress (Monahan et al., 1986). The production of sea spray aerosols has been studied in coastal Arctic seas during summer, but production was assumed minimal in winter due to sea ice. However, recent studies have demonstrated that sea spray aerosol is also emitted from open leads (e.g., Kirpres et al., 2019) and from blowing snow in winter (e.g., Heutte et al., 2024). In addition to sea spray, trace gases like dimethylsulfide (DMS), methanethiol, and isoprene are released from the ocean to the atmosphere, with constant fluxes between the atmosphere and ocean. In particular, DMS production, a biogenic trace gas contributing to aerosol formation, is produced by microbial degradation of dimethylsulfoniopropionate (DMSP), an abundant metabolite in phytoplankton and sea-ice algae that is thought to play important roles in osmoregulation and cryroprotection. Its production is related to nitrogen availability (Bullock et al., 2017). Elevated concentrations of DMSP and DMS are associated with ponded first-year ice where the freshwater lens beneath the melting ice acts as a physical concentrating mechanism and could promote biological production in response to osmotic stress. In contrast, regions with multi-year ice, characterized by low phytoplankton biomass and small flagellates, are not associated with elevated concentrations of DMSP and DMS (Lizotte et al., 2020). How DMS/DMSP production in the CAO will vary as it transitions from an ecosystem dominated by multi-year ice to first-year ice remains an open question.

Recent studies from the *Tara* Oceans project revealed that multiple DMS/DMSP cycling genes co-occurred in the same bacterial genome in metagenome-assembled genomes from polar oceans. The microbial assemblages from the polar oceans correlated significantly with water depth rather than geographic distance, suggesting that the differences in habitats between surface and deep waters rather than dispersal limitation are the key factors shaping microbial assemblages involved in DMS/DMSP cycling in the CAO (Teng et al., 2021).

### 1.2.4 Contaminants

Increasingly, contaminants are recognized as integral components of Arctic Ocean biogeochemical cycles, responding sensitively to physical and ecological changes across the atmosphere–sea ice–ocean system. The central Arctic atmosphere, cryosphere, hydrosphere, and biosphere are heavily influenced by anthropogenic activities, with contaminants originating both locally and from long-range transport via rivers, ocean currents, and atmospheric pathways. The loss and thinning of sea ice, enhanced stratification, and shifts in primary productivity modify the transport, transformation, and bioavailability of both legacy and emerging contaminants (Hung et al., 2022; Ghiglione et al., n.d.). Processes such as ice melt, permafrost thaw, and coastal erosion remobilize mercury (Hg), lead (Pb), and persistent organic pollutants (POPs) previously sequestered in frozen reservoirs, increasing their fluxes to the ocean (Schaefer et al., 2020; Rogalla et al., 2025). Seasonal stratification regulates contaminant exchange between surface and deeper waters, while the unique vertical structure of the Arctic Ocean leads to elevated methylmercury concentrations at shallower depths compared to other oceans, enhancing uptake by phytoplankton and subsequent biomagnification (Heimburger et al., 2015; Schartup et al., 2020).

Microbial communities, which are key drivers of nutrient and carbon cycling, also mediate contaminant transformations, including Hg methylation and the degradation of organic pollutants, processes that are being reshaped by warming (Villar et al., 2020; Ghiglione et al., n.d.). The increasing burden of chemicals of emerging Arctic concern, such as per- and polyfluoroalkyl substances (PFAS) and micro- and nanoplastics, adds further complexity. These substances can act as contaminant carriers, alter microbial activities, and influence biogeochemical feedbacks (Kettner et al., 2019; Materic et al., 2022; Ghiglione et al., n.d.). Atmospheric pathways remain a key driver of long-range contaminant delivery and cycling, linking emissions at lower latitudes with Arctic deposition (Dastoor et al., 2022). Similarly, snow and sea-ice processes govern contaminant retention and release, affecting both oceanic inputs and ecosystem exposure (Huang et al., 2023; Vancoppenolle et al., n.d.). Collectively, these interactions highlight the need to integrate contaminant dynamics within the broader framework of Arctic Ocean stratification, sea-ice evolution, and ecosystem function. Future surveys need to generate high-resolution, year-round observational data to refine our understanding of contaminant sources, transport, and fate, and to assess the ecological and human health risks posed by continued emissions and climate change.

## 1.3 Biodiversity and trophic interactions

Fundamental knowledge gaps in biodiversity and connectivity of communities, from ecosystem to individual species levels, persist in the CAO. There are compelling examples of ecosystem perturbations under climate change, such as the northward expansion of temperate species (from microalgae to marine mammals) with increased Atlantic water transport (Fossheim et al., 2015; Paulsen et al., 2016; Neukermans et al., 2018; Oziel et al., 2020; Husson et al., 2024). In addition, many arctic organisms are highly vulnerable to warmer temperatures (Deb and Bailey, 2023), which are expected to continue to increase in the coming decades (Post et al., 2019). However, most ecological studies have focused on Arctic shelves and did not include the deep basins of the CAO. A first pelagic trawling study in the Nansen and Amundsen Basins, however, revealed the presence of sub-Arctic and Atlantic-derived species all the way to 87.5°N (Ingvaldsen et al., 2023). Documenting biodiversity and connectivity in the CAO, using both multi-omics and functional trait perspectives, is thus critical, especially during the transition periods in spring and fall, for predicting the impacts of climate change on the CAO pelagic ecosystem functioning.

