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### Overview of the MOSAiC expedition

Fong, Allison; Hoppe, Clara; Aberle, Nicole; Ashjian, Carin J.; Assmy, Philipp; Bai, Youcheng; Bakker, Dorothee C.E.; Bozzato, Deborah; Stefels, Jacqueline; van Leeuwe, Maria

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1 **Overview of the MOSAiC expedition: Ecosystem**

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33 **ABSTRACT**

34 An international and interdisciplinary sea ice drift expedition, the ‘The  
35 Multidisciplinary drifting Observatory for the Study of Arctic Climate’ (MOSAIC), was  
36 conducted from October 2019 to September 2020. The aim of MOSAiC was to study  
37 the interconnected physical, chemical and biological characteristics and processes  
38 from the atmosphere to the deep sea of the central Arctic system. The ecosystem  
39 team addressed current knowledge gaps and explored unknown biological properties  
40 over a complete seasonal cycle focusing on three major research areas: biodiversity,  
41 biogeochemical cycles and linkages to the environment. In addition to the coverage  
42 of core properties along a complete seasonal cycle, dedicated projects covered  
43 specific processes and habitats, or organisms on higher taxonomic or temporal  
44 resolution. A wide range of sampling approaches from sampling, sea ice coring, lead  
45 sampling to CTD rosette-based water sampling, plankton nets, ROVs and acoustic  
46 buoys was applied to address the science objectives. Further, a wide range of  
47 process-related measurements to address e.g. productivity patterns, seasonal  
48 migrations and diversity shifts were conducted both in situ and onboard *RV*  
49 *Polarstern*. This paper provides a detailed overview of the sampling approaches  
50 used to address the three main science objectives. It highlights the core sampling  
51 program and provides examples of two habitat- or process-specific projects. First  
52 results presented include high biological activities in winter time and the discovery of  
53 biological hotspots in underexplored habitats. The unique interconnectivity of the  
54 coordinated sampling efforts also revealed insights into cross-disciplinary  
55 interactions like the impact of biota on Arctic cloud formation. This overview further  
56 presents both lessons learned from conducting such a demanding field campaign  
57 and an outlook on spin-off projects to be conducted over the next years.

## 58 1. INTRODUCTION

59

### 60 1.1. Motivation

61 The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC)  
62 expedition provides unique scientific opportunities to fundamentally understand the  
63 interlinked physical, chemical, and biological systems in the central Arctic Ocean.  
64 The science program was shaped over nearly a decade and provides a foundation to  
65 create new and important knowledge regarding the functioning of the Arctic  
66 ecosystem within the context of the coupled Arctic climate system. Five closely  
67 cooperating science teams were formed to develop and execute the integrated  
68 science plan, focusing on atmosphere, sea ice, ocean, ecosystem and  
69 biogeochemistry. This paper provides an overview of the multiple facets of  
70 ecosystem-related research to highlight the interlinked research activities at multiple  
71 trophic levels in relation to the environment. Within the MOSAiC ecosystem team  
72 (termed *ECO team* in the following), a total of 25 institutions across 15 nations  
73 contributed to generating the field observations and measurements as part of the  
74 research program. Similar overviews are available for other MOSAiC research  
75 topics, currently for sea ice physics, physical oceanography, and various aspects of  
76 the atmosphere (Nicolaus et al., 2022b; Rabe et al., 2022; Shupe et al., 2022), while  
77 an overview on biogeochemical research not covered in this article is forthcoming.

78 The integrated ecological observations and knowledge generated by the ECO  
79 team was specifically aimed at understanding seasonally-resolved processes on  
80 different scales. These are critical for future predictions related to climate change  
81 impacts on the Arctic system, including alterations to ecosystem structure and  
82 functioning (Intergovernmental Panel on Climate Change (IPCC), 2023). While the  
83 research is ongoing, new projects are emerging based on insights, data and  
84 collaborations.

85 Section 1 of this paper outlines the main ecological research objectives  
86 addressed via the MOSAiC ecosystem research, followed in the second section by a  
87 more detailed description of the scientific approaches and methods being used. The  
88 coordinated ecological research also included biogeochemical variables (e.g.  
89 macronutrient concentrations, seawater and ice carbonate chemistry, dissolved  
90 organic carbon) due to their close links to ecosystem processes. Example data sets  
91 provided in section 3 demonstrate what to expect in the forthcoming peer-reviewed  
92 publications. Lastly, section 4 provides insights into “lessons learned” and challenges  
93 when planning such a yearlong expedition and point towards some of the expected  
94 impacts that could arise from the compiled knowledge over the years to come.

## 1.2. The Central Arctic Ecosystem and its links to the environment

The Arctic Ocean harbors unique and diverse biological communities in all available habitats: sea ice, snow, seawater, atmosphere, and sediments. Although the Arctic Ocean was once considered a relatively species-poor region with limited biological activity, research in recent decades has revised this paradigm (Bluhm et al., 2011). For example, it is now known that there is high biodiversity in all habitats and high biological activity year-round, including in the winter season (Berge et al., 2015; Hobbs et al., 2020). Furthermore, the Arctic ecosystem is not easily generalized due to the particularly high spatio-temporal variability in biological, chemical, and physical processes (Bluhm et al., 2015). Arctic marine ecosystems have regionally varying complex community structures and activity patterns, largely driven by differences in abiotic factors like water temperature, depth, salinity, light, inorganic nutrients, and sea ice properties (Balmonte et al., 2018; Bluhm et al., 2018, 2015; Clement Kinney et al., 2023; Ershova et al., 2021; Polyakov et al., 2020). Other efforts to explore ecosystem-level research in the central Arctic include SHEBA (e.g., Ashjian et al., 2003; Sherr et al., 2003), the Circumpolar Flaw Lead study (Barber et al., 2015), N-ICE2015 (Assmy et al., 2017; Granskog et al., 2018), the Synoptic Arctic Survey (Snoeijs-Leijonmalm et al., 2022), Tara Arctic (Ibarbalz et al., 2023; Royo-Llonch et al., 2021), and the Russian ice drift studies (Melnikov, 1980). Yet, despite these valuable efforts, the seasonal cycle in the central Arctic remains understudied because the region is difficult to access in winter with thick and extensive sea ice cover and harsh conditions for work in the field. Remote sensing of biological properties is also limited by the ice-covered, seasonally dark and often cloud-covered Arctic (Babin et al., 2015). New comprehensive time series data are further needed to construct numerical models and test mechanistic hypotheses within the context of Earth System Models (e.g., CMIP5 and CMIP6 for the IPCC AR5 and 6, respectively; IPCC, 2023). Representations of the marine ecosystem are lacking or less advanced than other components of the Earth system within large-scale models. Therefore, MOSAiC research is a critically needed evaluation of the current state of the Arctic marine ecosystem, required to adjust our understanding to new ecosystem components, and improve our understanding of basic biological processes to enhance predictions of future system status.

The central deep Arctic Ocean is divided into four abyssal plains separated by the Lomonosov, Gakkel, and Alpha ridges. Even so, the upper water column (~ 1000 m) is contiguous with two major ice drift and ocean circulation patterns: the Transpolar Drift (TPD) System and the Beaufort Gyre. The MOSAiC field campaign was established on a sea-ice floe at the Siberian edge of the Amundsen Basin (Figure 1), close to the origin of the TPD. During the campaign, the floe drifted in the TPD across the central Arctic towards Fram Strait. Details regarding the sea ice conditions during MOSAiC are provided by Krumpfen et al. (2020) and Nicolaus et al. (2022b). The hydrography in the central Arctic Ocean is characterized by a strong, permanent vertical salinity gradient (halocline). The upper surface mixed layer in the Amundsen Basin is characterized by low salinity and largely cold waters, being affected by river discharge, ice melt / freeze processes and Pacific inflow inside the

139 TPD (Rabe et al., 2022; Rudels and Carmack, 2022; Schulz et al., 2023a). South of  
140 the Amundsen Basin, as separated by the Gakkel ridge, surface waters of the  
141 Nansen Basin (Figure 1) are less influenced by the TPD. Here surface waters carry a  
142 stronger signal of Atlantic sourced water masses (Schulz et al., 2023b). Below the  
143 surface mixed layer lay warmer and more saline waters of Atlantic origin. The core of  
144 the Atlantic Water is warmest and saltiest north of Svalbard and close to the Barents-  
145 Kara Sea slope. In addition, modelling studies suggest that Atlantic water can advect  
146 biomass from phytoplankton blooms developed in open waters upstream under the  
147 sea ice into the eastern Arctic (In addition, modelling studies suggest that Atlantic  
148 water can advect biomass from phytoplankton blooms developed in open waters  
149 upstream under the sea ice into the eastern Arctic (Clement Kinney et al., 2023). It is  
150 modified once it enters the basins and circulates around the Arctic, mainly along the  
151 shelf slopes as a deep circulation loop (Rudels and Carmack, 2022), and over time,  
152 becomes colder, fresher, and is subducted deeper in the water column. The  
153 influence of these major water sources (i.e. TPD- vs Atlantic-influenced) on the  
154 central Arctic Ocean depends on circulation dynamics, which control the proportion,  
155 layering, and mixing of different source waters and their respective nutrient  
156 inventories. In surface waters of the central Arctic, nutrient concentrations are  
157 variable, but low relative to the Arctic shelf regions and deeper water masses (Bluhm  
158 et al., 2015; Randelhoff et al., 2020).

159 The strong vertical gradients in nutrient concentrations, and factors such as  
160 irradiance and other ocean physico-chemical parameters, structure the pelagic  
161 realm. Highly diverse communities of phytoplankton and sea ice algae (Poulin et al.,  
162 2011) contribute to the primary production in the central Arctic (Gosselin et al., 1997;  
163 Wiedmann et al., 2020). Both ice and pelagic algae have developed several  
164 successful strategies to overcome months without sufficient light for photosynthesis  
165 (Johnsen et al., 2020) and rapidly utilize the light returning after the Polar night  
166 (Hoppe, 2022; Kvernvik et al., 2018). Still, the overwintering strategies and modes of  
167 nutrition of several key groups and species remain poorly understood. Also, lower  
168 trophic herbivores and omnivores, like sea ice meiofauna (Ehrlich et al., 2020;  
169 Patrohay et al., 2022) or pelagic zooplankton (Ershova et al., 2021; Hop et al., 2021),  
170 have evolved life cycles and physiological adaptations that allow them to survive and  
171 successfully compete under these extreme conditions in the ice-covered central  
172 Arctic Ocean. The microbial network, involving diverse bacterial and archaeal  
173 communities (Boetius et al., 2015), drives the remineralization of organic matter in  
174 ice and water (Balmonte et al., 2018; Laurion et al., 1995; Wietz et al., 2021), which  
175 is a key process for supplying nutrients for algal growth. However, heterotrophic  
176 bacteria and algae can also compete for inorganic nitrogen resources (Fouilland et  
177 al., 2007).

178 Sea ice provides a unique habitat for diverse biota ranging from viruses to  
179 marine mammals and birds. It sustains its own food web driven by the productivity of  
180 sea ice algae, which has been reported to contribute up to 55% of total primary  
181 production in ice covered areas (Gosselin et al., 1997; Wiedmann et al., 2020). This  
182 production is channeled through ice-associated herbivores including copepods and

183 amphipods, and fish (specifically Arctic/polar cod, *Boreogadus saida*). In fact, trophic  
184 marker studies have demonstrated that a substantial part of the organic matter from  
185 sea ice algae culminates in apex species like ringed and bearded seals, or Arctic  
186 birds (e.g. Carlyle et al., 2022; Kohlbach et al., 2016; Kunisch et al., 2021). Diversity  
187 in sea ice systems is high, including viruses, bacteria, over 1000 species of  
188 unicellular algae and protozoa (Poulin et al., 2011), and about 100 associated  
189 metazoan taxa living in the ice brine channel system or the bottom of the ice (Bluhm  
190 et al., 2018 and references within). Summer melt ponds and low-salinity meltwater  
191 accumulated in leads and under the ice are examples of unique habitats that can  
192 form, disappear, and be replenished again multiple times over relatively short time  
193 scales during parts of a seasonal cycle (Smith et al., 2023). Similarly, also under ice  
194 productivity can be high in ice covered regions: a recent high resolution biophysical  
195 modeling study has found that 63% of the total primary production in the central  
196 Arctic occurs in waters with  $\geq 50\%$  sea ice cover, and 41% of the total primary  
197 production in areas with  $\geq 85\%$  cover (Clement Kinney et al., 2020). While  
198 considerable information exists for some regions, seasons, and taxa, the majority of  
199 biological components in the ice and ocean have not been identified and quantified  
200 through a complete annual cycle, particularly in the high Arctic. Filling this knowledge  
201 gap by investigating the full range of trophic components from bacteria to metazoans  
202 and exploring their unknown connections has been an ambitious and challenging  
203 goal of MOSAiC ecosystem research.

204 The activities of and interactions between different taxonomic, functional, and  
205 trophic groups change in space and time. In the Arctic, the strong seasonality and  
206 high interannual variability in environmental conditions such as temperature, nutrient  
207 availability, and irradiance drive the ecosystem state, phenology, and functions  
208 (Ardyna and Arrigo, 2020; Kosobokova and Hirche, 2000; Leu et al., 2015). Climate  
209 change has already substantially altered the Arctic marine system through increased  
210 fractions of first-year ice, stronger and warmer inflow from the Atlantic and Pacific  
211 Oceans, freshening of the surface waters, later sea ice formation and earlier onset of  
212 melt (Ingvaldsen et al., 2021; Polyakov et al., 2020) with associated biological  
213 system responses. For instance, under-ice phytoplankton blooms, algal infiltration  
214 communities at the snow-ice interface, and shifts in biodiversity due to borealization  
215 are increasingly observed (Ardyna et al., 2020; Fernández-Méndez et al., 2018;  
216 Ingvaldsen et al., 2021). Different sensitivities to climate change drivers by various  
217 ecosystem components may cause mismatches between trophic levels, such as  
218 algae blooms occurring earlier than the zooplankton life stages depending on them  
219 as food (Søreide et al., 2010). Also, the shift from a dominance of a multi-year ice  
220 (MYI) or second-year ice (SYI) to a first-year ice (FYI) regime will likely impact sea  
221 ice biota; however, evidence for change is patchy due to the limited availability of  
222 sufficiently long time-series data (Campbell et al., 2022). Comparisons between FYI  
223 and MYI diversity of sea ice protists indicate substantially lower (by 39%) diversity in  
224 FYI compared to MYI (Hop et al., 2020). The diversity and presence of sea ice  
225 meiofauna taxa has also decreased, including the nearly complete absence of  
226 flatworms and nematodes in recent studies (Ehrlich et al., 2020). MYI might also act

227 as a seed bank for sea ice algae and fauna for adjacent newly forming and growing  
228 FYI (Olsen et al., 2017). Sea ice biogeochemical cycles could be impacted, as FYI is  
229 typically saltier, with higher brine volume fractions creating more habitable space,  
230 and permeability resulting in higher fluxes within the ice, and increased nutrient  
231 supply (Tedesco et al., 2019). Beyond these structural and functional changes in the  
232 sea ice ecosystem itself, an alteration of the relative contribution of sea ice algae  
233 versus phytoplankton to overall annual primary production also has consequences  
234 for other ecosystem components, including through the often tight sympagic-pelagic  
235 and sympagic-benthic coupling processes (Rybakova et al., 2019; Wang et al., 2015;  
236 Wiedmann et al., 2020).

237 Biological processes in ice and seawater are not only relevant for the marine  
238 ecosystem, but impact the entire Arctic System. These processes are linked to  
239 physical processes in the atmosphere, ice, and ocean through various coupled  
240 processes and feedback mechanisms (Figure 2). Whereas the strong  
241 interdependence between the seasonally changing sea ice properties and ocean-  
242 atmosphere physics is widely recognized (Shupe et al., 2022), the tightly coupled  
243 interaction between the sea ice and the biology and chemistry of the ocean  
244 underneath is not well understood and, as a consequence, often neglected in  
245 numerical models. Biological activity affects the cycling and transformation of  
246 inorganic molecules and organic matter, and exerts strong controls on the cycling of  
247 climate-active gases such as carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide  
248 (N<sub>2</sub>O), and dimethyl sulfide (DMS) in the ocean and ice, as well as across the  
249 atmosphere-ice-ocean interfaces (Falkowski et al., 1998). For example, CO<sub>2</sub>  
250 concentrations are controlled by a range of chemical and biological processes  
251 including organic production, remineralization, gas exchange, and inorganic calcium  
252 carbonate precipitation within sea ice and dissolution in sea ice meltwater  
253 (Angelopoulos et al., 2022; Fransson et al., 2011; Miller et al., 2011; Nomura et al.,  
254 2018; Rysgaard et al., 2012, 2007) leading to seasonally varying air-sea-ice CO<sub>2</sub>  
255 exchange (e.g., Fransson et al., 2013; Mo et al., 2022). Seasonal sea ice melt  
256 decreases the partial pressure of CO<sub>2</sub> (pCO<sub>2</sub>) of the stratified Arctic surface waters  
257 through dilution, ikaite dissolution, and supporting phytoplankton blooms near the  
258 surface (Fransson et al., 2017). In recent years, enhanced sea ice melt has exposed  
259 these low pCO<sub>2</sub> surface waters to high atmospheric pCO<sub>2</sub> levels, thereby promoting  
260 CO<sub>2</sub> uptake from the atmosphere (Qi et al., 2022). Over longer periods of time, the  
261 enhanced CO<sub>2</sub> uptake decreases the surface waters' pH buffering capacity and  
262 promoting vulnerability to ocean acidification (Qi et al., 2022). At the same time, the  
263 associated decreased buffer capacity for CO<sub>2</sub> promotes ocean acidification. Storm  
264 events in different seasons can impact air-sea CO<sub>2</sub> exchange by altering the surface  
265 layer pCO<sub>2</sub> through wind-induced mixing with subsurface water and by creating  
266 leads where direct air-sea gas exchange can occur (Fransson et al., 2017). For sea  
267 ice itself, rising temperatures and younger sea ice promote an increase in the brine  
268 volume fraction, which in turn enhances the transfer of gases and substances across  
269 gas-water interfaces within sea ice and between the sea ice and atmosphere  
270 (Nomura et al., 2018).



271 Marine biological processes can impact climate relevant processes through  
272 linkages beyond production cycles of climate-relevant gases. Biogenic compounds  
273 that become aerosol particles can become airborne through the air-water interfaces  
274 of the Arctic and serve as cloud condensation nuclei (CCN) and ice nucleating  
275 particles (INPs) in the atmosphere, affecting clouds and the radiative balance of the  
276 system (Creamean et al., 2022). This, in turn, may feedback on productivity through  
277 modulation of the light available to fuel primary production (Kauko et al., 2017). High  
278 standing stocks of organisms in the sea ice and water column also change the  
279 energy budget and heat uptake of these components as they increase the absorption  
280 of shortwave radiation, thereby affecting the freeze and melt cycles of their own  
281 habitat (Taskjelle et al., 2017; Zeebe et al., 1996). Also, sea ice microstructural  
282 properties relevant for gas exchange can be modified through ice algal production of  
283 extracellular polymeric substances (Krembs et al., 2011).