### 1.3.1 Microbiomes

Photosynthetic primary producers in the Arctic comprise sympagic ice algae and drifting pelagic phytoplankton. Both microalgal communities are taxonomically diverse, but pelagic diatoms generally dominate both abundance and species richness in spring (Poulin et al., 2011; Crawford et al., 2018). Commonly observed bloom species are pennate diatoms in the genera *Fragilariopsis* and *Nitzschia* and centric diatoms in the genera *Chaetoceros* and *Thalassiosira*, as well as the large colony-forming centric diatom *Melosira arctica*. Blooms of the prymnesiophyte *Phaeocystis pouchetii* have also been observed, while the endemic alga *Micromonas polaris* is a common species following blooms and in oligotrophic open water regions (Smith et al., 1991; Ardyna and Arrigo, 2020; Hop et al., 2020; Lovejoy et al., 2007). With a longer open water season in some regions, a second phytoplankton bloom likely dominated by dinoflagellates (Freyria et al., 2021) can also occur in early autumn (Ardyna et al., 2014). However, models suggest that enhanced stratification in the deeper basins result in the suppression of the nitracline and deepening of the subsurface chlorophyll maximum (Steiner et al., 2016).

While some species appear to be constrained to either sympagic or pelagic life, the distinction between communities is not strict. Pelagic phytoplankton can be incorporated into sea ice and ice algae can contribute to the early summer phytoplankton bloom once released from the ice (see other articles in this special collection). Molecular and community studies on algal adaptation and survival in sea ice are needed (Freyria et al., 2024).

Polar microbial communities consist of distinct microbiomes, which differ from tropical and equatorial regions (Ibarbalz et al., 2019; Boulton et al., 2025). In general, species and gene richness decrease towards polar regions (Fuhrman et al., 2008; Salazar et al., 2019). The most drastic difference between the Arctic, including the CAO, and other oceans is that photoautotrophy is dominated by picoeukaryotes. Also, *Prochlorococcus* and *Synechococcus*, which dominate the smallest phytoplankton size class in most of the World Ocean, are absent from the CAO (Lovejoy et al., 2007; Li et al., 2009; Duncan et al., 2022). The extent of prokaryotic diversity is difficult to assess as drastic shifts in bacterial and archaeal communities have been described from low to high latitudes, with entire clades endemic to polar regions (Galand et al., 2010; Salazar et al., 2019; Priest et al., 2023), displaying up to 83% of unclassified prokaryotic genomes at the species level (Royo-Llonch et al., 2021). As for most high Arctic studies, knowledge of microbial communities mainly originates from surveys conducted over Arctic shelves during the ice-free season. How microbial communities change through the entire seasonal cycle in the CAO remains poorly studied (Wietz et al., 2021; 2024), but the contribution to the pelagic microbiome originating from sea ice could increase during the transitional periods in spring and fall (Priest et al., 2023). A late summer transect across the Nansen and Amundsen basins indicated regional differences in protist and plankton communities related to regionality in stratification, nutrients, and light conditions (Kohlbach et al., 2025). Models can also help forecasting how arctic microorganisms may react to environmental changes (Lennon et al., 2024).

Interestingly, the Arctic Ocean community interactome has shown the highest connectivity compared to other biomes, perhaps explained by a potentially higher prevalence of mixotrophic microbial eukaryotic plankton in the Arctic (e.g., mixotrophic flagellates and ciliates), or by more complex food web structures, albeit characterised by specific energy flow pathways dominated by a small number of species (Chaffron et al., 2021). For viruses in the Arctic Ocean, community diversity differs drastically from other biomes and is elevated for both DNA viruses (largely infecting prokaryotes; Gregory et al., 2019) and RNA viruses (largely infecting microbial eukaryotes; Dominguez-Huerta et al., 2022; Zayed et al., 2022). These findings suggest that the virus community structure follows that of their microbial hosts and that the polar regions represent biological hotspots for viral diversity. These global patterns of marine microbial diversity, together with the high impact of climate warming in the Arctic Ocean, make the region a reservoir of microbial diversity of planetary importance that faces an uncertain future.

Microbial eukaryotic species do not live in isolation but rather establish numerous cell-cell interactions that can significantly impact their fate and therefore role in the ecosystem (Vincent et al., 2021). For instance, symbiotic relationships between eukaryotic microalgae and closely associated bacteria within their ‘phycosphere’ expand the host’s metabolism (Amin et al., 2012) or ice-binding properties (Guo et al., 2017). Such associations thus likely play an important role in the CAO (Duncan et al., 2022), including for eukaryotic cell evolution (Coale et al., 2024) and global biogeochemical cycling (Tschitschko et al., 2024). Symbiotic relationships are of particular relevance for abundant phytoplankton in the Arctic, such as diatoms that interact with viruses, bacteria, chytrids (Kilias et al., 2020), or ciliates, but little has been reported on such relationships in polar environments.

Only recently, genome-resolved analyses based on metagenomes and metatranscriptomes have been able to explore the metabolic capabilities of specific bacterial and archaeal taxa (Royo-Llonch et al., 2021). Such analyses highlighted the prevalence of mixotrophy within bacteria and archaea and identified the active members of arctic microbial communities, facilitating the characterization of arctic sentinel bacterial and archaeal taxa. Mixotrophy in prokaryotes can take the form of photoheterotrophy in bacteria or archaea containing proteorhodopsin (Béjà et al., 2000), harbouring bacteriochlorophyll *a* (aerobic anoxygenic phototrophic; Kolber et al., 2000), or carrying out chemolithoautotrophic inorganic carbon fixation and heterotrophy (Alonso-Sáez et al., 2010).

### 1.3.2 Higher trophic levels

Mesopelagic sound scattering layers from zooplankton and fish have been observed across the CAO (Snoeijs-Leijonmalm et al., 2021). Four large species of copepods, *Calanus hyperboreus*, *C. glacialis*, *C. finmarchicus* and *Metridia longa*, represent 70–90% of the mesozooplankton abundance (Thibault et al., 1999 and references therein; Wold et al., 2025) and ensure secondary production, which makes them crucial mediators between primary production and higher trophic levels. In addition to ice amphipods, such as *Apherusa glacialis* (Kohlbach et al., 2016), armhook squid (Snoeijs-Leijonmalm et al., 2022), euphausiids, pelagic amphipods, and gelatinous zooplankton dominate the macrozooplankton assemblage in the Nansen Basin, while copepods, amphipods, euphausiids, chaetognaths and gelatinous zooplankton dominate in the Amundsen Basin (Ingvaldsen et al., 2023; Wold et al., 2025). In a future CAO, the abundance of gelatinous zooplankton could increase with climate change (Geoffroy et al., 2019; Lombard et al., 2024), which could redirect the carbon flows towards different links of the food web. However, more baseline data on the current assemblages and trophic interactions are required to assess impacts of future changes.

The abundance and diversity of fish is relatively low in the CAO but could increase with ongoing sea-ice reduction and increased advection of boreal species northward. As a precautionary measure, a 16-year moratorium on commercial fisheries, The International Agreement to Prevent Unregulated Fishing in the High Seas of the Central Arctic Ocean, has been ratified by the European Union and nine other countries in 2021 (Vylegzhanin et al., 2020). This agreement aims to further our understanding of an ecosystem that is emerging below a retreating sea-ice cover before evaluating the possibility for sustainable commercial fisheries. At present, Arctic cod (*Boreogadus saida*) and, to a lesser extent, its close relative ice cod (*Arctogadus saida*) strongly dominate the pelagic fish assemblage, both near the ice interface (David et al., 2016) and at mesopelagic depths (Ingvaldsen et al., 2023). However, whether the *Boreogadus* and *Arctogadus* stocks from the CAO reproduce locally or are advected from shelf areas is not known (David et al., 2016). The importance of sea ice for early life stages of the key forage species Arctic cod is also debated (Geoffroy et al., 2023), with contradictory information that they are ice-associated (David et al., 2016) or can benefit from a shorter ice season (Bouchard et al., 2017). Other pelagic fish captured in the CAO include Atlantic cod (*Gadus morhua*), Glacier lanternfish (*Benthosema glaciale*), Greenland halibut (*Reinhardtius hippoglossoides*), haddock (*Macrocephalus aeglefinus*), black seasnail (*Paraliparis bathybius*), and redfish (*Sebastes mentella*) (Snoeijs-Leijonmalm et al., 2022; Ingvaldsen et al., 2023).

For many animals, the Arctic is a well-stocked larder. They migrate long distances to take advantage of the high biomass and lipid-rich diet that originate from energy transferred through lipid-rich copepods that graze on algae (Falk-Petersen et al., 2009). Yet, most marine mammals observed in the CAO remain at the periphery, close to the ice edge (e.g., Lowry et al., 2019), where they feed on pelagic fish or benthic organisms on the shelf and slope (Bluhm and

Gradinger, 2008). In general, the effect of climate change and reduced sea-ice extent on Arctic and ice-associated mammals and birds is predominantly negative (Steiner et al., 2021).

### 1.3.3 Chronobiology

Chronobiology is the study of periodic phenomena in living organisms. Biological rhythms are found in almost all species and are believed to be evolutionary adaptations to cyclical variations of the environment. Thus, chronobiology examines the mechanisms of the biological clocks and their interactions with other physiological systems (Canadian Society for Chronobiology, 2025). At temperate latitudes, biological rhythms are highly attuned to circadian day-night cycles. In the CAO, the extreme light regime resulting from both the alternation of polar night and midnight sun periods and the heterogeneous sea-ice cover push the limits of how biological clocks interact with the environment (Cohen et al., 2020).

Oceanographic and biological observations show that phytoplankton adopt various strategies to adapt to changes in light throughout the day and seasons. Microalgae, namely diatoms, survive periods of darkness of up to 6 months (Kvernvik et al., 2018; Lacour et al., 2019; Morin et al., 2020; Sciandra et al., 2022; Joli et al., 2023), while preserving the ability to rapidly return to photosynthetic growth on exposure to even minimal light. During the polar night, when irradiance levels do not allow autotrophy, normally phototrophic prokaryotes and protists have been assumed to switch to heterotrophy to grow (i.e. mixotrophy), but with lower net productivity (Bruhn et al., 2024). Phytoplankton growth under sea ice after the polar night can start as early as February in Baffin Bay (Randelhoff et al., 2020), which is consistent with the lowest light requirements for photosynthesis calculated by Raven et al. (2010) and reported for ice algae by Hancke et al. (2018). More recently, improved sensors detected photosynthesis in the CAO as early as March and at lower light requirements than reported by Hancke et al. (2018) and Hoppe et al. (2024). Adaptation to different photoperiods could then contribute to community renewal and species succession along the seasons, as suggested by observations in temperate regions (Longobardi et al., 2022). Different photoacclimation strategies were documented on polar species depending on whether day length is shorter or longer (Guérin et al., 2024). Most archaea, bacteria and eukaryotes are strongly affected by high latitude seasonality, with evidence from cell counts, biomass distribution and community composition (Iversen and Seuthe, 2011; Ladau et al., 2013; Onda et al., 2017). Gene expression patterns are also affected. Notably, photosynthesis and light-harvesting functions show high seasonal variation in their expression (Wutkowska et al., 2023), from nearly undetectable in January to highly expressed in July.