284

### 285 **1.3. The mission of MOSAiC ecosystem studies**

286 The MOSAiC sampling program used existing knowledge on ecosystem-relevant  
287 processes and components to fill major gaps in current knowledge and explore so far  
288 unknown links. The integrated MOSAiC ecosystem research program combined  
289 year-round consistent measurements of specific core properties (Table 1) with  
290 embedded individual research projects (supplementary Table S1) and opportunistic  
291 sampling. The core program included an extensive suite of biological and chemical  
292 components sampled from the water column, and undeformed level FYI and SYI.  
293 The aim of the core measurement program was to provide a consistent and  
294 continuous backbone of key measurements over the drift period, which would allow  
295 to link different integrative and complementary process studies. The project-specific  
296 measurements either provided higher temporal or spatial resolution beyond the  
297 weekly sampling program, or focused on processes or habitats that were not part of  
298 the core parameter time-series. Our investigations relied on a combination of  
299 traditional tools and more recently developed technologies and cross-cutting  
300 approaches. This combined approach facilitated linkages to previous studies, while  
301 providing new knowledge into the seasonality of high Arctic biological and  
302 biogeochemical processes at unprecedented temporal resolution. The work of the  
303 ECO team is focused on three fundamental and essential research questions: 1)  
304 Which species are present in the Arctic Ocean (WHO, i.e. Biodiversity)? 2) How do  
305 fluxes of energy and matter flow through food webs and habitats (HOW, i.e.  
306 Ecosystem functioning)? And 3) Why do physical and chemical parameters exert  
307 control on species distribution and activities and vice versa (WHY, i.e. linkages with  
308 the environment)?

309 *Biodiversity:* The program was designed to capture a full seasonal sampling of  
310 ice and seawater habitats, including the dark season, with a wide range of  
311 established and innovative tools to achieve the most complete species inventory for  
312 ice and pelagic biota of the Central Arctic.

313 *Ecosystem functioning:* The flow of matter and energy in ice and seawater  
314 substantially changes with time, driven by the strong seasonality of environmental

315 variables (e.g., light and ice freeze-melt cycles) and organism life cycles. Therefore,  
316 it was essential to systematically determine organism abundances, biomass, and  
317 activity rates throughout the MOSAiC drift. The program aimed to quantify the  
318 seasonal fluctuations in algal and bacterial productivity, organismal physiologies  
319 (including metatranscriptomes) and life cycles, as well as grazing by micro- and  
320 mesozooplankton, diets of key species, and vertical particle fluxes.

321 *Linkages with environment:* The combined analysis of ecosystem  
322 characteristics with all available MOSAiC environmental data allows us to assess the  
323 importance of bottom-up (e.g., light, nutrients, sea ice characteristics) versus top-  
324 down (e.g., grazing, predation) controls on biological standing stocks and activities  
325 over a complete seasonal cycle. The program aimed to assess the contributions of  
326 ecosystem processes to the Arctic climate system, e.g., by driving gas fluxes across  
327 ice-ocean-atmosphere interfaces, or by affecting the heat budget of sea ice directly  
328 or through interactions with clouds.

329 These three major focal science areas were approached by considering both  
330 their interconnection as well as their relation to the overall MOSAiC science  
331 objectives. Therefore, a consistent, coordinated, and methodological framework  
332 linking individual measurements within the ECO team was developed. This included  
333 strong interdisciplinary partnership with the other MOSAiC teams, like co-located  
334 measurements of sea ice and water column properties to identify biologically-  
335 relevant linkages between the two habitats. The unique year-round access to the  
336 high Arctic environment was used to investigate poorly understood and  
337 undersampled habitats and seasons. For example, high heterotrophic biological  
338 activities and unique biodiversity patterns in winter were expected to precondition the  
339 biological response to the return of the light in spring. We furthermore expected that  
340 meta-genomic and -transcriptomic data can be used to identify unique physiological  
341 mechanisms that sustain survival of organisms and ecosystem services under polar  
342 seasonality. The program aimed to provide information relevant for understanding a  
343 wider Arctic system by determining the fluxes of climate-relevant compounds like  
344 CO<sub>2</sub>.

345

## 346 **2. APPROACH AND METHODS**

347 The MOSAiC expedition (PS122) onboard the German research icebreaker RV  
348 *Polarstern* (Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und  
349 Meeresforschung, 2017) was organized into 5 cruise legs (Figure 1). The field  
350 campaign began in late September 2019, and north of the Laptev Sea (Krumpen et  
351 al., 2020; Nicolaus et al., 2022b) the first Central Observatory ice camp was  
352 established, which was used on cruise legs 1-3 until May 11, 2020 (Figure 3). Team  
353 ECO observations began on 15 October 2019, and the full regular weekly sampling  
354 by Team ECO started 31 October 2019, which involved measurements and sampling  
355 from the ship and ice floe. Leg 1 ended in mid-December and Leg 2 continued on  
356 until the end of February 2020. Leg 3 extended beyond its originally planned date  
357 due to logistical constraints caused by the global COVID-19 pandemic, and ended in  
358 mid-May 2020, when RV *Polarstern* had to leave the first Central Observatory.

359 Following a logistically necessary break, leg 4 re-established and occupied a new  
360 Central Observatory (Figure 4) at a different location on the same ice floe from 20  
361 June 2020 until the floe disintegrated in the Fram Strait on 31 July 2020. Continued  
362 observations were made during leg 5, which involved establishing a new ice camp  
363 (Figure 5) located on a new ice floe near the North Pole in the second half of August.  
364 The MOSAiC ice drift study ended 20 September 2020, with ECO science operations  
365 continuing in the marginal ice zone during the transit back to shore. More details on  
366 the MOSAiC campaign, can be found in Nicolaus et al. (2022b), Rabe et al. (2022)  
367 and Shupe et al. (2022).

368

## 369 **2.1 Water column work program**

370 Sampling and measurements in the water column occurred at frequencies from daily,  
371 to weekly, with opportunistic, intensive observation sampling occurring a few times  
372 over the duration of the expedition, which involved sampling at hourly time scales for  
373 20-30 hr periods. Sampling frequency was partially based on feasibility and cost-  
374 benefit evaluation. For most ECO properties, the primary sampling mode was weekly  
375 sampling, matching the anticipated rates of change in ecological properties relative  
376 to anticipated achievability of the sampling program by a small onboard team. The  
377 daily sampling for chlorophyll *a* (Chl-*a*) and microbial community structure resolved  
378 day-to-day changes in fundamental microbial properties, which would be missed with  
379 only once-weekly sampling. Herein, major operations executed by Team ECO  
380 organized by sampling frequency are briefly described, while detailed method  
381 descriptions will be provided in later, targeted publications.

382

### 383 *2.1.1. Continuous measurements and daily sampling approaches*

384 A Membrane-Inlet Mass Spectrometer (MIMS) connected to the ship's flow-  
385 through seawater system allowed the continuous measurement of dissolved O<sub>2</sub>  
386 and Ar concentrations to calculate O<sub>2</sub>/Ar ratios and infer net community  
387 production (NCP) (Tortell, 2005; Ulfsbo et al., 2014), Rokitta et al. unpublished  
388 results). The depth of the seawater intake port was 11 m below sea level at the  
389 keel of the ship. Continuous measurements of these properties were only  
390 interrupted during 1) routine maintenance procedures by instrument operators, 2)  
391 ship maintenance of flow-through systems, and 3) when discrete bottle sample  
392 measurements were performed. Therefore, gaps in continuous data mostly  
393 collected during March to October 2020 are approximately 1) once daily for 1-2  
394 hrs, 2) 1-2 times monthly for 3-6 hrs, 3) 3-4 hrs weekly. Onboard, routine  
395 calibration with reference gasses allowed for tracking of instrument drift over the  
396 course of the expedition.

397 The AUTOMated Filtration for marine Microbes (AUTOFIM) instrument  
398 (iSiTEC GmbH, Bremerhaven, Germany) automatically collected, filtered, and  
399 preserved water samples for molecular genetic analyses (Metfies et al., 2016)  
400 from December 2019 to October 2020. It is permanently installed on RV  
401 *Polarstern* a few meters from the flow-through seawater intake system at 11 m at  
402 the bow of the ship. AUTOFIM collected samples on a daily basis, and in some

403 instances at even higher temporal resolution to resolve spatial changes along the  
404 drift path. Samples were analyzed for microbial community structure using 16S  
405 and 18S rRNA amplicon sequence-based approaches.

406 The fishcam, an *in situ* video system (FishCam, MacArtney Germany GmbH,  
407 Kiel, Germany), was deployed on average at 375 m water depth (range 369 - 376  
408 m) from 23 October to 7 November 2019 and at 213 m depth (range 194 - 215 m)  
409 from 12 December 2019 to 11 March 2020 through a hole in the ice,  
410 approximately 500 m away from the ship (see Snoeijs-Leijonmalm et al. (2022)  
411 for details). The system included two HD Internet Protocol cameras, one looking  
412 sideward and one looking downward, two Luxus High-Power LED light sources of  
413 6000 lm each, and a mini-CTD. The system was connected to a personal  
414 computer onboard, running PortVis (Serial Port and Video Stream Visualizer)  
415 software, version 2.1. Camera images were recorded in LED on:off cycles of  
416 5:55, 15:15, or 55:5 min. Fish were also caught via long lines and fishing rods  
417 deployed through the moon pool or holes in the ice (Snoeijs-Leijonmalm et al.,  
418 2022).

419 Further, a number of discrete water samples were manually collected at a  
420 daily or near-daily frequency over the duration of the expedition from a single tap  
421 of the ship's flow-through seawater system, which was also used for the MIMS  
422 measurements. This included separate samples for 1) Chl-a (except from mid-  
423 December to end of February), 2) 16S and 18S rRNA amplicon-based microbial  
424 community analyses (except from mid-December to end of February), and 3) ice  
425 nucleating particles (INPs, full timeseries).

426 To investigate downward flux, a long-term ice-tethered time-series sediment  
427 trap (McLane PARFLUX Mark 78H-21) with 21 sampling cups was deployed at  
428 200 m water depth, and tethered to SYI, located ~1000 m away from the ship  
429 (Figure 3). Sinking particles were automatically collected for two week intervals  
430 (15 or 16 days) from March to November and every month (29-31 days) from  
431 December to February. The sampling cups were filled with salt-saturated artificial  
432 seawater and HgCl<sub>2</sub> prior to deployment. The sediment trap was operational from  
433 26 October 2019 to 31 July 2020.

### 434 435 *2.1.2. Discrete sampling*

436 The primary sampling approach for the weekly ECO time-series of water column  
437 biological and chemical properties relied on the ship CTD rosette, a suite of  
438 plankton nets, and a number of small animal- and particle-imaging instruments  
439 with deployments over three consecutive days per calendar week. The CTD  
440 sensor packages, calibration methods, and post-processing are described in  
441 Rabe et al. (2022) and Tippenhauer et al. (2023a, 2023b). In brief, discrete  
442 biological samples were collected from 12-liter OTD bottles attached to the  
443 shipboard 24-bottle CTD rosette (PS-CTD). From November 2019 to May 2020,  
444 additional water column sampling was conducted via a 5-liter 12-Niskin bottle  
445 CTD rosette from Ocean City (OC-CTD; via a sheltered in-ice hole located 300  
446 meters from RV *Polarstern*; see Figure 3). In the period between mid-March and

447 mid-May, the PS-CTD was not operational due to the loss of the ice hole  
448 alongside the ship (see Rabe et al., 2022), so all water column ECO samples  
449 were collected at Ocean City. During this period, use of the OC-CTD led to a  
450 lower vertical depth resolution as the total water volume collectable in one cast  
451 was substantially less with the OC-CTD (60 L) versus the PS-CTD (288 L). All  
452 sampling events are listed in Table S4. Sampling order from the individual rosette  
453 bottles primarily followed WOCE procedures (Woods 1985), which prioritizes  
454 sampling of tracers, gases, and nutrients in time before the sampling of other  
455 properties. The sequence prioritized sampling of time-sensitive properties and  
456 limited contamination between parameters. Co-location of many properties  
457 across a smaller number of depth horizons was prioritized over higher vertical  
458 resolution of a few properties (Figure 6). Additionally, upper 200 m water column  
459 sampling was prioritized over full water column profiling to better resolve upper  
460 ocean interactions with sea ice and the atmosphere. Sample types requiring large  
461 volumes (e.g. POC/N, DNA and RNA) made it necessary to collect samples in  
462 additional casts following a primary full water column cast used to collect small  
463 volume ECO samples. Standard water depth horizons for biological properties  
464 were 2 m, 10 m, Chl-a fluorescence maximum (if present based on CTD  
465 fluorescence sensor profile) or 20 m, 50 m, 100 m, and the Atlantic Water core  
466 depth. The depth of the Atlantic Water core, detected as the local temperature  
467 maximum in each profile, varied significantly along the drift path, from  
468 approximately 100 m close to Fram Strait up to 400 m in the Amundsen Basin  
469 (Rabe et al., 2022; Schulz et al., 2023b). The depth-resolved sampling for Chl-a,  
470 nutrients, and total DNA collected from the PS-CTD and OC-CTD rosettes over  
471 the drift duration relative to a reference depth (400 m) and bottom depth highlight  
472 the focus of sample collections in the upper water column (Figure 7).

473 Samples collected by team ECO during the routine CTD rosette-based water  
474 column sampling included a wide range of standard variables such as inorganic  
475 nutrients (nitrate+nitrite, nitrite, silicic acid, phosphate and ammonium) as well as  
476 total dissolved nitrogen and total dissolved phosphorus, total dissolved inorganic  
477 carbon (DIC) and total alkalinity (TA), dissolved organic carbon (DOC), colored  
478 dissolved organic matter (CDOM), Chl-a, algal pigments, POC and PON  
479 concentrations as well as their isotopic composition, biogenic silica (bSi), total  
480 deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) for sequencing,  
481 taxonomic cell counts (via light microscopy), as well as cell abundance (via flow  
482 cytometry). Samples for primary and bacterial production, dissolved oxygen,  
483 DOM characterization after solid-phase extraction, and <sup>14</sup>C-DIC were collected at  
484 a lower temporal frequency and with larger gaps due to instrumentation failures.  
485 Additionally, several complementary samples were collected on a routine basis,  
486 such as those for measurements of O<sub>2</sub>/Ar ratios in discrete samples, INPs,  
487 neutral sugars, and <sup>15</sup>N-nitrate isotopes. Processing of preserved water or filters  
488 mainly occurred at the shore-based laboratories, with exceptions of onboard  
489 measurements of nutrients (Nov 2019 to May 2020), dissolved oxygen (March to  
490 Oct 2020), primary and bacterial production (Dec 2019 to May 2020), and a

491 subset of Chl-a samples (March to May 2020). Details on sample processing  
492 methods can be found in supplementary Table S2.

493 We aimed for all analyses for each variable to be done in the same laboratory  
494 and/or using the same instrument to decrease uncertainty due to laboratory or  
495 instrument calibration (see supplementary Table S2 for details). In cases where  
496 this was not possible (DIC/TA, DNA, RNA, POC/N), interlaboratory calibration  
497 samples were collected. In the case of nucleic acid samples, aliquots from the  
498 same extracted samples of the core time series were used for specific  
499 sequencing approaches in specialized labs (e.g. metabarcoding, genomics,  
500 sequencing of specific metazoan or functional primers). Details on the ECO multi-  
501 omics sampling program are given in Mock et al. (2022).

502 The seasonal life cycles and vertical distribution of zooplankton abundance  
503 and biomass were studied using imaging tools and plankton nets, deployed on  
504 the same or on two consecutive days during a calendar week. From November to  
505 March, a multinet midi (Hydrobios), three ring nets, the Underwater Vision Profiler  
506 (UVP) and the Light-frame On-sight Key Species Investigation system (LOKI)  
507 were deployed through a large hole in the ice alongside the RV *Polarstern*  
508 yielding an almost weekly resolution for many targeted parameters (Tables S4  
509 and S5). The multinet was equipped with five nets of 150  $\mu\text{m}$  mesh size to  
510 sample five discrete depth intervals between 2000 m and the ocean surface.  
511 Those samples were processed for zooplankton identification, abundance, and  
512 biomass at shore-based laboratories. The LOKI was deployed approximately  
513 weekly from 1000 m to the surface. In addition to high resolution images, the  
514 instrument obtained hydrographical parameters, e.g. depth, temperature, salinity,  
515 oxygen concentration and fluorescence. The UVP was mounted on the PS-CTD  
516 rosette and casts were conducted from various depths to the surface. Ring nets  
517 of 1 m<sup>2</sup> area (150- and 1000- $\mu\text{m}$  mesh) and 0.28 m<sup>2</sup> area (53- $\mu\text{m}$  mesh) were  
518 deployed to varying depths up to 2000 m, to collect zooplankton for analysis of  
519 taxonomy, energy content, biomarkers and gut DNA (Table S4). However, the  
520 hole next to the vessel could not be maintained in April and May due to strong ice  
521 dynamics. During that period, only a 150- $\mu\text{m}$  mesh Nansen net and the 53- $\mu\text{m}$   
522 mesh ring net could be deployed at the ice hole at OC. The Nansen net was  
523 equipped with an opening/closing device and was deployed in a series of single  
524 casts to the same depth intervals as sampled by the Multinet down to a maximum  
525 depth of 800 m. Additional ring net tows were conducted over the same depth  
526 intervals as used for the Multinet to collect animals for biochemical and genetic  
527 analyses and physiological rate measurements. In addition, during all seasons, a  
528 net was attached to the under-ice Remotely Operated Vehicle (ROV) 'Beast'  
529 (Katlein et al., 2017) for sampling 2-3 depth horizons: the ice-ocean interface, 10  
530 m, and 50 m under the ice.