Pelagic zooplankton and fish in the CAO conduct seasonal vertical migrations but, in contrast to temperate regions, high-amplitude diel vertical migrations are limited to short periods in spring and fall (Gjøsæter et al., 2017; Geoffroy et al., 2019; Bandara et al., 2021; Priou et al., 2021; Snoeijs-Leijonmalm et al., 2022). Diel vertical migration of zooplankton can also be driven by the moonlight cycle during the polar night (Last et al., 2016). Through vertical migrations, both zooplankton and fish contribute to carbon export through faecal pellets and respiration, with seasonal changes in their vertical distribution directly impacting the biological carbon pump. Increased under-ice irradiance in spring and fall due to less sea-ice and snow attenuation could impact the vertical distribution of pelagic organisms and keep them deeper for longer (Flores et al., 2023).

The mechanisms by which polar species adapt to different photoperiods are still poorly understood. However, understanding these processes is essential for accurately evaluating the effects of changes in snow and sea ice, which could alter the light environment and influence the entire photosynthetic community. In terrestrial organisms, circadian clocks and photoreceptors are at the heart of photoperiodic regulation (Song et al., 2014). The circadian clock components have been elucidated so far only in a few marine animals and microalgae (Häfker et al., 2022), but remain uncharacterized in polar species. Reports on terrestrial organisms emphasize the importance of natural genetic variation in circadian clocks and photoreceptors for adaptation over large areas (Millar, 2016). Recent metagenomic and metatranscriptomic studies in picoeukaryote green algae showed unexpected circadian component diversity across latitudes and a lack of functional clocks in tropical strains, underscoring the diversity of photoperiod adaptations in marine phytoplankton (Rigonato et al., 2025).

A diverse range of signaling photoreceptors, which detect light intensity and wavelength to control biological functions, have been found in the genomes of marine organisms and environmental genomic datasets (Jaubert et al., 2017; Coesel et al., 2021). These include blue light photoreceptors such as Cryptochrome photoreceptor, Aureochromes, Light-Oxygen-Voltage histidine kinase families, and Phytochrome photoreceptors, which are known for integrating light and temperature signals in plants. The diatom phytochrome, found at high latitudes but absent from equatorial regions (Duchêne et al., 2025), may play a role in adapting to different photoperiods. Marine algae and bacteria also contain green-absorbing rhodopsins, highly diverse light sensors with a retinal chromophore, involved in various light-driven energy and sensory processes (Rozenberg et al., 2021). Originally discovered in bacteria, light-driven proton pump rhodopsins, which are considered major contributors to solar energy capture in the sea, are also found in the genomes and transcriptomes of various marine microbes (Koh et al., 2010), including some Polaribacter lineages (González et al., 2008; Royo-Llonch et al., 2021) and Arctic native eukaryotes like dinoflagellates, stramenopiles, haptophytes, and cryptophytes (Vader et al., 2018). The xanthorhodopsin variant from the polar diatom *F. cylindrus* has been shown to influence biomass productivity under iron-limiting conditions (Strauss et al., 2023). The role of proteorhodopsin-based photoheterotrophy in the CAO remains unclear, but it is believed to be crucial for enhancing light absorption and supporting photoheterotrophy in low-light environments. More broadly, photoreceptors are expected to play an important role in restoring photosynthesis and growth capacity when returning to light and in entraining the circadian clock to daily and seasonal cycles.

### 1.3.4 Sea ice-pelagic interactions

The cryo-pelagic coupling is generally less studied than pelagic ecosystems because logistical difficulties prevent detailed and undisturbed sampling under the ice. However, sympagic fauna play a crucial role in transmitting carbon energy and high-quality organic material from the ice-water interface to the pelagic and benthic food webs (Amiraux et al., 2021; 2023). Sea-ice algae are key contributors to net primary production and could contribute up to 57% of total primary production in the Arctic (Gosselin et al., 1997). Ultimately, ice algae significantly support the entire marine food web, including marine mammals, providing over 50% of total carbon requirements throughout the year and across all Arctic Ocean regions (Kohlbach et al., 2016; Kunish et al., 2021; Koch et al., 2023). However, uncertainty in estimates of productivity by sea-ice algae are extremely high, due to their patchy distribution, technological challenges in sampling, and difficulties in obtaining in situ productivity estimates (Fernández- Méndez et al., 2014; Katlein et al., 2015). Modelling tools can provide insight into ice algal growth and distribution (Hayashida et al., 2021; Haddon et al., 2024). However, to date there are no methods comparable to remote sensing to monitor the large-scale occurrence of ice algal production, limiting our ability to quantify their contribution and understand their regulation.