531 To determine zooplankton abundance and biodiversity, usually complete  
532 samples from Multi-, Nansen-, and ROV net casts, as well as samples taken with  
533 the small ring net, were preserved with hexamethylenetetramine-buffered 4%  
534 formaldehyde, stored at room temperature and subsequently processed in

535 laboratories in Germany (AWI) and the US (University of Rhode Island). Live  
536 specimens for biochemical analyses and physiological rate measurements were  
537 sorted from ring net samples under a stereomicroscope onboard and determined  
538 to the lowest possible taxonomic level. Only when abundances were low, large  
539 organisms were also sorted from Multi- and ROV net samples allocated for  
540 taxonomic analyses to obtain sufficient individuals. Most of the live specimens  
541 (>10,000 individuals during the entire expedition) were deep-frozen, either  
542 individually or pooled in groups depending on size, for biochemical  
543 measurements (e.g., total lipid content, C/N ratio, energy content, lipid class  
544 composition, omega-3 fatty acids and level of animal sterols such as cholesterol  
545 and desmosterol,  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values), as well as for molecular studies of gut  
546 contents (copepods, amphipods) and for biodiversity (gelatinous zooplankton).  
547 Key mesozooplankton species (e.g., *Calanus glacialis*, *C. hyperboreus*, *Metridia*  
548 *longa*, *Themisto spp.*) were photographed prior to freezing to digitally measure  
549 certain characteristics, e.g., prosome length (copepods) and oil sac volume  
550 (*Calanus spp.*). For experimental work, individuals of key species were incubated  
551 for at least 24 h to determine egg production, grazing and respiration rates, and  
552 thereafter, deep-frozen to measure organic carbon and nitrogen contents to  
553 calculate biomass specific rates (see details in Case Study 1 below).

554

## 555 2.2. Sea ice coring and processing

556 The coordinated sea ice sampling by the MOSAiC teams ICE, ECO, and BGC was  
557 designed to study the seasonal changes of physical, biological, and geochemical  
558 properties of FYI and SYI in an interdisciplinary context (see also Angelopoulos et  
559 al., 2022; Nicolaus et al., 2022b; Evgenii Salganik et al., 2023a). During fall 2020,  
560 ice areas of undeformed FYI and SYI were identified that were safely accessible by  
561 snow machine, relatively homogeneous, and large enough to accommodate repeat  
562 visits, potentially for the entire drift. Most importantly, sites had to be located away  
563 from RV *Polarstern* to avoid and minimize the impacts of 1) artificial light pollution,  
564 2) regular on-ice foot traffic, 3) fumes and particulate material from the ship's  
565 exhaust system and snow machines, and 4) 'technically clean water' discharges  
566 from the ship.

567 Tents were set up at each ice coring site to protect newly extracted ice cores  
568 from adverse environmental conditions during sectioning, which could quickly alter  
569 ice and its physical, biological, and chemical properties. Cores for biological  
570 properties were collected using a 9-cm diameter KOVACS Mark II coring system.  
571 All coring events are summarized in supplementary Table S6. Most cores were  
572 sectioned and parsed into sterile Whirlpak bags directly inside the tent under low  
573 and/or red-light conditions to minimize artifacts. In some instances, complete cores  
574 were bagged directly in the field and processed on the ship, but in-field sectioning  
575 was prioritized when conditions were amenable. Ice core properties were derived  
576 from individual core sections or pooled core sections (Figure 8) depending on  
577 individual property requirements. Core section pools provided larger melt volumes  
578 and sub-sampling for multiple properties from single horizons. Small-scale



579 horizontal variability was reduced by pooling core sections, creating a more  
580 homogeneous master sample from which to derive related properties.

581 Six to eight full-length ice cores designated for ecological and biological  
582 properties were sectioned using similar sectioning schemes and parsed into new,  
583 sterile Whirlpak bags in the field. Cores were sectioned from the bottom into two 5  
584 cm sections, and then subsequently at 10 cm intervals from top and bottom,  
585 leaving a variable length middle section. Middle sections varied by several cms  
586 across 3-4 cores. Two pools (termed ECO1 and ECO2) using this procedure were  
587 generated and sub-sampled for a majority of biological properties from these two  
588 sets (Figure 8). In addition, the bottom 0-3 cm or 0-5 cm of sea ice from 3-4 cores  
589 were collected, sectioned, and pooled for individual sets of measurements of net  
590 primary productivity (NPP pool) and occasionally bacterial production (from NPP  
591 pool), as well as a pool for metatranscriptomes (RNA pool) in the field.  
592 Occasionally, full profiles of BP were measured from ECO1 pools.

593 A single core was collected for bulk salinity, oxygen isotopic composition, and  
594 inorganic nutrients. This core was sectioned in the field at 5 cm intervals from the  
595 top and bottom, leaving a variable-length middle section (Nicolaus et al., 2022b;  
596 Evgenii Salganik et al., 2023a). Individual cores were collected for DIC/TA and  
597 gypsum. These cores were bagged completely in the field and either sectioned and  
598 processed onboard, or stored frozen for future processing onshore.

599 Ice cores and sections were transported back to the ship in coolers, protecting  
600 cores from fluctuations in light and temperature. All ECO pool samples were melted  
601 after the addition of 0.2  $\mu\text{m}$  filtered surface seawater (typically 50 ml per 1 cm of  
602 core section) to reduce the impact of osmotic stress and cell loss (Campbell et al.,  
603 2019; Chamberlain et al., 2022; Garrison and Buck, 1986). Ice core sections in  
604 bags were melted in the dark at room temperature (18-22°C) and checked every 4-  
605 6 hours. Upon completed melt, which took 12 to 40 hours, bags were transferred  
606 into dark, temperature-controlled laboratory containers, and parsed for sub-  
607 sampling of biological properties under red light to minimize artificial light  
608 stimulation of biological activities. Samples for Chl-a, algal pigments (HPLC  
609 analyses), particulate organic carbon and nitrogen (POC/N), biogenic silica (BSi),  
610 taxonomic counts (light microscopy) and cell abundances (flow cytometry), INPs,  
611 and neutral sugars were typically collected from ECO1 pool (Figure 8). DNA  
612 samples were filtered through 0.2  $\mu\text{m}$  filters from ECO2 pool, and the filtrate was  
613 reserved for DOC and CDOM determinations. For each melted core section, melt  
614 volume factors were derived from added meltwater volume, which were used to  
615 derive to calculate melted ice volumes. Data are reported as per unit volume  
616 melted ice core as no correction for differences in density of ice and melt water  
617 were available.

618 Core sections for measurements of inorganic nutrients and nitrate isotopic  
619 composition were directly melted in the dark. Samples were pre-filtered through a  
620 0.45  $\mu\text{m}$  filter membrane and either analyzed directly onboard, or frozen for  
621 analysis onshore.

622 DIC/TA cores were sectioned onboard in a freezer laboratory (-15°C) at 10 cm  
623 intervals from top and bottom, with a variable length middle section. Sections were  
624 placed inside gas-tight bags and air was removed using a vacuum pump to avoid  
625 CO<sub>2</sub> exchange. These core sections were directly melted in the dark at 4°C, without  
626 addition of buffer or conservational solution. Melted samples were transferred into  
627 250 ml borosilicate bottles, augmented with 60 µL of saturated mercuric chloride  
628 (HgCl<sub>2</sub>) solution, and sealed with a septum cap to prevent CO<sub>2</sub> exchange with the  
629 atmosphere, then stored cool until post-cruise analyses in Japan (Nomura et al.,  
630 2020).

631

### 632 2.3. *Event- and process-driven sampling*

633 In addition to the time-series sampling of water column and sea ice, additional  
634 samples were collected either on an opportunistic or event- and process-driven  
635 basis (see supplementary Table S7 for an overview on all sampling events). For  
636 many of these sampling events, a smaller subset of parameters was sampled, with  
637 Chl-a and nutrients being the most regularly sampled properties.

638 Water samples for biological properties were collected from leads from the  
639 upper 1.5 m of water directly below newly forming ice or within the sea surface  
640 using peristaltic or hand pumps, from October thru early March, and again from  
641 early July till the end of the drift in September 2020. Newly-forming ice was  
642 collected by sieves, saws, buckets, and/or ice corers throughout the drift period,  
643 except during the continuous melt period between June and end of July 2020.  
644 Ecological properties of the seasonally occurring melt ponds were sampled only  
645 during August and September 2020. Similar to leads, both ice and water from  
646 within and under melt ponds were sampled. Ice from leads and melt ponds was  
647 processed without filtered seawater addition on most sampling instances, while  
648 filtered seawater was added to ice collected between March and May 2020, similar  
649 to the handling of time-series samples of sea ice. Sampling of various stages of ice  
650 formation and consolidation was conducted in the marginal ice zone (MIZ) during  
651 the transit back to shore at the end of the field campaign (September 2020). Here,  
652 a small number of biological properties from sea ice, direct under-ice waters, and  
653 the water column was collected from 3 stations. Ice types collected from these  
654 transit stations were primarily from ice floe edges, and were not consolidated. The  
655 distribution of biological properties in pressure ridges (deformed sea ice) was  
656 studied using ice coring of keel blocks and collecting water from ridge keel voids  
657 (seawater-filled voids between ice blocks in the ridge keel) and below ridges (see  
658 case study 1 for details).

659 Water directly from the ice-water interface below level ice was collected  
660 except for August to October 2020 for project-specific experimental work by  
661 deploying a hand pump through a borehole in the ice. Similarly, under-ice water  
662 from the upper 2 m of the water column was occasionally sampled via hand pumps  
663 in connection to the time-series common coring activities.

664 In addition to these more opportunistic sampling events, intensive observation  
665 periods (IOPs) were included to address research questions on timescales shorter

666 than the one-week interval of the time-series. For example, higher frequency  
667 temporal sampling (i.e., 4-10 time points in 20 - 30 hr periods) was conducted to  
668 observe potential diurnal dynamics as well as biological changes as a result of  
669 important events such as high wind periods, or the onset of freeze. In the beginning  
670 of December, a 24-hr IOP with zooplankton collections via both ROV nets and  
671 LOKI was conducted. In July, two 24 hr IOPs were conducted. The first one in the  
672 beginning of July consisted of 3 LOKI casts and six CTD rosette casts from the  
673 ship to cover diurnal patterns in the water column. A second IOP was conducted  
674 one week later during rapid melt to also investigate diurnal patterns in the direct  
675 under-ice habitat. In September 2020, two IOPs were conducted. In the beginning  
676 of September, a 36 hr intensive observation period in collaboration with team  
677 OCEAN was conducted to investigate the effects of a high wind event. Collections  
678 of under-ice waters occurred within a temporary on-ice laboratory, termed  
679 'EcoLodge,' established during the summer period. From June to mid-August 2020,  
680 EcoLodge1 was situated approximately 110 m from the ship on level ice, i.e. closer  
681 than other major sites but with an under-ice environment that was comparable in  
682 terms of ice thickness to the FYI coring site, and with surface waters less affected  
683 by disturbance from the ship compared to the PS-CTD rosette system. Here,  
684 under-ice water with brackish salinity (10-15) was sampled using a peristaltic  
685 pump, and filtered directly for Chl-a, POC/N, and microbial community structure  
686 analyses. Samples for inorganic nutrients and cell abundance were also collected.  
687 During August and September, the re-established EcoLodge2 was located  
688 approximately 300 m from the ship on level ice and approximately 15 m from a  
689 small, dynamic lead. Here, ice thickness was 125-130 cm. EcoLodge2 served as a  
690 hub for under-ice water sampling via a peristaltic pump at 14 timepoints over 36  
691 hrs. One week later a similar IOP at EcoLodge2 with 12 time points over 24 hrs  
692 was conducted to assess the impacts of the onset of freeze up.

693

#### 694 2.4. *Modifications to ship-based and on-ice routine operations for ecosystem* 695 *sampling*

696 A number of regular ship operations were considered as potential sources of  
697 contamination, for which we took precautions to limit their potential impact. For  
698 example, prior to MOSAiC, the ship would regularly release gray water  
699 continuously from an outlet located starboard side at 5 m depth. The location and  
700 constant release of gray water posed a potential risk to our sampling efforts as this  
701 location was within meters of the main PS-CTD sampling. While gray water is  
702 technically clean enough to drink, it could carry residual microbial, DOM and  
703 nutrient contamination. Also, there was a chance that the gray water, being less  
704 saline than ambient seawater, would float towards the surface and interact with the  
705 underside of the ice floe, potentially altering important characteristics of the ice and  
706 its development. Therefore, during MOSAiC, gray water was retained in the ship's  
707 hold for 2-3 days, had salt added back into the solution to increase its salinity, and  
708 pumped to 150 m depth from the ship's moon pool. Gray water pumping was  
709 conducted on days when no active water column sampling was conducted.

710 A monthly cleaning routine of the engine's boiler systems was one aspect of  
711 normal ship operations, which we had not been aware of in advance, that may  
712 have had an impact on our sampling efforts around the ship. Unlike gray water  
713 handling, this operation was not possible to adapt. While the dates of the monthly  
714 release and of measurements on and around those dates can be reviewed to  
715 identify any abnormalities, no direct measurements on possible contamination were  
716 done.

717 The ship also emitted continuous artificial light during the drift. Due to safety  
718 regulations, the use of light near the ship during our water column sampling could  
719 not be significantly reduced. When sampling of the PS-CTD rosette during times of  
720 natural darkness (i.e., the Polar night), we reduced the light contamination during  
721 sampling by combination of room shading and shaded containers for sample  
722 collections (Marangoni et al., 2022). Since the floe drifted in different directions and  
723 speeds compared to the water column below, the effects of light pollution on water  
724 column-based time series sampling of biogeochemical and many biological  
725 parameters can be expected to be minimal. However, e.g. physiological rates of  
726 sampled organisms as well as diel vertical migration pattern may have been  
727 impacted (Ludvigsen et al., 2018). Comparing migration patterns from different  
728 devices and locations (e.g., Acoustic Zooplankton Fish Profilers (AZFPs) located at  
729 different distances from the ship; Berge et al unpubl. results) may help to evaluate  
730 potential impacts. For sea ice, potential impacts of artificial light pollution on  
731 photosynthetic biomass and physiology are much larger, as small effects may  
732 accumulate over time. To account for this, the long-term sea ice time-series sites  
733 were established >1 km from the ship, where light pollution was not detectable. In  
734 the field, shaded tents were used for ice processing to reduce the effect of strong  
735 ambient light and temperature increases on ice samples during summertime. In the  
736 ship-board labs, samples were processed in temperature-controlled, red- and/or  
737 low-light conditions.

738 In addition to reducing artificial light pollution, we also aimed to reduce the  
739 introduction of nutrients and dissolved carbon to our sea ice samples through our  
740 melt process. For most ecological properties collected from sea ice, buffering the  
741 melt process with a known volume of saline solution can reduce the impact of  
742 osmotic stress and cell loss (Garrison and Buck, 1986). Therefore, we planned to  
743 make and add an artificial saline solution, consisting of distilled water and analytical  
744 grade sodium chloride, to our sea ice core sections. However, the onboard nutrient  
745 analyzer showed that the artificial saline solution contained about  $1 \mu\text{mol kg}^{-1}$   
746 nitrate+nitrite, which, at the start of the drift, was more than 10 times the ambient  
747 sea surface water nitrate+nitrite concentration. Therefore, despite our preparations,  
748 filtered surface seawater additions were used in the ice core melting process,  
749 which impacts some of our parameters such as DOC or INP.

750

## 751 *2.5. Integrative approaches across the Team ECO work program*

752 In the following sections, some of the approaches that were employed to gain a  
753 holistic understanding of seasonal variations in species composition and food web

754 dynamics are highlighted. Further, pathways are identified towards synthesizing  
755 different data sets to address overarching questions in how organisms, and  
756 physical properties and processes, control the flow of material and energy. In  
757 addition, the integrated multi-omics approaches are detailed in Mock et al. (2022).

### 758 2.5.1. *Imaging*

759 Imaging has become an essential tool in zooplankton studies in the last two  
760 decades (Giering et al., 2022; Lombard et al., 2019). The *in situ* cameras LOKI  
761 and UVP resolve plankton distributions at high vertical resolution (Kiko et al.,  
762 2017; Schulz et al., 2015). The main strength of the UVP is detecting marine  
763 snow, large-sized single-cell organisms (e.g., Rhizaria; Biard et al., 2016), and  
764 gelatinous zooplankton (Stemmann et al., 2008). The resolution of the images  
765 (1.5 megapixel, picture size depend on organisms size), however, is relatively low  
766 and often does not allow for species identification, especially of the dominant  
767 zooplankton group Copepoda. The LOKI concentrates the organisms with a net,  
768 leading to a flow-through chamber (Schulz et al., 2010). Jellyfish are often  
769 destroyed by the net, but LOKI captures Copepoda and other abundant taxa  
770 (e.g., Ostracoda, Chaetognatha) in high quality images, allowing the  
771 determination of copepod genera, species, and often developmental stages  
772 (Schmid et al., 2016). In addition to *in situ* imaging, preserved net samples  
773 collected during MOSAiC have been scanned using the laboratory on-desk  
774 system ZooScan and single object images have been extracted with the software  
775 application ZooProcess (Gorsky et al., 2010). To classify plankton organisms and  
776 share images among experts worldwide, all images taken by LOKI, UVP, and  
777 ZooScan have been uploaded to EcoTaxa. This is a web-based platform that is  
778 an established tool in classifying zooplankton organisms (Picheral et al., 2017) by  
779 applying simple machine learning techniques to predict taxonomic categories  
780 from image parameters. ZooProcess automatically provides size-related  
781 parameters of each object, and in combination with the taxonomic classification  
782 allows for estimating the zooplankton biomass from preserved net samples  
783 (Cornils et al., 2022) from the ice-ocean interface to the deep ocean (max. 2000  
784 m).

786 To study the occurrence of squid and fish in the CAO (Snoeijs-Leijonmalm et  
787 al., 2022), a continuously recording deep-sea video system (FishCam, MacArtney  
788 Germany GmbH, Kiel, Germany) was deployed at 200-400 m water depth. Part of  
789 the videos (180 hrs) were studied in real-time mode (Snoeijs-Leijonmalm et al.,  
790 2022) while an automated procedure for identifying periods of interest (i.e.,  
791 appearance of large organisms) in the extensive remainder of the video material  
792 is currently being developed. The combination of visual techniques, machine  
793 learning, and discrete sampling of animals and particulate matter can work  
794 together to address long-standing questions on the distributions and controls on  
795 these ecosystem components, where few such data are available.

### 798 2.5.2. *Biomarkers and carbon transformations*

799 Biomarkers are molecules (e.g., fatty acids, amino acids, sterols) or isotopic  
800 compositions of elements (e.g., carbon) that are somewhat source-specific to  
801 primary producers and are incorporated mostly unchanged into the tissue of their  
802 consumers. Tracing these biomarkers within the zooplankton and fish community  
803 is an essential tool in food web studies that address the relative importance of  
804 different sources of organic matter, the role of key Arctic primary producers, and  
805 the nutritional status of higher trophic levels (Kohlbach et al., 2022; Kunisch EH  
806 et al., 2021; Leu et al., 2020). Compared to previous studies, trophic marker  
807 analyses of the MOSAiC samples are improvements in two major aspects. First,  
808 a very broad range of trophic markers is being explored including fatty acids,  
809 sterols, highly-branched isoprenoids, bulk stable isotope compositions, fatty acid-  
810 specific stable isotope compositions, and essential amino acid specific stable  
811 isotope compositions (eAA-SIA) to balance the strengths and shortcomings of the  
812 individual approaches. Second, all the different trophic markers are measured  
813 from the same parent samples of homogenized animal tissue to allow a direct  
814 comparison of the results and to link the nutritional status of the animals to their  
815 food resources. Alongside the trophic marker approaches, animals were also  
816 collected for DNA sequencing of gut content. This approach provides a high  
817 taxonomic resolution of the ingested species and will further support the  
818 interpretation of the trophic marker data (Cleary, 2015).