On Arctic shelves, sea-ice reduction generally diminishes sympagic-benthic coupling due to the reduction of large aggregates sinking from the sea ice to the benthos. The longer open water season rather benefits pelagic organisms and promotes remineralization in the water column (Grebmeier et al., 2006; Zhulay et al., 2023). In the deep basins of the CAO, organic material can sink to depth and sequester carbon over long time scales. However, Lalande et al. (2014) compiled under-ice carbon flux measurements and suggested that, in the CAO, nutrient limitation would constrain carbon export in the deep basins despite reduced sea ice and increased light, in contrast to the more productive shelves. Additionally, new physico-chemical conditions in the sea ice and underlying water are expected to alter algal biomass and succession, export pathways, and degradation processes (Rontani et al., 2018; 2021; Burot et al., 2021), including both biotic (bacterial and zooplankton degradation) and abiotic mechanisms (photo-oxidation and autoxidation). Important questions thus remain for the CAO, including whether ice algal production increases with thinning sea ice, how its nutritional quality and role in ecosystem functioning might change, and whether there are sufficient nutrients to support increased pelagic phytoplankton production with the combined effect of sea-ice retreat and increased wind-driven mixing (e.g., Lincoln et al., 2016; Lund-Hansen et al., 2020).

The mobile heterogeneous sea ice of the CAO contributes to the dispersion of pelagic organisms. Ice cover contributes to the exporting of microbial clades from the surface to the deep sea in the Arctic and provides strong vertical microbial connectivity (Fadeev et al., 2021). Quiescent diatoms in older sea ice contribute to the algal community in leads and young Arctic sea ice (Kauko et al., 2018). Sea ice also transports early life stages of pelagic and benthic organisms, including ciliates, foraminifera, rotifers, platyhelminthes, harpacticoid copepods and nematodes

(Kiko et al., 2017, Marquardt et al., 2023), in addition to ice amphipods (Gulliksen and Lønne, 1991) and fish (David et al., 2016). Therefore, continuous sea-ice loss may decrease the horizontal and vertical export efficiency, with potential negative repercussions for Arctic deep-sea ecosystems and pelagic biodiversity (Fadeev et al., 2021), particularly for species with low dispersal capacities (Kiko et al., 2017).

## 2. Future research directions: scientific scope

Building on the literature review provided in Section 1, we here introduce a strategy to increase our understanding of the pelagic communities and processes in the CAO. We identify specific research questions and hypotheses from which to develop future scientific studies in the CAO. Specifically, utilising *Tara Polar Station*, we suggest an approach to address knowledge gaps related to seasonality in ocean physical conditions, biogeochemical fluxes, and biodiversity and trophic interactions across a complete 16-month transpolar drift during the first Tara Polaris expedition (Figure 2). Long-term research questions (>5 years) are addressed in another article of this special collection (Ardyna et al., n.d.).

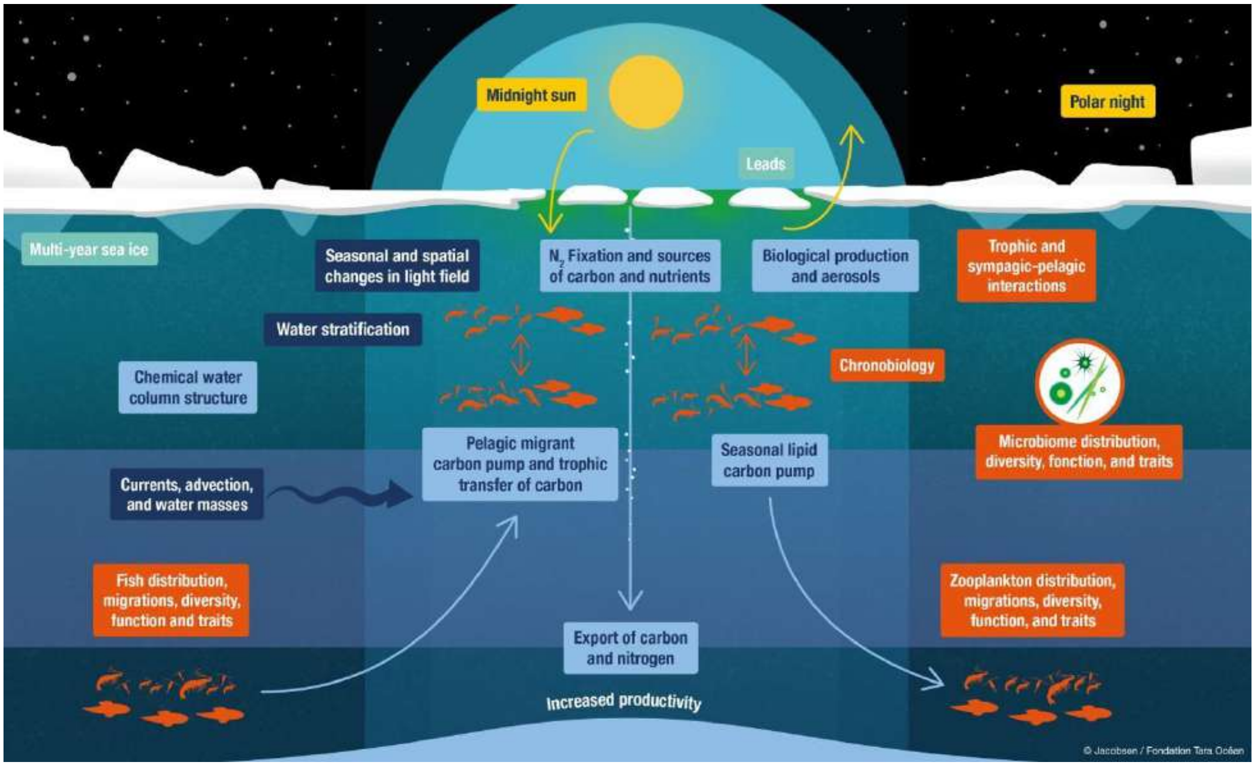

**Figure 2**. **Pelagic processes in the Central Arctic Ocean for which knowledge gaps persist.** Ocean physical conditions (dark blue), biogeochemical fluxes (light blue), and biodiversity and trophic interactions (orange). All processes listed here will be addressed during the Tara Polaris I expedition.

The overarching objective of the pelagic studies to be conducted during the Tara Polaris I expedition is to *assess how hydrographic and sea-ice conditions drive pelagic biogeochemical and ecological functioning in the CAO*. Specific research questions and hypotheses related to each pelagic component have been identified (Tables 1 and 2).

**Table 1**. Research questions and hypotheses related to the physical environment and biogeochemical fluxes in the Central Arctic Ocean (CAO).

**How are changes in upper ocean stratification, meltwater layers, and sea ice influencing pelagic habitats in the CAO?**

*Hypothesis*

Increased advection of Atlantic and Pacific waters contributes to sea-ice reduction and modifies all pelagic habitats.

**How important are sea-ice coverage and $N_2$ fixation in driving nutrient fluxes in the CAO?**

- How are changes in timing and intensity of sea-ice formation impacting nutrient fluxes?
- How are microorganisms driving $N_2$ fixation related to sea ice?

*Hypotheses*

- A reduced ice cover and longer productive season increase the role of regenerative and microbial food webs, reducing the role of $N_2$ fixation.
- Despite sea-ice reduction, stratification maintains low vertical fluxes of nutrients compared to other oceans.

**How are water mass distribution, upper ocean stratification, sea ice, lightscape, and biological community compositions impacting carbon export to depth and transfer across trophic levels?**

- What are the seasonal characteristics of the vertical matter flux, and how do they link to the physical environment, primary production, and the plankton communities?
- Which plankton are the most important carbon flux-predicting taxa, and how do they change seasonally?
- What is the role of carbon-dense fatty acids and glycerolipids in trophic networks?

*Hypotheses*

- Advection of warmer Atlantic water will have cascading impacts on the timing, quantity, and composition of the sinking organic matter from upper ocean layers.
- Viruses are as predictive of carbon flux in the CAO as they are for the global oceans.

- Temperature increase can lead to exhaustion of lipid storage earlier during the polar night and interrupt lipid-dependent trophic interactions in food webs.

**What are the roles of sea ice, pelagic-sympagic coupling, and biological production on sea spray aerosols in the CAO?**

- What climate-active molecules are produced biogenically?
- What are the origins and concentrations of marine organic aerosols in winter?
- What are the main sources of DMS, methanethiol, and DMSP, and how, when, and how much are transferred to the atmosphere?
- Which genes are expressed in relation to DMSP production?

*Hypotheses*

- Newly open water and lead formation in winter contribute significantly to aerosol production.
- Differences in habitats between surface and deep waters rather than dispersal limitation are the key factors shaping microbial assemblages involved in DMS/DMSP cycling.

**Table 2**. Research questions and hypotheses related to trophic interactions in the Central Arctic Ocean (CAO)

**How are biodiversity, functions, and traits of pelagic communities linked to physical oceanography and sea ice?**

- What are the seasonal shifts in community composition and function (from microbiome to fish)?
- What is the role of sea ice in maintaining biodiversity and connectivity?
- Is there more symbiosis in the CAO than elsewhere?
- How are symbiotic relationships changing over the seasons?
- Is advection of boreal species modifying energy pathways and trophic networks?
- Are local and advected populations competing?
- Are metazoans more vulnerable to virus and pathogen infections under warmer conditions?

- To what extent do viruses alter the microbiome via lysis, horizontal gene transfer, and metabolic reprogramming?
- How are metabolic interactions within microbial communities reacting to changes in salinity during formation and melting of sea ice?

*Hypotheses*

- Sea ice is a vector that contributes to increase significantly the diversity and abundance of the pelagic microbiome in spring and fall.
- Longer productive seasons do not mean more efficient energy transfer to the food webs.
- Local and advected populations coexist, with niche partitioning and distinct spatio-temporal distribution patterns.

**How do seasonal changes in sea ice and lightscape impact chronobiology?**

- How are local sea ice and lightscape conditions modifying the timing of the ice algal and phytoplankton blooms?
- Which components of the microbial communities are active during each season?
- What are the responses of polar organisms during different light and photoperiodic conditions- across seasons?
- What is the role of photoreceptors and endogenous clocks during extreme and variable light conditions?
- How do gene flows impact chronobiology and ontogeny across seasons?
- What is the lower light limit for autotrophic activity and what is the role of mixotrophy?
- How ubiquitous is photosynthetic biomass (pelagic and sympagic) during polar night and to what extent is the photosynthetic capacity down-regulated?
- Are changes in the timing of the blooms resulting in more mismatch events for zooplankton?

*Hypotheses*

- Changes in the photoperiod is a critical environmental cue that, thanks to photosensing and endogenous timekeepers, drives phenology and species succession of Arctic populations.
- Photoreceptors and circadian clock components establish biological rhythms across seasons and are targets of adaptation to different sea-ice and lightscape conditions.
- Weak-light photosensing and rhodopsin-based photoheterotrophy are implicated in restoring photosynthesis and growth at the end of the polar night.
- Mixotrophy is more prevalent in protists than prokaryotes.