819 One key question for studying Arctic marine food webs is to elucidate the role  
820 of ice algae as a source of organic matter. Trophic biomarkers determined across  
821 the food web including the particulate organic matter in surface waters and ice  
822 cores, as well as zooplankton, will help to identify seasonally varying food web  
823 interactions from primary producers to individual zooplankton species. These  
824 food web interactions will be linked to primary and bacterial production rates as  
825 well as vertical flux studies to enable more complete insights into the Arctic  
826 biological system.

### 827 2.5.3. *Ecological modeling*

829 A variety of bioinformatic and statistical modeling techniques aim at elucidating  
830 changes in composition and metabolic potential of Arctic marine microbial  
831 communities to improve our understanding of their influence on global  
832 biogeochemical cycles. The mechanistic understanding of ecological patterns is  
833 initially based on information from gene sequences combined with a descriptive  
834 approach of community members using co-occurrence networks that illustrate the  
835 occurrence of species at the same place and time (Popa et al., 2020). This graph  
836 approach, in which nodes are species and edges represent the correlation  
837 strength of their seasonality patterns, enables identification of i) central species  
838 (node hubs) and ii) species communities (network clusters) that are defined by  
839 several populations which are abundant in the same time period (Berry and  
840 Widder, 2014). The outcome of such studies allows us to investigate the  
841 seasonality of microbial community composition, activities, and functions. Further,

842 it enables the identification and definition of yet unknown ecological processes.  
843 These processes include the interaction of present species with each other and  
844 the environment. To understand this interaction in detail and especially to identify  
845 key parameters with strong impact on the Arctic ecology, it is necessary to  
846 combine all measured data into a modeling framework (Faust and Raes, 2012).  
847 For example, the co-occurrence information of photoautotrophic species with  
848 grazers isolated from the ice and water column combined with environmental  
849 parameters like water depth, temperature, daylight, etc., can be modeled using a  
850 Lotka-Volterra (LV) framework (Lotka, 1920; Volterra, 1927) with seasonal forcing  
851 approach (Sauve et al., 2020; Vandermeer, 1996). As a result, these models can  
852 be used to test several species interaction scenarios after varying the  
853 environmental parameters (Succurro and Ebenhöf, 2018). Furthermore,  
854 extending the LV by the dynamics of the available resources within the  
855 ecosystem (MacArthur consumer-resource models; Goldford et al., 2018;  
856 MacArthur, 1970) permits the development of a powerful, theoretical tool to  
857 explain the formation and occupation of ecological niches in dependence on  
858 external parameters with predictive capabilities for several future scenarios.

859 Microbial community structure and metabolic potential data are also being  
860 leveraged for biogeochemical predictions using machine learning. These  
861 techniques are well suited to complex, high dimensional, community structure  
862 data and can be used to extract patterns of succession and biogeochemical  
863 signatures from sequence information (Bowman, 2021). For example, the  
864 Random Forest (RF) regression model is effective at predicting biogeochemical  
865 signatures from amplicon sequence data, providing the potential for extending the  
866 data coverage of less frequently sampled key biogeochemical variables (Dutta et  
867 al., 2022). Additionally, potential microbial drivers for these processes can be  
868 identified by applying permutation to the RF models to assess the contributions of  
869 specific community members to model performance (DiMucci et al., 2018). Self-  
870 organizing maps (SOMs) are used to partition the microbial community into  
871 functionally distinct modes that can be applied as discrete variables in a variety of  
872 statistical (Bowman et al., 2017) and mechanistic (Kim et al., 2022) models. This  
873 discrete variable reflects key genetic traits of the microbial community, provides  
874 reasonable estimates of physiology, and allows for correlation between variability  
875 in taxonomic structure and function. Eco-physiological information can then be  
876 used to modify and better parameterize data-assimilative marine biogeochemical  
877 models for hypothesis testing and *in silico* experimentation – such as quantifying  
878 previously identified questions regarding microbial controls on ecological  
879 processes and assessing the sensitivity of carbon flow through the microbial food  
880 web to climate change scenarios.

881

882

### 883 **3. RESULTS**

884 The MOSAiC Ecosystem work program generated > 50,000 unique samples and  
885 activity measurements characterizing organisms and processes from viruses to fish.



886 We sampled 195 CTD rosette casts, 44 multi-nets, and 21 FYI and 20 SYI common  
887 ice coring events. We also collected samples from > 40 time points and sites during  
888 events and IOPs covering a complete Arctic seasonal cycle. A majority of sampling  
889 events were co-located in time and space or spanned long periods of continuous  
890 measurement and/or sample collection (Figure 6). Vertical distributions of most  
891 properties in the upper 400 m of the water column were resolved over the drift, but,  
892 when possible, also full water column depth profiles of core properties at once-  
893 weekly intervals were collected (Figures 7). The resolution of the year-long  
894 observations to map essential ecosystem properties differed depending on  
895 complexity of sampling and needed volumes, e.g. nutrient sampling could be  
896 executed more frequently and with greater vertical resolution (Figures 7A, B) than  
897 Chl-a (Figures 7C, D) and total DNA sampling (Figures 7E, F).

898

### 899 *3.1. Environmental controls over the drift period*

900 The MOSAiC expedition provided a wealth of environmental observations from ice,  
901 ocean, and atmosphere. These data provide a critical context to interpret the  
902 biological observations during the drift period. An evaluation of the meteorological  
903 conditions during the MOSAiC drift indicates that unusually cold temperatures  
904 relative to decades-long climatology occurred in November 2019 and March 2020  
905 (Rinke et al., 2021). Additionally, Rinke et al. (2021) also identified that the 2019-  
906 2020 drift year had more frequent storm events in spring, and that summer had a  
907 longer sea ice melt season, from late May to early September, approximately a  
908 month longer than the median from 1979 – 2019. Also, relative to climatology, the  
909 July and August 2020 period was the all-time warmest.

910 Throughout winter, RV *Polarstern* drifted in northerly directions, with the  
911 northernmost location at 88.6°N reached at the end of February 2020. Throughout  
912 spring and summer, the floe drifted in southerly directions, with periods of faster  
913 (mid-March to mid-April) and slower (mid-April to mid-July) drift speeds. The annual  
914 changes in air and water temperature, surface ocean salinity, incoming PAR  
915 (photosynthetically active radiation), and surface ocean nutrient concentrations along  
916 the drift track are illustrated in Figure 9. These properties are relevant examples of  
917 environmental changes over the annual cycle, which potentially influence ecosystem  
918 processes. Air temperatures at 2 m (Figure 9B) varied between values as low as -  
919 40°C in March and up to 6°C during the summer months (Cox et al., 2023; Shupe et  
920 al., 2022), driving sea ice freeze-up and melt (Nicolaus et al., 2022b; Evgenii  
921 Salganik et al., 2023a). Upper water column (10 m depth) temperatures (Figure 9C)  
922 were much less variable, with average daily temperatures near the freezing point  
923 during most of the year. Except for the transit periods, maximal temperatures of  
924 about -1.3°C were reached at the end of July. Surface ocean salinity (Figure 9C)  
925 reflected drift location (Rabe et al., 2022; Schulz et al., 2023b), with rather low levels  
926 during drift in the TPD in winter 2019/20. In February and March, TPD influence was  
927 gradually replaced by an increasing contribution of more saline Atlantic-influenced  
928 waters. After crossing the Gakkel Ridge in late March, average daily surface salinity  
929 remained high until reaching the ice edge in Fram Strait with stronger influence of

930 lower salinity waters from the polar waters of the East Greenland Current during July  
931 2020 (Schulz et al., 2023b).

932 Solar incoming irradiance (Figure 9D), shown as PAR, at the surface of the  
933 sea ice decreased quickly in fall and was below the detection limit from 8<sup>th</sup> of  
934 October until March 13<sup>th</sup>, marking the period of the polar night. Surface PAR  
935 increased as the solar elevation increased, and reached maximal values of >1300  
936  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$  from May to July (note the data gap between mid-July and mid-  
937 August). Thereafter, PAR decreased again, with daily maximum values below 200  
938  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$  at the end of the drift.

939 Nutrient concentrations in surface waters (upper 30 m) varied with water  
940 masses and through the seasons as the floe drifted (Figure 9E). As the floe drifted  
941 northwards, silicic acid and phosphate concentrations increased from November to  
942 January, from 1.5 to 4.7  $\mu\text{mol kg}^{-1}$  and 0.19 to 0.52  $\mu\text{mol kg}^{-1}$ , respectively. Nitrate  
943 remained mostly constant until February at  $1.05 \pm 0.37 \mu\text{mol kg}^{-1}$ . Silicic acid was  
944 nearly constant until early February, but phosphate concentrations dropped to 0.35  
945  $\mu\text{mol kg}^{-1}$  after early January. Trends diverged further thereafter as the drifted further  
946 southward, with nitrate and phosphate increasing to 4.7 and 0.42  $\mu\text{mol kg}^{-1}$ ,  
947 respectively, in May, but with silicic acid decreasing to 2.5  $\mu\text{mol kg}^{-1}$ . These opposing  
948 trends for the different nutrients likely reflect characteristics of the different water  
949 masses as distinguished using the temperature and salinity observations, with  
950 increasing influence of Atlantic waters containing relatively more nitrate and  
951 phosphate, and less silicic acid. When sampling at the floe resumed in the second  
952 half of June, maximum sea water nitrate, silicic acid, and phosphate concentrations  
953 of 6.0, 7.5, and 0.66  $\mu\text{mol kg}^{-1}$ , respectively, were measured. Towards the end of  
954 August though, as the drift continued southwestward, nitrate levels quickly  
955 decreased to  $<0.5 \mu\text{mol kg}^{-1}$ , but phosphate ( $\sim 0.58 \mu\text{mol kg}^{-1}$ ) and silicic acid (7.8  
956  $\mu\text{mol kg}^{-1}$ ) remained comparably high. This is consistent with polar waters of the East  
957 Greenland Current in Fram Strait, with more influence of silicic acid rich Pacific-  
958 derived waters and/or the Transpolar Drift. Thereafter, nutrient concentrations were  
959 variable between  $\sim 0.5 - 2 \mu\text{mol kg}^{-1}$  nitrate, 1-9  $\mu\text{mol kg}^{-1}$  silicic acid, and 0.2-0.7  
960  $\mu\text{mol kg}^{-1}$  phosphate over the summer and fall, as RV *Polarstern* repositioned on a  
961 new floe close to the North Pole.

### 962 963 3.2. Observed organisms and biodiversity

964 Despite the extreme seasonal variations in irradiance and other environmental  
965 drivers (Figure 9), the same functional and taxonomic groups (flagellates,  
966 dinoflagellates, and diatoms) were the major contributors to the sea ice protist  
967 assemblages in the different seasons (Figure 10), although there were seasonal  
968 changes in their relative and absolute abundances. Ongoing analyses based on  
969 taxonomic counts via light microscopy, cell abundances via flow cytometry, 18S-  
970 metabarcoding, and metagenomics (e.g., metagenome-assembled genomes of  
971 protists) (Table S2) will elucidate seasonal trends in ice and water column protists in  
972 unprecedented detail. Interestingly, the same groups and genera (e.g.,  
973 *Gymnodinium* spp., *Pseudo-nitzschia* spp., unidentified flagellates) contributed

974 significantly to the protist communities in both habitats over the fully annual cycle  
975 despite strong variations in environmental conditions (Figure 9). Importantly,  
976 significant contributions of both in-ice microalgae (e.g., *Nitzschia frigida*) as well as  
977 under-ice-attached microalgae such as *Melosira arctica* to the protist assemblages  
978 were observed. The latter species was so abundant in certain under-ice habitats that  
979 it formed its own microhabitat, which team ECO sampled in more detail.

980 A diverse and abundant zooplankton community (Figure 11) was observed  
981 over the entire MOSAiC campaign. Ongoing analyses focus on the interplay between  
982 seasonal (Figure 9) as well as regional patterns to decipher their seasonally resolved  
983 biogeography. The different methods employed to assess fish (Table S2) show that  
984 their stocks in the Central Arctic Ocean were very low. Still, Atlantic cod was found  
985 unexpectedly as far north as 85.9°N, along with lanternfish, armhook squid, and the  
986 Arctic endemic polar cod *Boreogadus saida* (Snoeijs-Leijonmalm et al., 2022).

987 Consequences of different community structures for food web dynamics and  
988 biogeochemistry are being addressed at each trophic level by different methods  
989 along the drift track and over the annual cycle. Initial analyses indicate active fecal  
990 pellet production and sinking in both winter and summer season (Figure 12).  
991 Analyses of carbon, nitrogen, algal pigments, and material types from sinking  
992 particulate organic matter collected in short-term and long-term sediment traps will  
993 enable estimates of time-integrated fluxes of material over specific periods of the  
994 winter and summer seasons below level- and ridged sea ice, and from along the drift  
995 track at 200 m depth. Additionally, ongoing analyses of particle size spectra from the  
996 LISST and UVP will allow higher resolution estimates of POM fluxes. Profiles from  
997 the UVP also generated images of particles > 100 micron in size and based on  
998 machine learning techniques, these images can be cataloged into particle-specific  
999 types, further informing changes in particle size abundances and distributions along  
1000 the drift.

1001

1002 *3.3. Potential impacts of diverse and ephemeral habitats on ecosystem processes*

1003 Consistent with previous research, our initial observations suggest that the presence  
1004 of meltwater layers represents a drastic change in the environmental and chemical  
1005 nature of the upper ocean, and elicit changes in biological properties and activities  
1006 (Smith et al., 2022). Stratification in the upper 1-2 m of the ocean creates a strong  
1007 gradient and boundaries which most organisms are unable to cross, thus creating  
1008 small microhabitats within each of these layers. These adjacent layers may support  
1009 potentially disparate activity rates, standing stocks, and biogeochemical fluxes  
1010 despite their close spatial relation. As such, meltwater layers may introduce habitat  
1011 structuring which greatly impacts ecosystem functioning. Furthermore, meltwater  
1012 layer formation affects the gas exchange process with the atmosphere, such that a  
1013 meltwater layer at the surface may lead to the equilibrium of gases with the  
1014 atmosphere, thereby reducing the gradient of concentration with the atmosphere and  
1015 the flux (Smith et al., 2023; von Appen et al., 2021). The mixing of meltwater and the  
1016 underlying seawater during summertime potentially produces water with low CO<sub>2</sub>  
1017 concentration.

1018 Based on opportunistic sampling, we could observe ecosystem processes in  
1019 various other sea ice types, resulting from different formation processes (Figure 13).  
1020 Summer season sampling in leads (Figure 13 A, B) and water close to the bottom of  
1021 the ice provided further insight into how ice dynamics and ephemeral phenomena  
1022 may alter biological responses over time-scales missed by our regular weekly  
1023 sampling. It indicated the formation of extremely high biomass layers on the  
1024 boundary between meltwater and seawater, with distinct composition and  
1025 biogeochemical characteristics (Smith et al., 2023). New ice formations, typically  
1026 ranging from 1 to 10 cm in thickness, and from loosely-formed crystals to  
1027 consolidated nilas ice, were sampled periodically throughout the drift, primarily from  
1028 leads near or across the central floe (Figure 13 C, D), with preliminary data indicating  
1029 higher organismal abundances and Chl-a concentrations than the surrounding  
1030 seawater (data not shown). Our series of samples of newly formed ice at different  
1031 time periods over the annual cycle will provide us with complementary data on how  
1032 environmental conditions (Figure 9) influence biological and ecological processes  
1033 during initial thermodynamic ice formation. Sea-ice ridges (Figure 13 G, H) were also  
1034 sampled periodically for biological properties and vertical export of material during  
1035 MOSAiC. This habitat featured seawater-filled voids with an accumulation and high  
1036 activity of microbial biota (see 3.5.1. for details).

1037

#### 1038 *3.4. Gaps in time-series measurements*

1039 Overall, the MOSAiC ecological field program captured a large number of co-located  
1040 properties at a regular frequency. However, with differing competencies across each  
1041 field team, and despite efforts to cross-train and build redundancy in skill sets, there  
1042 are some gaps in the ecosystem time-series measurements. While risk assessments  
1043 and prioritization schemes were devised, execution in the field was determined by  
1044 what could be achieved by the field team, and different factors at different times  
1045 contributed to variations in the continuity of specific data sets. Here, we outline the  
1046 key gaps in measurements, so that future users of MOSAiC ECO data sets can  
1047 easily identify when in the annual cycle certain measurements are not available.  
1048 Activity rate measurements, such as primary and bacterial production, only began in  
1049 January and late December 2019, respectively. Samples for water column DOM  
1050 characterization after solid-phase extraction are only available from April, May,  
1051 August and September 2020. <sup>15</sup>N-nitrate isotopes from sea ice were collected from  
1052 December 2019 onwards. RNA samples from bottom portions of sea ice are only  
1053 available from April 2020 onwards. There were no daily discrete sample collections  
1054 for Chl-a and microbial community structure from December 2019 to end of February  
1055 2020. Likewise, MIMS data from December 2019 to the beginning of March 2020 is  
1056 of substantially lower reliability compared to the rest of the drift.

1057

#### 1058 *3.5. Case Studies*

1059 In the following, two selected case studies are presented to illustrate the kinds of  
1060 results the ECO team is working on to address specific scientific questions. These  
1061 examples have been chosen because they demonstrate the interdisciplinary

1062 connections within MOSAiC, specifically regarding the role the geophysical  
1063 restructuring of ice had on habitat and with respect to how biological processes  
1064 contributed to elemental transformations and influenced central Arctic  
1065 biogeochemistry.