- Seasonal gene flow between species and ecotypes via migration, horizontal gene transfer, or viral-mediated transfer shape circadian clock adaptation and regulation, thereby modulating seasonal responses in growth, development, and reproduction.
- The timing of Arctic copepodite production is tightly tied to the ice-algal bloom, while boreal copepodite species are synchronized with the phytoplankton bloom.
- Advected zooplankton from the south (e.g., *Calanus finmarchicus*) take advantage of the new phytoplankton blooms in the late productive season.
- Interactomes increase through metabolic exchanges during the polar night.

**Do fish reproduce in the Central Arctic Ocean, and how do they occupy the under-ice habitat?**

- Are fish laying eggs and hatching in the basins?
- Is the abundance of pelagic fish sufficient for sustainable commercial fisheries?
- How do fish and their zooplankton prey occupy the sympagic and pelagic habitats across seasons?

*Hypotheses*

- Fish, including Arctic cod, do not reproduce in the Central Arctic Ocean and are only advected from shelf areas.
- Fish abundance is too low for sustainable commercial fisheries.
- Only early life stages of fish occupy the sympagic zone.

# 3. Approach

Measurements and sampling will be partly conducted from the moonpool of *Tara Polar Station* and from instruments deployed from the ice (Figure 3). Observations from the moonpool will be concentrated on the hull-mounted thermosalinograph and echosounder, as well as sensors mounted on the conductivity-temperature-depth (CTD) rosette. Water samples will be collected with the rosette, and plankton samples will be collected with nets deployed from the moonpool.

Sampling from the ice outside the footprint of *Tara Polar Station* will include CTD sensors with acoustic Doppler current profilers and turbulence sensors, short- and long-term sediment trap deployments with underwater vision profilers, a self-contained high-frequency echosounder (acoustic zooplankton and fish profiler), and under-ice ichthyoplankton net deployments. Sampling frequency will vary from daily to weekly. Additional sampling with higher resolution will be conducted with an extended team during the crucial transition periods in spring and early fall (Tables S1–S3).

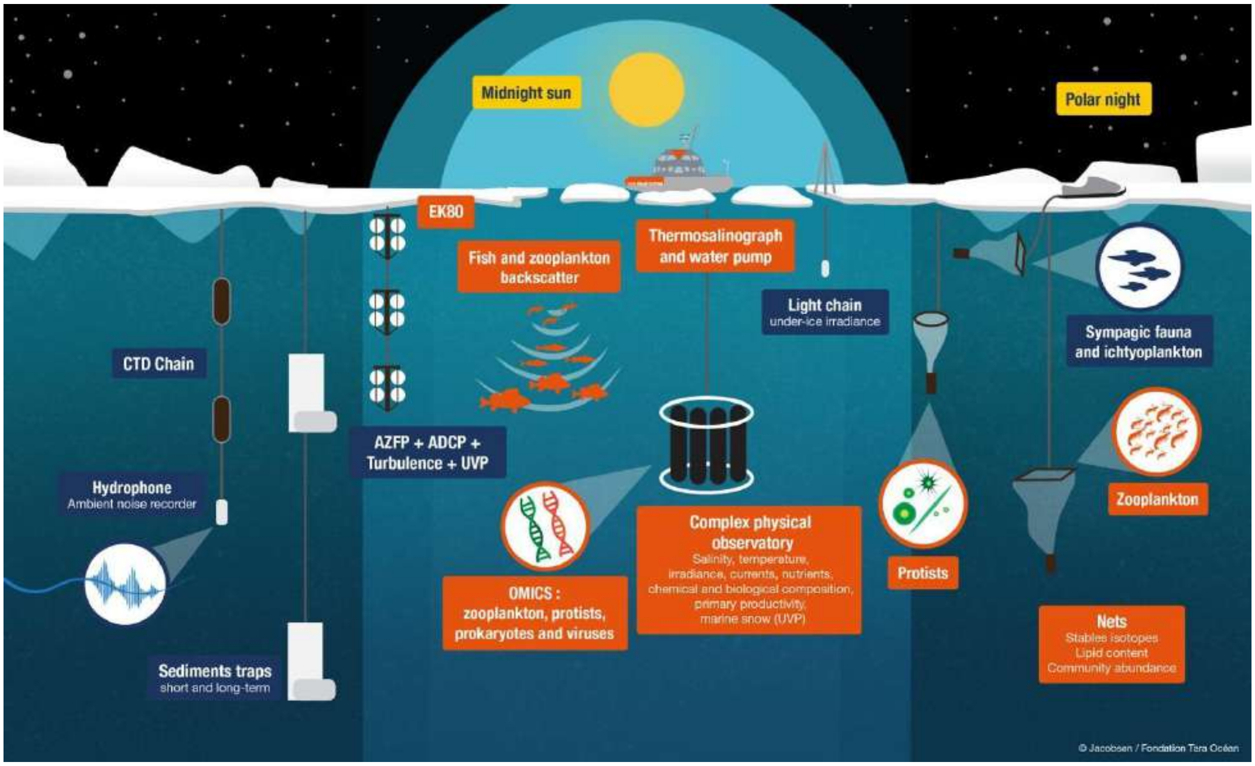

**Figure 3**. **Pelagic deployments from and around *Tara Polar Station* planned for the Tara Polaris I expedition**. Deployments from (orange) *Tara Polar Station* include the hull-mounted echosounder (EK80) and the rosette with conductivity-temperature-depth (CTD) sensors, underwater vision profiler (UVP), nets, and more. Surrounding deployments (blue) include an acoustic zooplankton and fish profiler (AZFP), acoustic Doppler current profilers (ADCPs), and more.