1066

### 1067 3.5.1. *Pressure ridges, unique habitats for ice-associated biota?*

1068 Level, undeformed sea ice provides a wide range of niches for ice-related  
1069 organisms, ranging from biota living in the brine channel systems within the ice to  
1070 under-ice flora and fauna living at the ice-water interface (Lund-Hansen et al., 2020).  
1071 These level sea-ice systems are studied in detail using the ICE and ECO time-series  
1072 (see also Nicolaus et al., 2022b). However, deformed sea ice in pressure ridges  
1073 adds substantial three-dimensional diversity in the available habitat space through  
1074 macroporosity (voids filled with seawater between ice blocks, often referred to as  
1075 rubble) in the ridge keels (Fig. 14). Ridge keels in the Arctic can reach substantial ice  
1076 drafts exceeding 20 m keel depth (Wadhams and Toberg, 2012), making ridge  
1077 coring or observations of voids within ridges exceptionally challenging. Sporadic  
1078 observations from previous Arctic studies suggested unique biological hotspots  
1079 associated with the water filled voids in unconsolidated keel rubble and ice block  
1080 surfaces within the pressure ridges (Fernández-Méndez et al., 2018; Gradinger et  
1081 al., 2010; Syvertsen, 1991). Truly understanding the ecological processes  
1082 associated to pressure ridges was the core of one dedicated research project (*Safe*  
1083 *HAVens for ice-associated flora and fauna in a seasonally ice-covered Arctic Ocean*  
1084 *(HAVOC)*), that across several MOSAiC teams performed detailed and  
1085 interdisciplinary observations of ridges (Figure 14) in the MOSAiC Central  
1086 Observatories (CO1 and CO2), with the aim to study the year-round physical and  
1087 biological characteristics of sea ice ridges.

1088 Relocations of *Polarstern* and sea-ice deformation events in the CO caused  
1089 disruptions in the time-series, resulting in four different pressure ridge sites being  
1090 studied during December 2019 and August 2020, with most HAVOC data being  
1091 collected between January and July 2020. Sampling included ice drilling, coring, and  
1092 ridge ice and void water sampling to study the temporal evolution of physical  
1093 characteristics of pressure ridges such as consolidation and melting (Lange et al.,  
1094 2023; E. Salganik et al., 2023; Evgenii Salganik et al., 2023b). Further, the ridges  
1095 were studied as habitats by examining the relationship between ridge structure and  
1096 biological properties (e.g., algal and microbial diversity in ice and void water), under-  
1097 ice hyperspectral imaging of algal biomass distribution along the pressure ridge  
1098 keels (Figure 15), and vertical particle flux in the proximity of the ridges using  
1099 sediment traps. The essential comparative measurements of level first-year and  
1100 second-year sea ice properties were provided by the ICE and ECO time-series data.

1101 Ongoing interdisciplinary discussions within the HAVOC team already showcased  
1102 significant science gains.

- 1103 • Ridge consolidation: Freeze and melt cycles within ridge rubble are more  
1104 complex than for level sea ice and significantly impact biological habitat  
1105 diversity and availability. For example, refreezing of snow-slush transported to

1106 ridge keel during dynamic event in early spring and surface meltwater in  
1107 summer led to rapid ridge consolidation with implications on the structure and  
1108 functioning of the microbial community and habitat loss for larger fauna in  
1109 ridge keels (Salganik et al., 2023ab, Lange et al., 2023).

- 1110 • Hyperspectral imaging of the bottom of level and ridged sea ice indicates  
1111 higher fractions of ice surfaces inhabited by algae in the ridged ice (Figure  
1112 16). For this purpose, a new Relative ice algal Biomass Index (RBI) was  
1113 developed (Lange et al., submitted).
- 1114 • Ice surfaces and water-filled voids within ridges contained distinct microalgal  
1115 and bacterial communities in contrast to level sea ice and seawater.
- 1116 • Changes in ice structure due to ridge formation, consolidation, and melting  
1117 have consequences on biological processes reaching beyond the physical  
1118 location of ridges, as frozen organic material can be released during ridge  
1119 formation in winter, and melt water can accumulate under level ice next to  
1120 ridges during summer, both affecting food availability and habitat for under-ice  
1121 fauna and flora, respectively.
- 1122 • A new sediment trap deployment methodology under the ridge revealed  
1123 unique ice-associated particle dynamics and vertical flux measurements,

1124 Upcoming analyses will focus on comprehensive characterizations of ridge  
1125 properties (e.g., using time-series data) and will be compared to those from level ice  
1126 and under-ice seawater samples. This will help to assess how ridge biodiversity and  
1127 ecosystem functioning are driven by this specific physical habitat (i.e. find answers to  
1128 the who, how and why?). In addition to the knowledge gain, the field experience with  
1129 sampling ridges provides an additional legacy product by HAVOC and MOSAiC  
1130 through methodological recommendations for future ridge studies.

1131

### 1132 3.3.2. Effects of seasonally changing mesozooplankton grazing on carbon and 1133 nitrogen cycling in the central Arctic

1134 Mesozooplankton are important transformers of organic carbon (C) and nitrogen (N),  
1135 converting phytoplankton and microzooplankton into larger-sized biomass (Figure  
1136 17). Mesozooplankton feeding activity and fecal pellet production regulates the  
1137 retention of organic C and N in the upper ocean mixed layer versus their transfer to  
1138 deeper waters. The Arctic mesozooplankton community is often dominated by  
1139 copepods of the genus *Calanus*, including two high-Arctic species (*C. hyperboreus*  
1140 and *C. glacialis*) as well as the advected North Atlantic indicator species *C.*  
1141 *finmarchicus* (Ershova et al., 2021). These species' life cycles differ in their  
1142 adaptations to Arctic seasonality. Until MOSAiC, there had been no year-round direct  
1143 measurements of *Calanus*-related food web dynamics in the Central Arctic. This is a  
1144 complex and challenging task, as evaluating the importance of mesozooplankton-  
1145 mediated transformations and fluxes requires quantification both of standing stocks  
1146 and of rate processes as well as understanding of zooplankton diet in relation to food  
1147 abundance. It was achievable within the MOSAiC framework only through the tight  
1148 collaboration of several science teams providing time series data of ocean and sea

1149 ice physical properties, food availability (microalgae and microzooplankton  
1150 abundances and standing stocks), as well as quantification of mesozooplankton  
1151 standing stocks and distributions. These time series data provide the necessary  
1152 context for a research project (Collaborative Research: The role of planktonic lower  
1153 trophic levels in carbon and nitrogen transformations in the Central Arctic, a MOSAiC  
1154 proposal) focused on direct measurements of the transformations of C and N by the  
1155 zooplankton using rate process measurements. The key overarching questions are:

- 1156 • How closely aligned are the life histories and productivity cycles of the  
1157 dominant secondary producers to the ice algal and/or phytoplankton blooms?
- 1158 • What are the transformations that occur (e.g., respiration, feeding,  
1159 growth/reproduction, fecal pellet export) and how do these vary throughout  
1160 the year?
- 1161 • How do food webs change seasonally? What is the importance of ice vs.  
1162 water column production to spring zooplankton productivity and how important  
1163 is the microbial food web during summer to growth and overwintering survival  
1164 of mesozooplankton?

1165 To answer these questions, project members participated in the MOSAiC  
1166 cruise from December 2019 to October 2020, with supportive measurements  
1167 provided by Team ECO before that period. The experimental studies included  
1168 measurements of respiration, egg production timing and rates, egg hatching success  
1169 of two dominant copepods (*C. glacialis* and *C. hyperboreus*), and grazing rates on  
1170 both phytoplankton and microzooplankton of dominant copepods (*C. glacialis*, *C.*  
1171 *hyperboreus*, *Metridia longa*). These experiments were augmented by DNA gut  
1172 content analyses. In spring and early summer, when the ice floe had drifted across  
1173 the Gakkel Ridge into the more Atlantic-influenced Nansen Basin, the Atlantic  
1174 indicator species *C. finmarchicus* also was included. Individual copepods were  
1175 photographed for identification and used for determination of carbon and nitrogen  
1176 content, and trophic marker characteristics.

1177 The final detailed analyses of the data sets will relate the experimental rate  
1178 measurements to their distribution as estimated from nets and the LOKI, prey type  
1179 and food concentrations will be augmented by gut DNA contents. The outcomes of  
1180 will provide critical data to all three ECO science questions ('who', 'how', and 'why'),  
1181 help determine the C and N flow through the planktonic ecosystem (Figure 17)  
1182 during different seasons over the course of the drift (Figure 9), and provide critical  
1183 information for integrative ecosystem modeling during the ECO synthesis phase.

1184  
1185

#### 1186 **4. STATUS, LINKAGES, PERSPECTIVES, AND SCIENTIFIC IMPACTS**

1187

##### 1188 *4.1. Current status and major achievements*

1189 MOSAiC ECO sample and data analyses are still ongoing, and new and exciting  
1190 data and scientific findings will continue to emerge over the next decade.

1191 Nevertheless, some major achievements can already be identified, some of which



1192 will lead to a step-change in understanding of the ‘whos, hows, and whys’ of the high  
1193 Arctic ecosystem:

- 1194 • The largest number of samples to assess biodiversity ever collected at such a  
1195 high spatiotemporal resolution in the central Arctic Ocean will allow for a  
1196 comprehensive ecosystem description from viruses to fish and squid for all  
1197 seasons along the drift.
- 1198 • Unprecedentedly high winter standing stocks and activity levels of organisms  
1199 in the largely unstudied high Arctic polar night were observed.
- 1200 • The biological property measurements in a diverse range of seasonally-  
1201 occurring habitats were conducted, including in-depth characterizations of  
1202 biological hotspots (e.g., pressure ridges, meltwater layers).
- 1203 • Rate measurements for key biological processes (e.g., primary and bacterial  
1204 production, zooplankton grazing and respiration rates) throughout all seasons  
1205 provide a crucial foundation for the parameterization of biogeochemical  
1206 models over complete annual cycles.
- 1207 • The largest sequencing effort for polar ecosystems will provide a benchmark  
1208 for biodiversity change (Mock et al., 2022).
- 1209 • Cross-cutting analysis have revealed that Central Arctic biological processes  
1210 can affect the atmospheric composition during the melt season (Yue et al.,  
1211 2023) and have the potential to impact cloud processes (Creamean et al.,  
1212 2022).
- 1213 • MOSAiC ECO supported a large and diverse suite of projects covering either  
1214 a particular season or environment, or a full year, which will enable us to  
1215 obtain a wealth of knowledge on specific aspects of species biology and  
1216 ecology, and a better understanding of seasonal changes in these aspects.

1217  
1218 The co-located, in-depth characterization of environmental conditions driven by the  
1219 interdisciplinary character of MOSAiC allows to link biological observations to abiotic  
1220 driving factors (e.g., for fast transition periods that are hard to predict in terms of  
1221 timing), and in turn to determine when biological interactions are likely the main  
1222 driving force of ecosystem dynamics (Behrenfeld, 2010). As one example, nutrients,  
1223 representing one major controlling factor of Arctic productivity (Randelhoff et al.,  
1224 2020; Tremblay et al., 2015), indicate strong spatial differences across water masses  
1225 along the drift (Schulz et al., 2023b) that dominate variability due to potential signals  
1226 of seasonal uptake and limitation dynamics. The presence of surface ocean nitrate  
1227 concentrations around 2  $\mu\text{M}$  at the end of summer and into fall at  $>84^\circ\text{N}$  warrant  
1228 close inspection concerning the dynamics supplying nutrients to the sunlit layers,  
1229 potentially indicating iron limitation of primary production in Nansen Basin  
1230 (Rijkenberg et al., 2018). This could lead to a paradigm shift in our understanding of  
1231 Arctic primary production (Ardyna and Arrigo, 2020; Tremblay et al., 2015;  
1232 Wassmann and Reigstad, 2011). The large imprint that water masses had on  
1233 important environmental drivers such as nutrient concentrations illustrate that many  
1234 statements about the Arctic cannot be generalized but need to be region-specific.

1235 The interdisciplinary approach of MOSAiC will also allow us to better  
1236 parameterize and map cross-disciplinary linkages that may not be obvious a-priori.  
1237 For example, sea ice algae might change the energy absorption of ice and ocean  
1238 (Manizza et al., 2013), thereby affecting Arctic heat budgets along the atmosphere-  
1239 ice-ocean continuum (Shupe et al., 2022). New tools such as hyperspectral imagers  
1240 deployed on remotely operated vehicles (see case study 1) may enable  
1241 comprehensive mapping of ice algae potentially facilitating improved quantitative  
1242 evaluation of biological effects on ice transmission and heat budgets.

1243 Comprehensive studies of a number of periodically-occurring habitats found  
1244 them to be biological hotspots, including meltwater-influenced systems and pressure  
1245 ridges. Unique habitat-specific processes may provide major additions to fluxes of  
1246 energy and matter; thus, their quantification is needed for a complete view on high  
1247 Arctic biogeochemistry and ecology. Our data will allow us to evaluate the relative  
1248 role of these short-lived hotspot habitats compared to the perennial habitats, such as  
1249 level sea ice. Several of these habitats develop during the summer season (e.g.,  
1250 melt ponds, meltwater layers, unconsolidated water-filled voids in pressure ridges),  
1251 but later in the year may have residual structuring of habitats, which affect  
1252 organismal life strategies during different periods of the annual cycle. While these  
1253 features primarily form during the summertime, their altered states can persist into  
1254 later seasons and even the following year. For example, remnants or “fingerprints” of  
1255 these hotspots may be identifiable, such as refrozen melt ponds or refrozen  
1256 (consolidated) voids in ridges, and characterized during the winter season as  
1257 overwintering habitats for a range of Arctic organisms.

1258

#### 1259 *4.2. Challenges and Lessons Learned*

1260 MOSAiC observations and samples were conducted year-round, often in challenging  
1261 conditions. This required frequently adapting standard ship and on-ice operations  
1262 and team operations as well as adjusting the science objectives. Given the major  
1263 focus of MOSAiC on interactions between atmosphere, sea ice, and ocean, we  
1264 intentionally limited our work program to focus on the ecological and biogeochemical  
1265 components that are relevant for the sea ice and upper ocean, excluding the deepest  
1266 water layers and the benthos. Additionally, in an effort to focus on measurements  
1267 that would elucidate biological feedbacks in the Arctic climate system, we did not  
1268 include observations of megafauna, such as sea birds and mammals, although they  
1269 provide important ecosystem services and are highly impacted by climate change  
1270 (Hamilton et al., 2022).

1271 Some unique challenges we addressed in the preparation phase were related  
1272 to potential impacts of the anticipated long-term drift on the scientific data collection.  
1273 Key adaptations were made in conjunction with other science teams and the ship’s  
1274 crew (see section 2.4 for details). Additionally, during the preparation phase, we took  
1275 steps to train and prepare field personnel to execute a variety of tasks and protocols  
1276 encompassing a broader range of activities than they would have been responsible  
1277 for within an expedition of narrower scope than MOSAiC. Building competencies and  
1278 redundancies in the skill sets of field personnel was important to realizing the diverse

1279 work program. However, it was not always possible, and in some instances gaps in  
1280 our time-series measurements exist because it was not feasible for the field team to  
1281 accomplish all the tasks (see Section 3.4). Additional modifications were necessary  
1282 onboard based on expected irregular disturbances (e.g., storms, ice break-up) as  
1283 well as unexpected events (e.g., the COVID-19 outbreak). In the future, improved  
1284 prioritization of sample collections, development of more semi-automated sampling  
1285 and processing devices, and increased training on unfamiliar data logging routines  
1286 will strengthen execution of complex work programs. Our experience with MOSAiC  
1287 ECO work will also provide us with the opportunity to better determine which suites  
1288 of properties are most needed for addressing future questions and objectives related  
1289 to high Arctic ecosystem changes.

1290 Our data analyses will need to disentangle temporal versus spatial aspects to  
1291 observed changes in biological properties and ecological processes over the course  
1292 of the drift. This can be nicely illustrated by the development of nitrate concentrations  
1293 over the course of the expedition (Figure 9E). Even though nitrate is considered one  
1294 of the two major limiting factors for Arctic primary production (Tremblay et al., 2015),  
1295 its concentrations increased over the main microalgal growing season, i.e., from  
1296 March to July. While this seems counterintuitive at first, it can be explained by the  
1297 drift of the ice floe into areas with increasingly larger influence by nitrate-rich Atlantic  
1298 water masses (Rabe et al., 2022; Schulz et al., 2023b). Such water mass effects  
1299 also influence other measured parameters such as DOM characteristics (Gonçalves-  
1300 Araujo et al., 2016, Kong et al., under review), and potentially the presence or  
1301 absence of certain organismal groups and species (Kaiser et al., 2022). Also, the  
1302 faster-than-expected drift speed of the main MOSAiC floe resulted in earlier arrival  
1303 into Atlantic inflow-influenced waters and proximity to the ice edge, resulting in  
1304 significant deformation and instability of the first Central Observatory. Therefore,  
1305 after the logistical departure in May 2020, the ice camp had to be relocated to a  
1306 different part of the original ice floe and a second Central Observatory was  
1307 established. While these aspects are part of the nature of a drift campaign, their  
1308 influence on how one can interpret our observations is central to our understanding  
1309 of ecosystem processes during the MOSAiC field year.

1310

#### 1311 *4.3. Ecosystem research in the context of Arctic System Science*

1312 MOSAiC was designed to improve our understanding of the governing principles of  
1313 the Arctic climate system and thus can be used in an earth system science  
1314 approach. This is particularly urgent as the Arctic is warming four times faster than  
1315 the global average (Rantanen et al., 2022). Developing baseline knowledge on the  
1316 'who', 'how', and 'why' of the high Arctic was the foundational principle of the  
1317 ecosystem science program, and the data already demonstrate multiple connections  
1318 within the ecosystem compartments and to the whole Arctic system including the  
1319 presence of INPs of marine biological origin (Creamean et al., 2022). The Arctic  
1320 Ocean can be both a source and sink for greenhouse gases, like CO<sub>2</sub> and methane.  
1321 Annual cycles of fluxes of such substances are currently being investigated in  
1322 relation to bacterial biodiversity, algal activity, and respiration. For instance, it is

1323 expected that a combination of the broad scope of information from several MOSAiC  
1324 science teams will help resolve the “ocean methane paradox” explaining periodically  
1325 enhanced CH<sub>4</sub> concentrations in ocean surface waters (Rees et al., 2022). Great  
1326 uncertainty exists regarding the future role of the Arctic Ocean as a source or sink for  
1327 CO<sub>2</sub>, where melting of sea ice combined with increased productivity could regionally  
1328 lead to an intensified sink (Rees et al., 2022), while other Arctic areas might  
1329 experience a reduction of carbon fixation and export due to increased sea ice melt-  
1330 induced stratification (von Appen et al., 2021). Other processes which can potentially  
1331 lead to CO<sub>2</sub> outgassing by the Arctic Ocean include decreased solubility driven by  
1332 warmer temperatures, equilibration with the atmosphere (Cai et al., 2010; Else et al.,  
1333 2013), or wind-driven mixing of surface waters with more carbon-rich subsurface  
1334 layers (Lannuzel et al., 2020). MOSAiC ECO data will fill important regional and pan-  
1335 Arctic knowledge gaps in our understanding and may help to determine those  
1336 mechanisms that will drive the effects of climate change on the Arctic carbon cycle.

1337 A set of different ecosystem and fully coupled Arctic Ocean models will be  
1338 essential tools for integrating information across the ecosystem and the entire Arctic  
1339 system using MOSAiC data, targeting not only specific questions like carbon cycling  
1340 in the Arctic or production of climate relevant greenhouse gases, but also  
1341 transferring these process-focused knowledge gains into products to understand  
1342 climate change on larger regional and temporal scales. The unprecedented increase  
1343 in knowledge on biodiversity and gene expressions in relation to environmental  
1344 variables (Mock et al., 2022) will allow for the application of models to elucidate  
1345 metabolic and energetic fluxes within the Arctic microbial consortia (Succurro and  
1346 Ebenhöf, 2018). This combined application of different model types (e.g. see will be  
1347 an important tool to differentiate the intertwined role of spatial and temporal  
1348 variability in MOSAiC data sets.

1349

## 1350 **5. OUTLOOK**

1351 The knowledge created by the ecological research during MOSAiC will provide a  
1352 lasting legacy for future studies focusing on the Arctic System. For the first time,  
1353 biodiversity and ecosystem functioning were studied on multiple trophic levels over a  
1354 full seasonal cycle using traditional and novel approaches.

1355 The legacy of MOSAiC goes beyond publications, developing novel sampling  
1356 approaches and the openly accessible data archives. Indeed, the open and growing  
1357 network of researchers across many nations and disciplines can be expected to  
1358 have a lasting effect on Arctic marine research, particularly considering the high  
1359 number of early career scientists that are already involved. New spin-off projects  
1360 initiated through MOSAiC include projects on microbial processing and  
1361 biogeochemical modeling, remote sensing of under-ice blooms, sea ice-ecosystem  
1362 modeling, and a yearround ecosystem study in an Arctic fjord. The gained  
1363 knowledge will help to evaluate the importance of the Arctic for climate regulation.  
1364 Although incomplete, several publications have demonstrated the broad range of  
1365 currently known ecosystem services provided by the Arctic marine system to  
1366 humans including regulation of greenhouse gases and biodiversity (Malinauskaite et

1367 al., 2019). MOSAiC-based knowledge will also support political decision-making  
1368 processes through, e.g., Arctic Council initiatives on the management of Arctic  
1369 marine ecosystems (e.g. PAME). Although MOSAiC ECO covers a very broad range  
1370 of ecological topics and will fill many knowledge gaps, many research questions  
1371 remain unanswered or are now newly defined. The free, findable, accessible,  
1372 interoperable, and reusable MOSAiC data will be a major milestone of success,  
1373 providing together with the gained knowledge, the backbone for interdisciplinary  
1374 marine Arctic research for decades to come.

1375         The broad range of realized measurements and samples from MOSAiC ECO  
1376 will make it possible to move from the observed answers of the ‘who’ and ‘how’ to  
1377 developing process-based mechanistic understanding of the ‘why’, also by means of  
1378 modeling approaches (see below). Mechanistic understanding in turn will allow  
1379 moving beyond the specific locations and conditions during our observational period.  
1380 The observation of high levels of biomass presence and organismal activity during  
1381 the months-long cold and dark polar night, for example, provides the foundations for  
1382 new investigations regarding overwintering mechanisms, strategies, and  
1383 physiological adaptations. The combination of rate measurements, observations on  
1384 different life stages, physiological and food web experimental work, as well as  
1385 information originating from metagenomics and metatranscriptomics will allow an  
1386 improved understanding the current overwintering mechanisms. Also, it will provide  
1387 improve scenarios regarding the potential impacts of a future warmer Arctic with a  
1388 reduced and changed ice cover, for example on effects on winter survival, annual  
1389 productivity, and biogeochemical cycles. Here, synergies between the ECO team  
1390 and the BGC science with its focus on trace and greenhouse gases as well as  
1391 cycling of sulfur, nitrogen and carbon will be essential. Entrainment of the detected  
1392 processes and rates into ecosystem and biogeochemical models will also greatly  
1393 improve the validity of such future scenario estimations. While a one-year field-  
1394 period cannot observe climate change trends directly, MOSAiC science is a step-  
1395 change in Arctic ecosystem understanding that will provide a baseline upon which  
1396 future changes can be identified, while also providing the potential for improved  
1397 projections of future changes based on the advanced process-based interdisciplinary  
1398 understanding.

1399

1400

#### 1401 **Data accessibility statement**

1402 Drift track data for each MOSAiC leg is available via Pangaea (Haas, 2020; Kanzow,  
1403 2020; Rex, 2021a, 2021b, 2020).

1404 Combined surface ocean temperature and salinity from different sensors as  
1405 described in (Schulz et al., 2023b) is available via the Arctic Data Center (Schulz et  
1406 al., 2023a),

1407 Air temperatures at 2 m over the MOSAiC floe are available at the Arctic Data Center  
1408 (Cox, 2023).

1409 Incoming PAR data was derived from radiation station measurements published at  
1410 PANGAEA (Nicolaus et al., 2023b, 2023a, 2022a).

1411 Data publication of nutrient data is under way. Data is available upon request from  
1412 Sinhué Torres-Valdes (sinhue.torres-valdes@awi.de). Other metadata shown is  
1413 either available in the supplementary information or will be published together with  
1414 the data once quality controlled, and are available from the authors upon request.  
1415

### 1416 **Author contributions**

1417 Developed the concept and design: AAF and RRG with input from co-authors

1418 Conducted the field sampling: AAF, CJMH, CJA, YB, JPB, JB, DB, RGC, GC, EJC,  
1419 JMC, ESD, SLE, AAF, JG, CEG, NH, AI, BAL, KM, OM, DN, LMO, SR, SS, ES, KS,  
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1421 Drafted and revised the article: AAF, CJMH and RRG with contributions from  
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2145 **Tables**

2146

2147 **Table 1. MOSAiC ecosystem core measurements.** Catalog of biological and  
2148 biogeochemical properties and processes measured during the MOSAiC expedition.

2149 Additional geochemical properties (i.e. gases) were measured by the MOSAiC

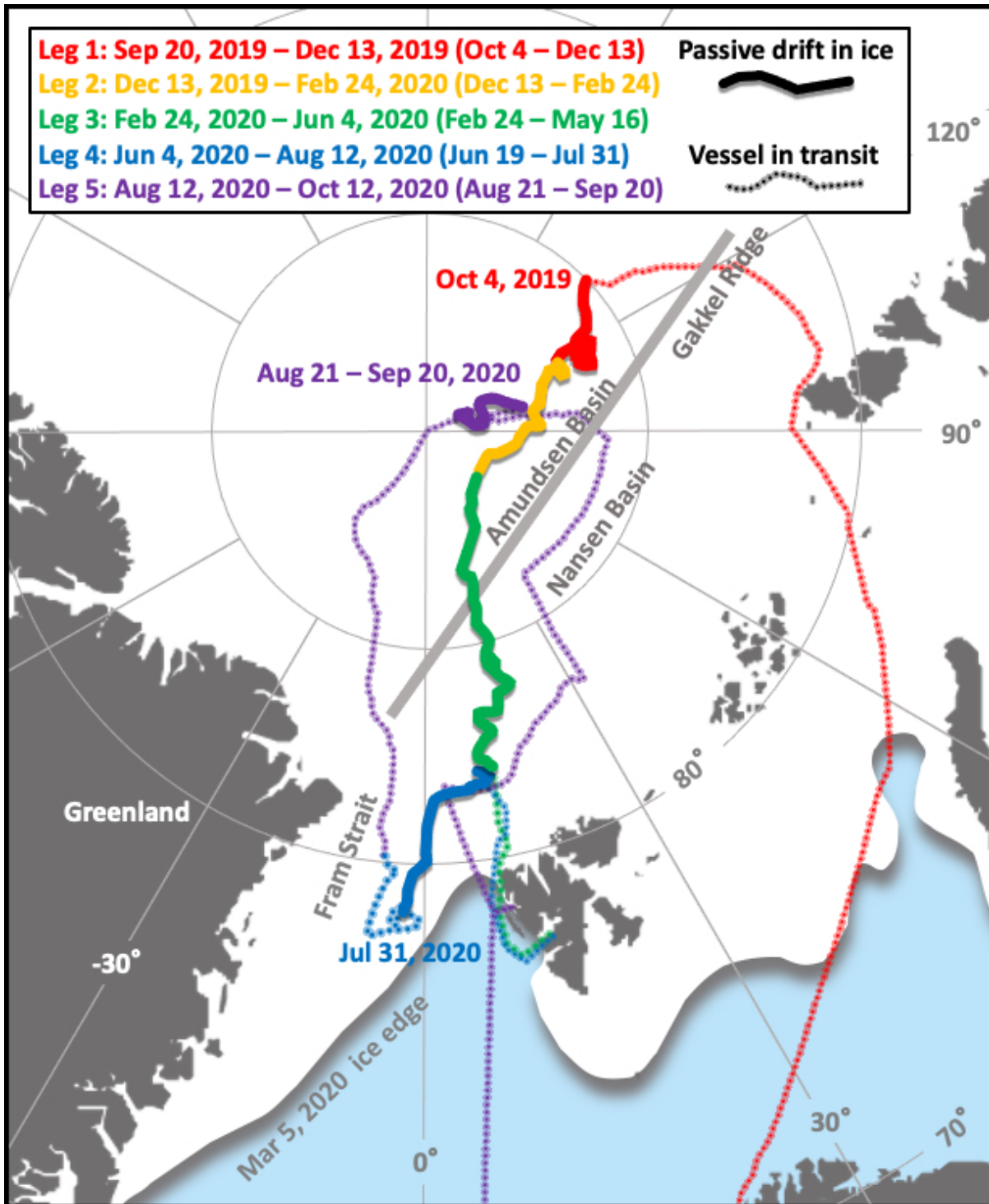
2150 Biogeochemistry Team. Details can be found in the supplementary Table S2.

2151

<b>ECO variable</b>	<b>Sampled environments</b>	<b>Method</b>
Nutrients (nitrate+nitrite, ammonium, phosphate, silicic acid, dissolved organic nitrogen, dissolved organic phosphorus)	Water column, ice, special habitats	Colourimetric continuous flow; AA3 (SEAL)
Dissolved oxygen (DO)	water column	Winkler titration
Carbonate chemistry: total alkalinity (TA) and dissolved inorganic carbon DIC)	water column, special habitats	VINDTA
Carbonate chemistry: TA, DIC	ice, special habitats	Coulometry/ VINDTA
Dissolved organic carbon (DOC) and nitrogen (DON), concentrations	water column, ice, special habitats	TOC-VCPN, high temperature catalytic combustion
Dissolved organic matter characterization and chemometrics	water column, special habitats	Ultrahigh resolution mass spectrometry
Particulate organic carbon and nitrogen (POC and PON); stable isotopic composition and concentrations	water column, ice, special habitats, short- and longterm sediment traps	%C, %N, $\delta^{13}\text{C}$ , $\delta^{15}\text{N}$ ; EA-IRMS (Flash 2000-Delta V Plus, Thermo Scientific)
POC and PON, concentrations	water column, ice, special habitats, short- and longterm sediment traps	Euro EA 3000, HEKAtech
Biogenic silica (bSi)	water column, ice,	Photometrically after NaOH digestion
Oceanic particle size spectra and distributions	Water column	Optical - Underwater Vision Profiler (UVP)
Chlorophyll a (Chl-a)	water column, ice, special habitats	Fluorometric analyses of extracted samples
Pigment biomarkers	water column, ice, special habitats	High Performance Liquid Chromatography (HPLC)
Enumeration and diversity of prokaryotes, eukaryotic microbes and viruses	water column, ice, special habitats	Attune NxT (ThermoFisher) and FACS Calibur (Becton Dickson) flow cytometers (FCM)
Diversity and abundance of protists	water column, ice, special habitats, sediment traps	Inverse light microscopy
Diversity of prokaryotes and eukaryotic microbes	water column, ice, special habitats, underway	16S/18S rRNA amplicon sequencing (Illumina)

Metagenomes	water column, ice, special habitats	Illumina
Metatranscriptomes	water column, ice, special habitats	Illumina
Primary productivity (NPP)	water column, ice, special habitats, underway	<sup>14</sup> C-based incubations
Net community production (NCP)	surface water	MIMS O <sub>2</sub> /Ar
Bacterial productivity (BP)	water column, ice, special habitats, underway	<sup>3</sup> H-leucine incubations
PSII fluorescence-based photophysiology	water column, special habitats	FRRF; FastOcean with FastAct /Fastact2 (Chelsea Tech)
Mesozooplankton: abundance/distribution	water column	Microscopy, Zooscan
Small mesozooplankton: abundance/distribution	water column	Microscopy, Zooscan
Macrozooplankton: abundance/distribution	water column	Microscopy, Zooscan
Macrozooplankton: biomarkers	water column	diverse
Macrozooplankton: carbon & nitrogen	water column	Elemental analyser
Surface mesozooplankton: biomarkers	water column	diverse
Surface mesozooplankton: carbon & nitrogen	water column	Elemental analyser
Surface mesozooplankton: individual respiration	water column	optodes
Deep mesozooplankton: biomarkers	water column	diverse
Deep mesozooplankton: carbon & nitrogen	water column	Elemental analyser
Deep mesozooplankton: individual respiration	water column	optodes
Mesozooplankton: high vertical resolution distribution	water column	Microscopy, Zooscan
Under-ice fauna: abundance/distribution	ice	Microscopy
Grazing rates (microzooplankton & copepods)	water column	experiments
Egg production (copepods)	water column	experiments
Gut contents & DNA (fish, copepods, amphipods)	water column	Microscopy, scales, DNA
Energy content macrofauna	water column	oxygen calorimeter

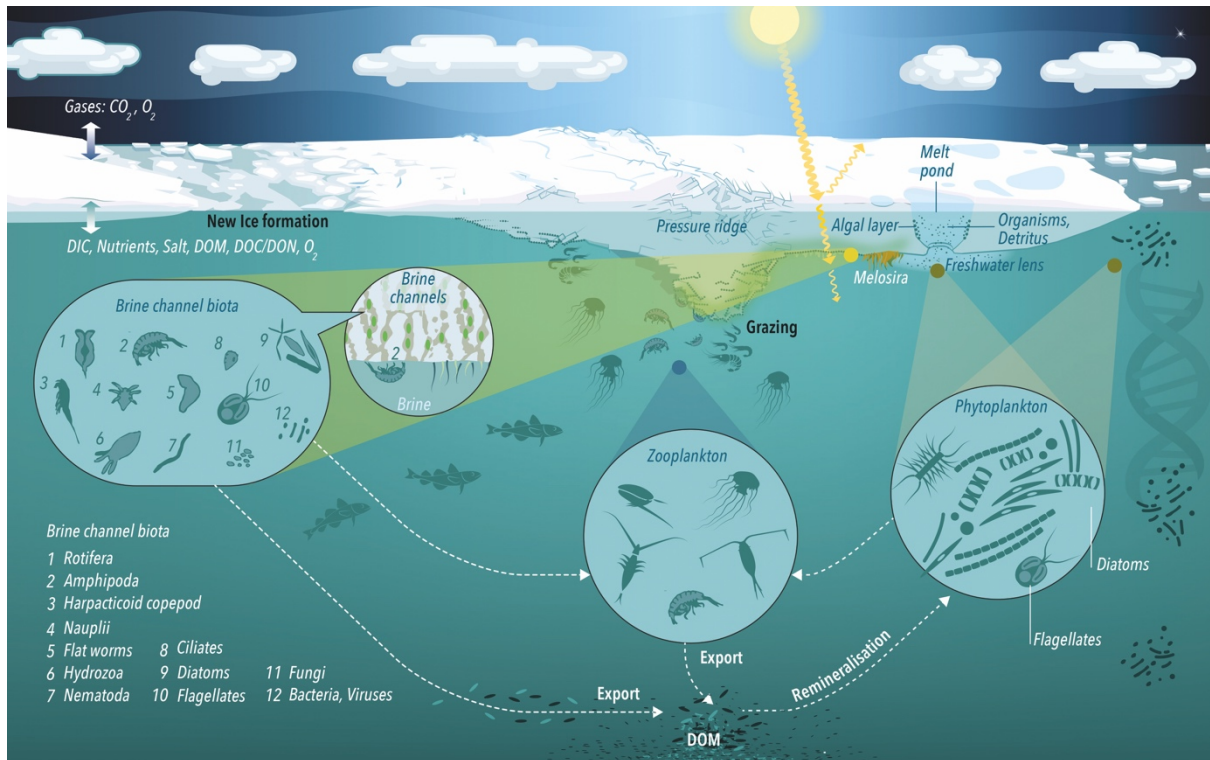
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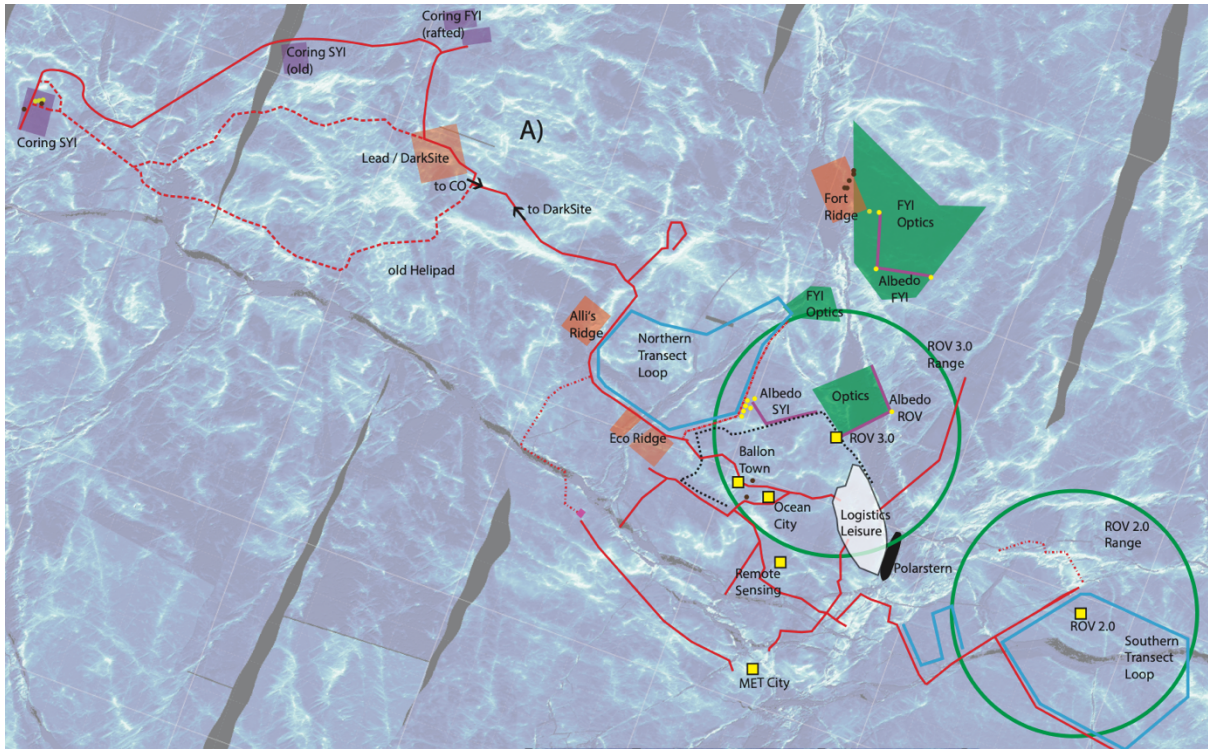
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2156 **Figure 1. MOSAiC expedition track.** Passive periods of drift are shown in solid-  
2157 colored lines, with each color-coded line delineating one of the MOSAiC legs. Dates  
2158 are periods of each leg and dates shown in parentheses identify passive drift periods  
2159 per leg. Dotted lines depict transit tracks of the ship initially and for repositioning after  
2160 legs 3 and 4. The solid grey line approximates the location of the Gakkel Ridge  
2161 between the Amundsen and Nansen Basins. The approximate sea ice edge at the