Our approach will combine direct measurements with laboratory analyses. Using state-of-the-art omics, culturing and imagery approaches, including long read sequencing metagenomics (Oxford Nanopore) and single cell genomics, will be strongly emphasized. An exploration of global community multi-omics (i.e., barcodes, genomics, transcriptomics, proteomics, and metabolomics) for pelagic plankton communities in the CAO will benefit from the integrative approach in microbial oceanography that was spearheaded by *Tara* Oceans (Alberti et al., 2017). Specific focuses will be on i) coupling single cell imaging and isolation with omics and ii) taking advantage of the possibility to monitor real-time changes in community composition via portable long read sequencing of specific genetic markers (e.g., 16S, 18S, cytochrome *c* oxidase subunit I) to monitor ecosystem responses in real time and to adapt analyses accordingly.

Ultimately, environmental measurements, biological observations and experiments need to be integrated to understand the functioning of the ecosystem and test future scenarios. We will synthesize and integrate observations and laboratory analyses using an ecosystem modelling approach to quantify the flow of energy through the CAO ecosystem (Eddy et al., 2021). At present, an ecosystem model for the CAO that integrates either the midnight sun or the polar night period has not been developed. We will use the Ecopath with Ecosim ecosystem modelling approach to represent energy flow from primary producers through the food web (Christensen and Walters, 2004). Ecopath with Ecosim is a mechanistic model based on mass balance of carbon or wet mass that has been applied to answer questions about ecosystem structure and function, fisheries impacts on ecosystems, and climate change impacts on ecosystems (Worm et al., 2009; Tittensor et al., 2018). Building on this framework, we will examine contaminant dynamics, focusing on mercury and its transformation into methylmercury, which biomagnifies in Arctic food webs (Gillies et al., 2024). Development of an ecosystem model for the CAO will allow for hypothesis testing about ecosystem structure and function. After model development, simulations can be run of scenarios of changing sea ice and primary production, with potential impacts on fisheries. The model can also help to prioritize future sampling efforts to address critical data gaps that may emerge or energy pathways and/or mechanisms that are highly uncertain or sensitive.

# 4. Connectivity with other themes

Undeniably, pelagic processes in the CAO relate directly to the atmosphere and sea-ice environment. Pelagic contaminants (Ghiglione et al., n.d.) are delivered via similar pathways as carbon and nutrients, including atmospheric deposition, sea-ice melt, and lateral transport (Schmale et al., 2025). The exchanges are reciprocal, with sea spray aerosols and biogenic trace gases transferred to the atmosphere from bubble bursting and outgassing, respectively, at sea surface. Atmospheric nitrogen can also be deposited in the form of nitrogen oxides, ammonia, and ammonium (Reay et al., 2008). Snow and ice thickness, including melt ponds, directly influence primary production, diel vertical migrations of pelagic organisms, and the retention or release of contaminants by modifying the underwater lightscape and ice–ocean interface. Colonisation from sea ice and interaction between the pelagic and sympagic ecosystems, including the contribution of ice algae to carbon export, further demonstrate the clear links between sympagic and pelagic habitats (Vancoppenolle et al., n.d.). Dust and other aerosols transported in the atmosphere to the Arctic from lower latitudes, e.g., from wildfires, can amplify phytoplankton blooms (Ardyna et al., 2022), ballast marine snow, and carry associated contaminants. Finally, pelagic studies to be conducted during Polaris I in 2026–2027 will provide baseline information on oceanography, biodiversity, carbon export, and contaminant distributions against which long-term changes can be assessed over the next 20 years (Ardyna et al., n.d.).

## 5. Foreseen outcomes

Using a combination of both traditional sampling methods and state-of-the-art omic and imagery approaches, the Tara Polaris expeditions provide an opportunity to understand seasonal changes in traits, functional roles, and trophic interaction of key species across multiple trophic levels, especially during the polar night, which remains poorly documented in the CAO. The drifts will also open a window on the transition periods between seasons, as their timing influences many pelagic processes that are difficult to catch by ship-based sampling. Participation in the Tara Polaris program will foster a truly interdisciplinary approach for pelagic studies during which a multitude of measurements are synchronised in space and time. In addition to providing new information on the physical environment, biogeochemical flux processes, biodiversity and active traits of all trophic levels across different basins of the CAO, this research program will ultimately allow for a better understanding of the role of the CAO in the global carbon and nutrient cycles. Finally, through new observations and modelling (e.g., Steiner et al., 2019), the Tara Polaris expeditions will provide new insights to inform the working group on commercial fisheries in the Arctic, especially regarding pelagic fish distribution and the occurrence, or absence, of fish reproducing and hatching in the CAO. They will also enhance a global understanding on the very unique biodiversity and processes at play in the CAO to support both the ambition of the actual implementation of the CAO Fisheries agreement and the future mitigation of broader impacts that could arise in a melted CAO.

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## Author contributions

Geoffroy, Reigstad and Polyakov wrote the initial outline of the manuscript. Babin, Bowler, Karp-Boss, and Troublé defined the project and structure of the article. All authors contributed to the writing of at least one section, reviewed  the final manuscript, and approved its submission.

## Competing interests

The authors declare no competing interests.

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