2162 annual maximum (Mar 5, 2020) and minimum (Sept 15, 2020) is also shown.  
 2163 Modified after (Shupe et al., 2020).  
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 2166 **Figure 2. Ecosystem compartments and processes of the Central Arctic.**  
 2167 Illustrated are the primary components and processes investigated by the ECO team  
 2168 during the MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic  
 2169 Climate) expedition.  
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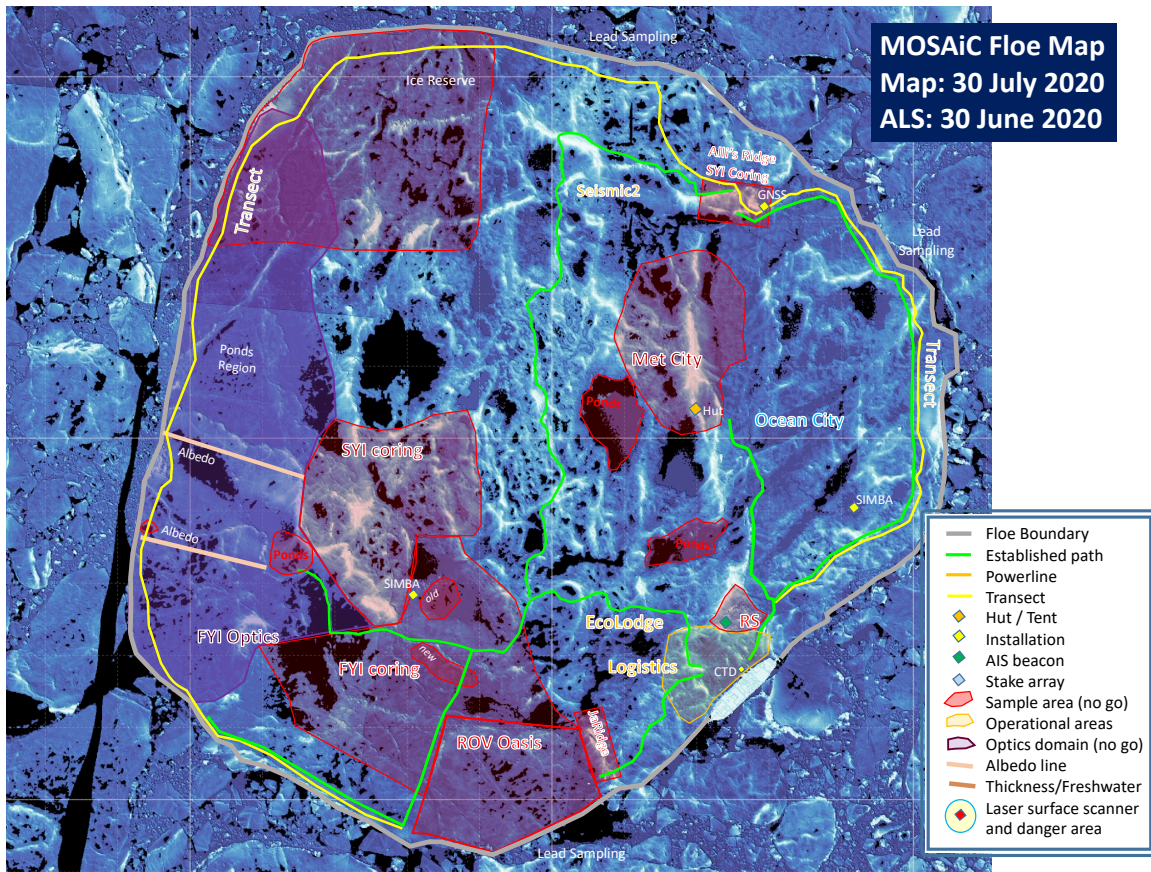


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**Figure 3. Main sampling locations and measurement sites of the first MOSAIC Central Observatory**

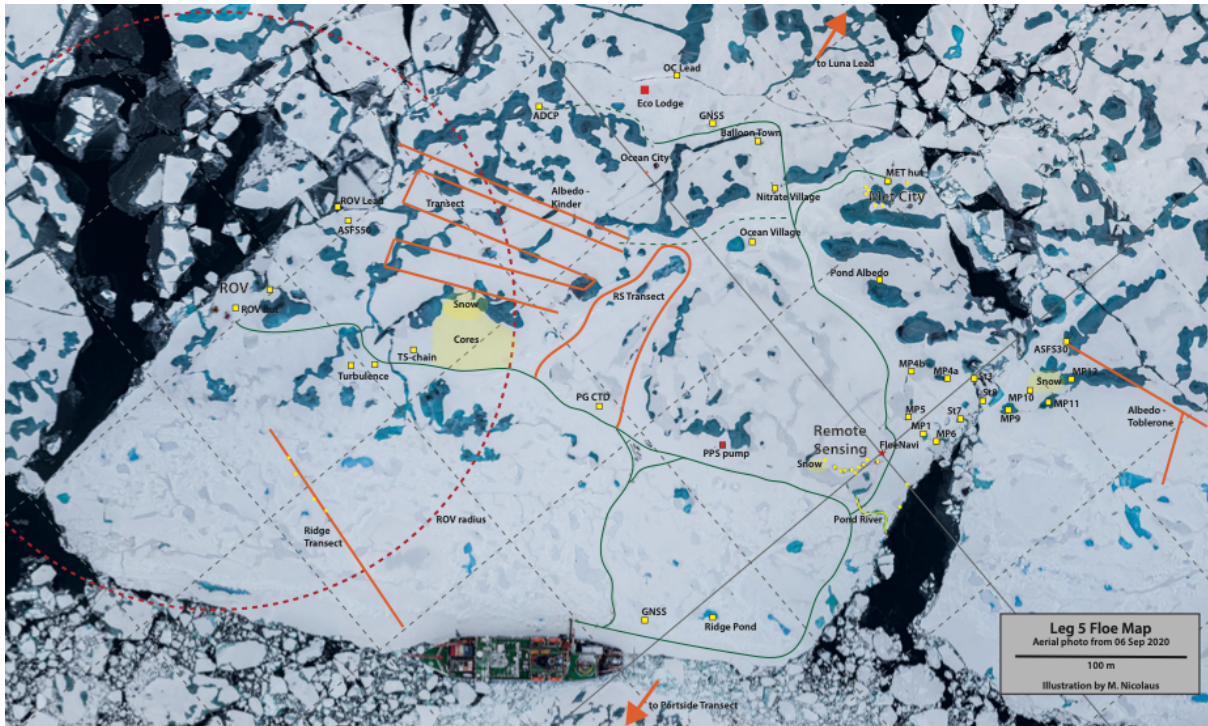
**in April 2020.** Map background shows the airborne laser scanner (ALS) image from April 23, 2020 with grey areas indicating no data. White, brighter areas depict sea ice of greater elevation (i.e. ridge sails). Some site locations were approximate due to active ice dynamics. Sites labeled “old” were previously active sampling locations, but were no longer accessible and maintained after the winter. The primary water column sampling locations during October 2019 and May 2020 were conducted at RV *Polarstern* (black) and Ocean City (yellow square). Common ice coring sites are shown in purple and approximately 1 km from RV *Polarstern*. The map had been simplified to show main sampling and measurement positions for the ecosystem work program. Additional MOSAIC measurement sites from teams ATMO, ICE, and OCEAN can be viewed in the respective MOSAIC Overviews by Nicolaus et al. (2022b), Rabe et al. (2022) and Shupe et al. (2022).





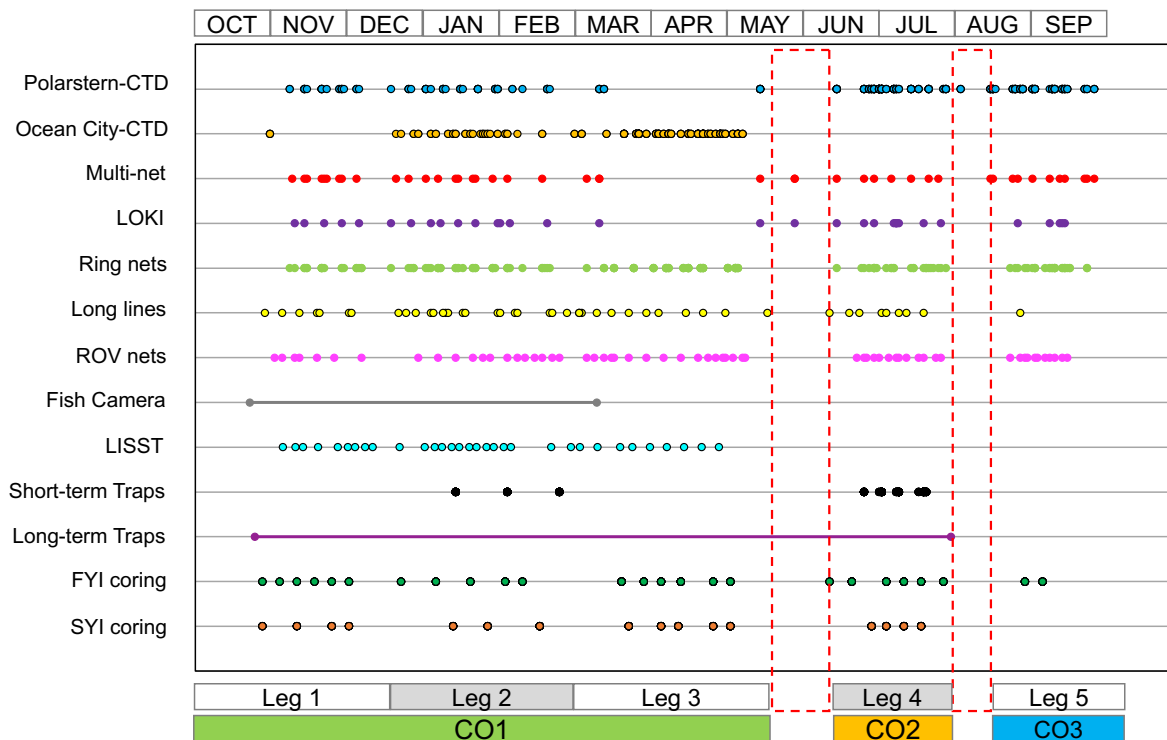
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**Figure 4. Main sampling locations and measurement sites of the second MOSAIC Central Observatory during summer 2020.** Primary water column sampling was from RV *Polarstern* (light blue, lower righthand side). Ocean City did not have a CTD-rosette system. FYI coring site was an original portion of the FYI site established in Oct 2019. SYI coring site adjacent to FYI shown here was a reserve SYI site identified earlier, but was not actively sampled. Original SYI coring site is not depicted in this map as that part of the ice floe detached from the main floe. SYI coring in June and July 2020 occurred near Alli’s ridge. ECO Lodge was established beyond the perimeter of the logistics area. The map had been simplified to show main sampling and measurement positions for the ecosystem work program. Additional MOSAIC measurement sites from teams ATMO, ICE, and OCEAN can be viewed in the respective MOSAIC Overviews by Nicolaus et al. (2022b), Rabe et al. (2022) and Shupe et al. (2022).



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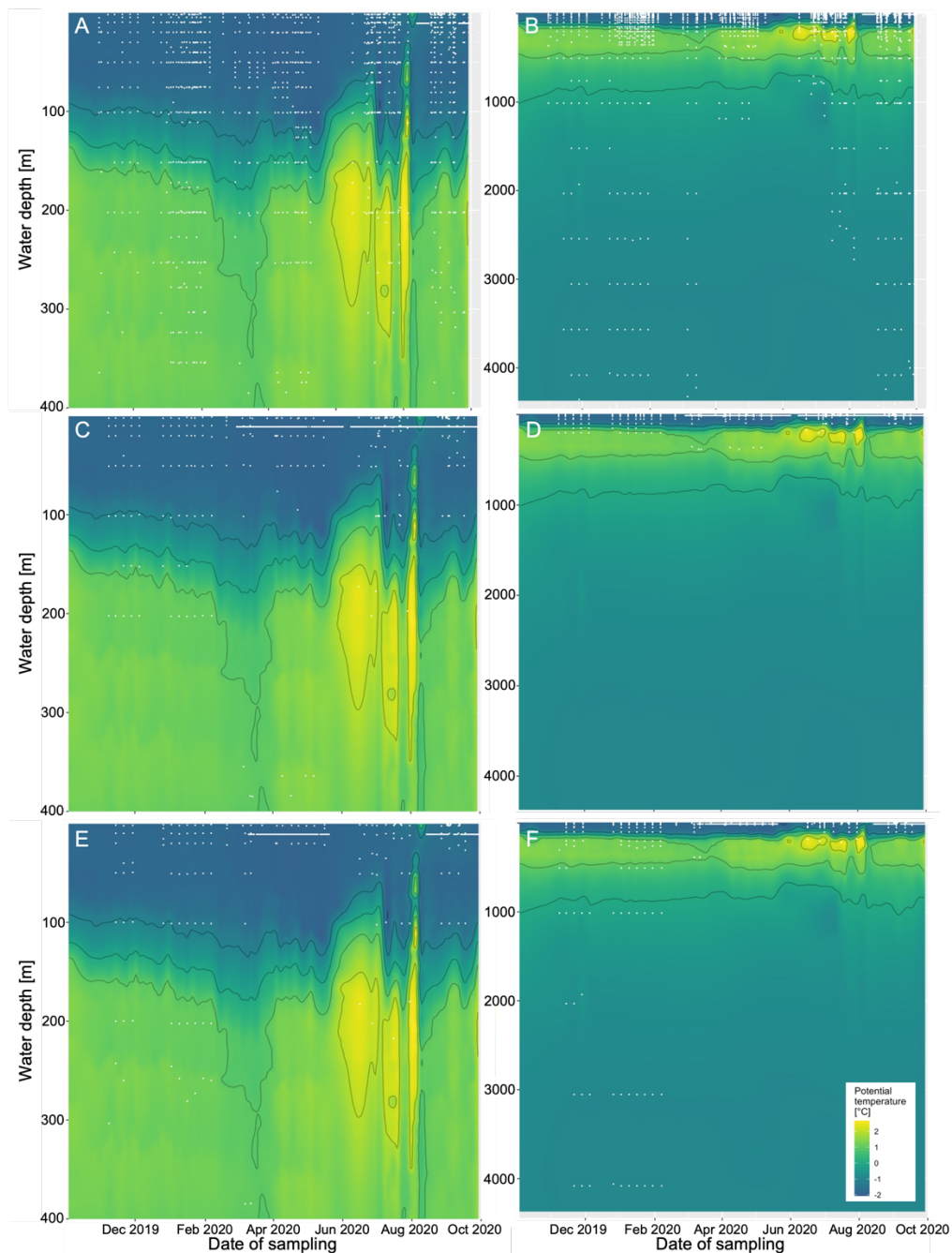
**Figure 5. Main sampling locations and measurement sites of the third MOSAiC Central Observatory during late summer 2020.** The background of the map is an aerial photo of the ice floe (photo credit S. Graupner). Primary water column sampling was from RV *Polarstern* (light blue, lower righthand side). Ocean City did not have a CTD-rosette system. Ice cores (not new ice formations) in August and September 2020 were sampled from a single site (yellow area). New ice formation and waters from the upper ocean (1-2m) were sampled at RS, OC, ROV, and Luna leads. ECO Lodge (red square) was established adjacent to Ocean City lead, approximately 300 m from the ship. The map had been simplified to show main sampling and measurement positions for the ecosystem work program. Additional MOSAiC measurement sites from teams ATMO, ICE, and OCEAN can be viewed in the respective MOSAiC Overviews by Nicolaus et al. (2022b), Rabe et al. (2022) and Shupe et al. (2022).



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**Figure 6. Ecosystem observations and measurements during the field phase of MOSAiC.** Each row shows the dates of a sampling event for a specific type of gear (e.g. Polarstern-CTD) or sampling activity (e.g. FYI coring). Solid lines indicate instrumentation deployed through the ice for a continuous period. A number of parameters are collected from an individual sampling event, such as deployment of the Polarstern-CTD rosette system. Alternating white and grey horizontal bars at the bottom of the chart indicate the MOSAiC leg. Colored horizontal bars indicate from which Central Observatory (CO) samples were collected. Dashed red line boxes identify the periods when RV Polarstern was transiting to/from an ice floe. LOKI = Light-frame On-sight Key species Investigation system (zooplankton camera system). ROV nets = Plankton nets towed by a Remotely Operated Vehicle. LISST = Laser In-Situ Scattering and Transmissometer (particle counter). FYI = First Year Ice. SYI = Second Year Ice.

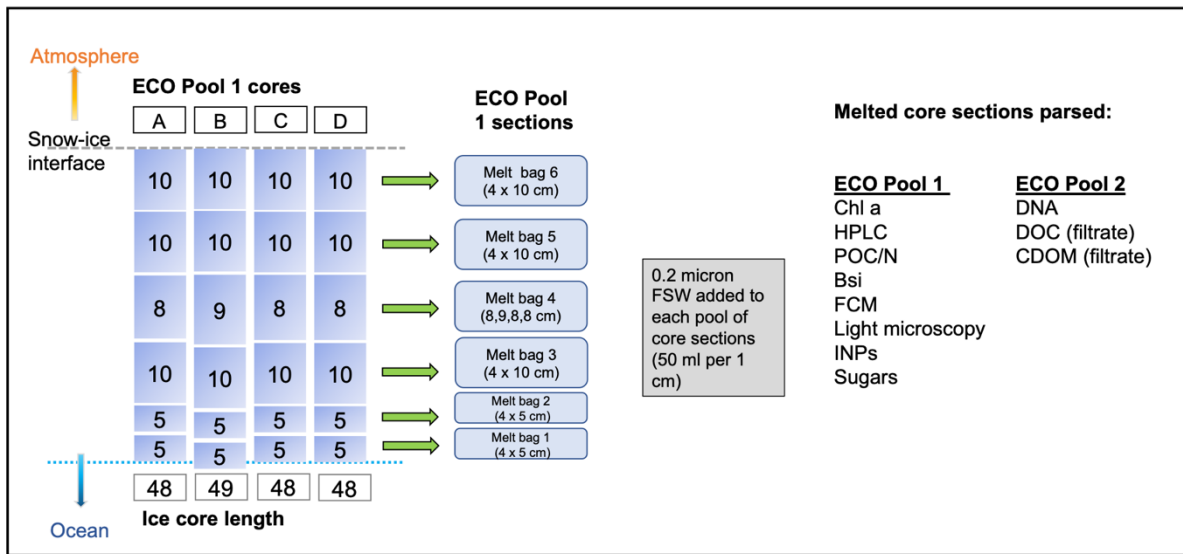




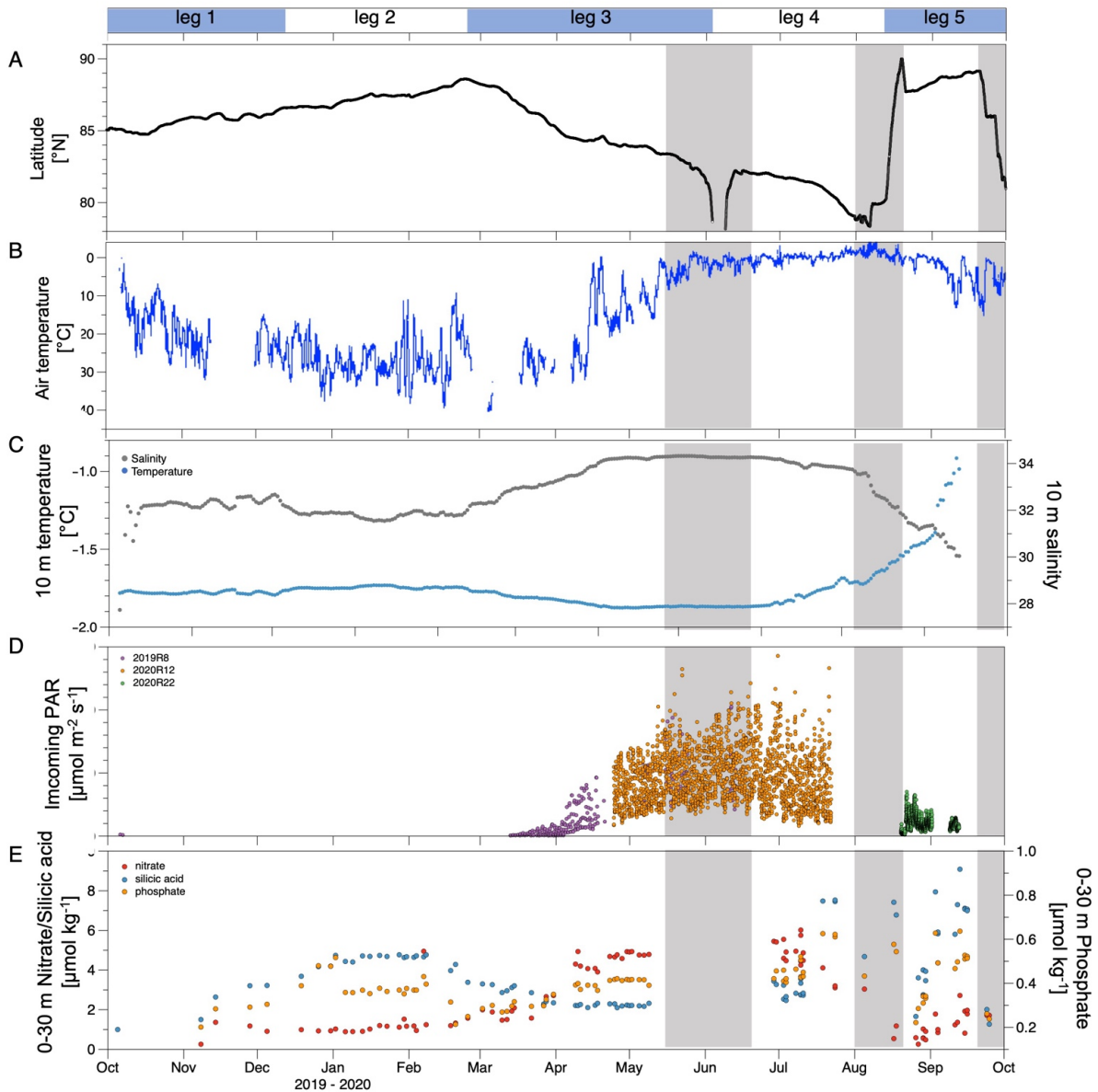
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**Figure 7. Distribution of CTD-rosette-based water column samples for nutrients, Chl-a, and total DNA in depth and time.** Discrete samples (white circles) for the upper 400 m (A, C, and E) and for full depth (0-4000 m; B, D, and F) are overlain on temperature contours with isotherms shown by thin, solid lines. Temperature data shown here are from temperature sensors mounted to the CTD-rosette system. During mid-March to May 2020, the Polarstern-CTD was not operational due to the closure of the ice hole alongside the ship; water column sampling was limited to the upper 1000 m using the OC-CTD-rosette system. A) Nutrient samples collected in the upper 400 m; B) Nutrient samples collected over the full water column depth; C) Chl-a samples collected in the upper 400 m; D) Chl-a samples collected over the full water column depth; E) Total DNA samples collected

2243 in the upper 400 m; F) Total DNA samples collected over the full water column  
 2244 depth.  
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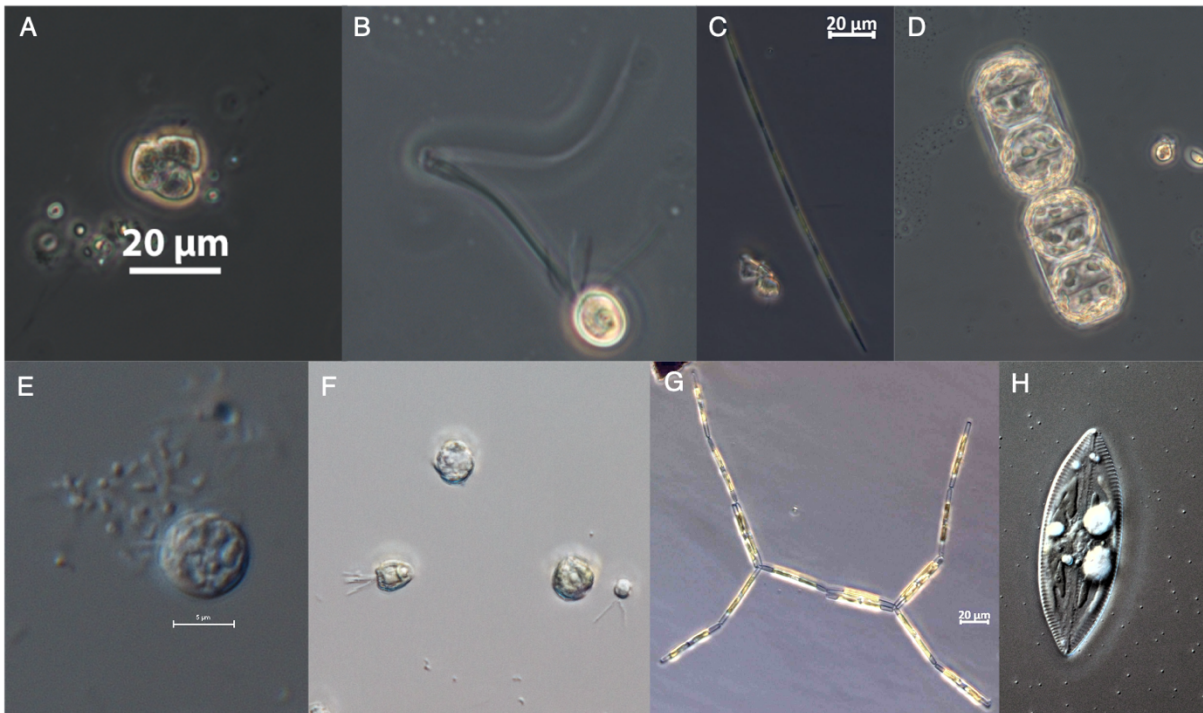
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 2247 **Figure 8. Ecological sea ice core pooling and processing.** Full length cores were  
 2248 sectioned in the field and placed in prelabeled melt bags. Filtered seawater (FSW)  
 2249 was added onboard to each melt bag, and after complete melt, pooled sample were  
 2250 parsed for different properties. When possible, 2 ECO pools were generated.  
 2251 Properties collected from each pool are shown, see Table 1 for abbreviation  
 2252 explanations. Additional samples were collected from SALO18 and DIC/TA cores as  
 2253 well as additional bottom sections.  
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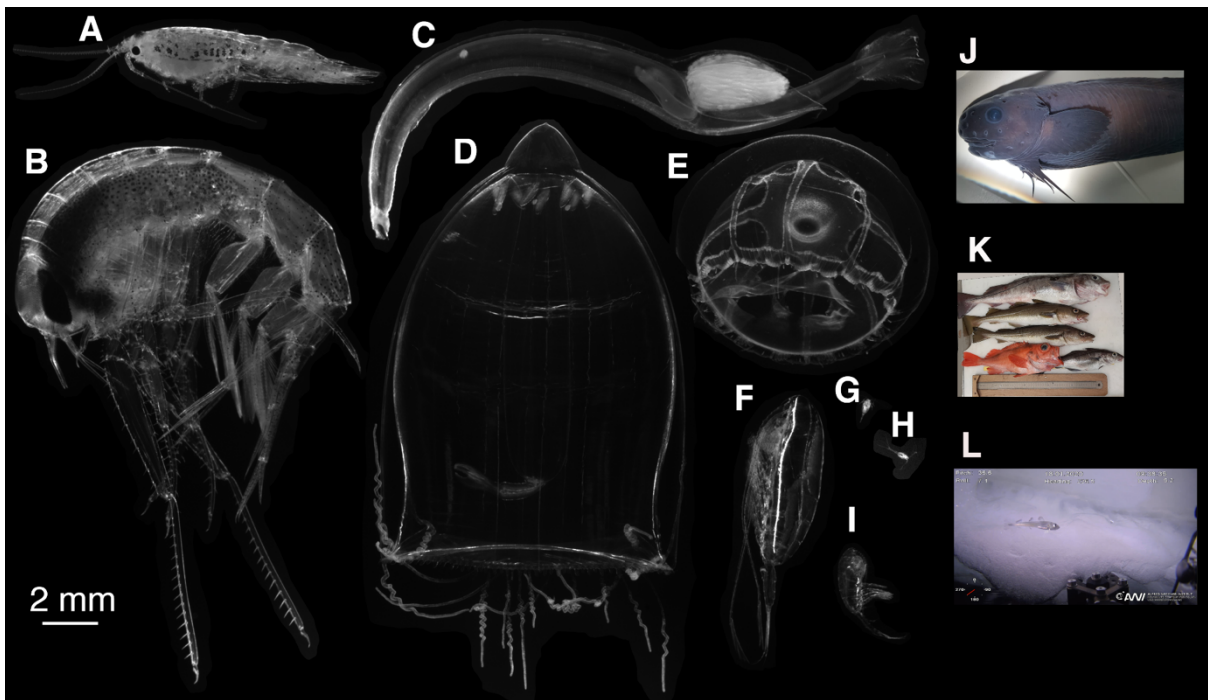
**Figure 9. Environmental conditions over the annual cycle.** A) latitude ( $^{\circ}$ N), B) air and C) surface ocean temperature (blue) and salinity (grey) at  $10 \pm 3$  m depth, D) incoming PAR (photosynthetically active radiation, 400-700 nm, measured as photon flux density), and E) surface ocean nutrients (nitrate+nitrite, silicic acid, and phosphate) from the upper 30 m water depths. Grey shaded areas indicate transit periods. Here, latitude and nutrients are from the location of RV *Polarstern*, while PAR, water temperature, and surface air temperature are representative of CO conditions.





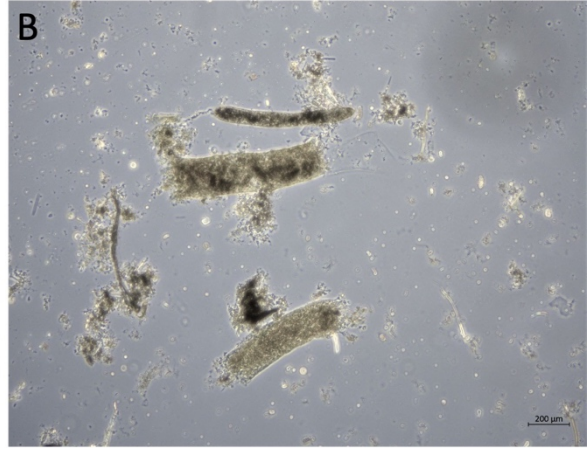
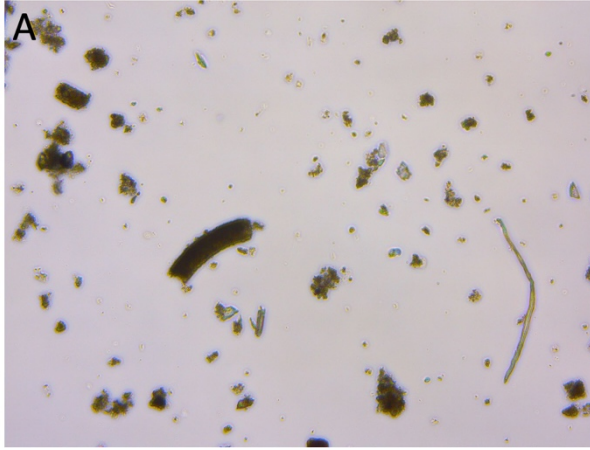
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**Figure 10. Dominant pelagic (water column) and sympagic (ice-associated) protists during the MOSAiC cruise.** A) dinoflagellate belonging to Gymnodiniaceae, B) unidentified flagellate, C) *Pseudo-nitzschia* sp. and D) *Melosira arctica* from water column samples; E) and F) unidentified flagellates, G) *Nitzschia frigida* and H) *Navicula* sp. from bottom sea ice samples.



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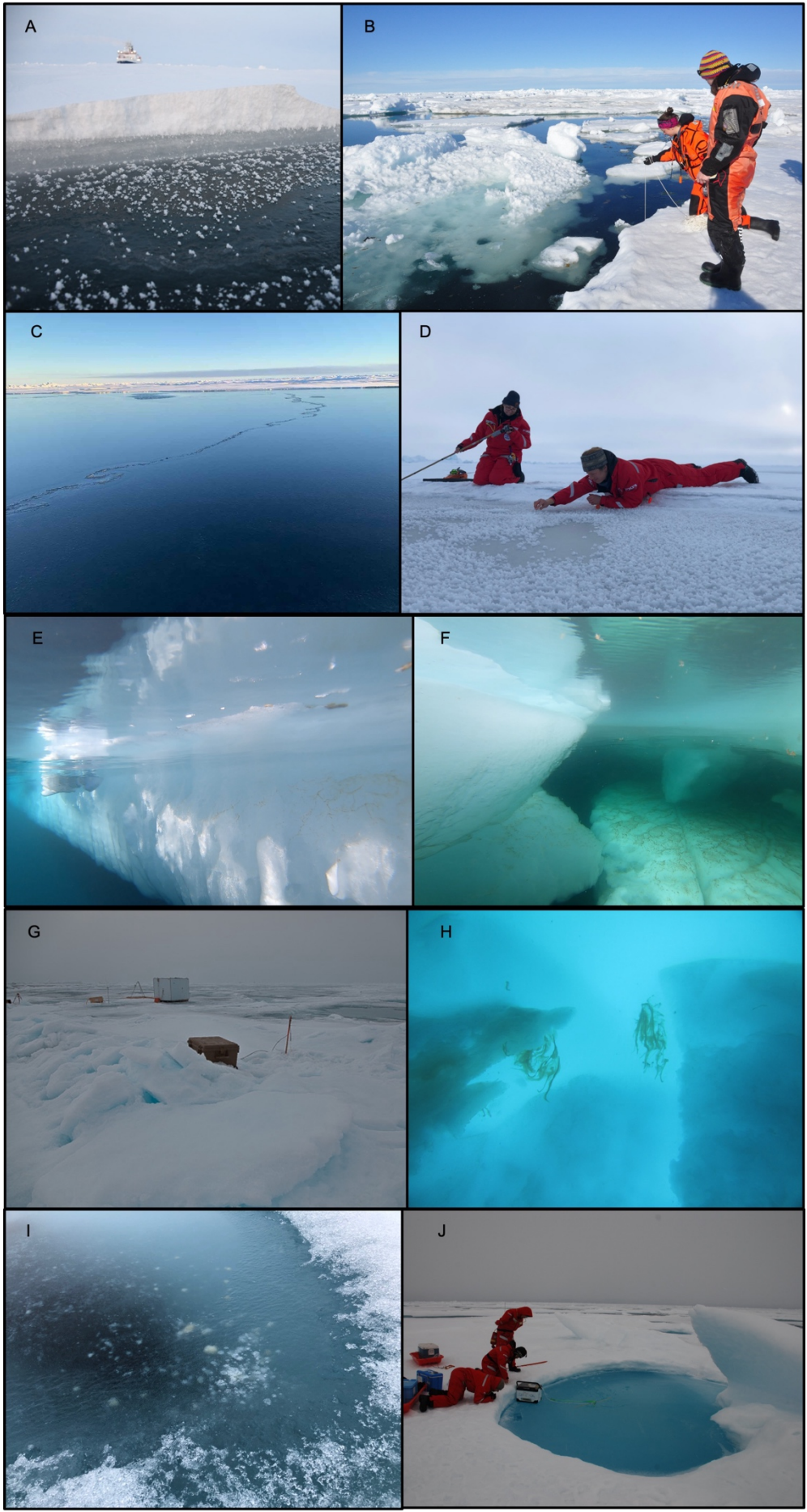
**Figure 11. Zooplankton and fish species caught during the MOSAiC cruise.** A) *Apherusa glacialis*, B) *Themisto libellula*, C) *Eukrohnia hamata*, D) *Aglantha digitale*, E) *Botrynema ellinorae*, F) *Calanus hyperboreus*, G) *Microcalanus* sp., H) *Oithona similis*, I) *Metridia longa*, J) *Paraliparis bathybius*, K) from top to bottom: Haddock (*Melanogrammus aeglefinus*), 2 x Atlantic cod (*Gadus morhua*), Beaked redfish (*Sebastes mentella*), Haddock (*Melanogrammus aeglefinus*); L) *Boreogadus saida*. The specimens A - I were obtained with the LOKI (Lightframe on-sight key species investigation), further sampling methods were J) zooplankton ring net, K) longlines, and L) ROVnet camera.



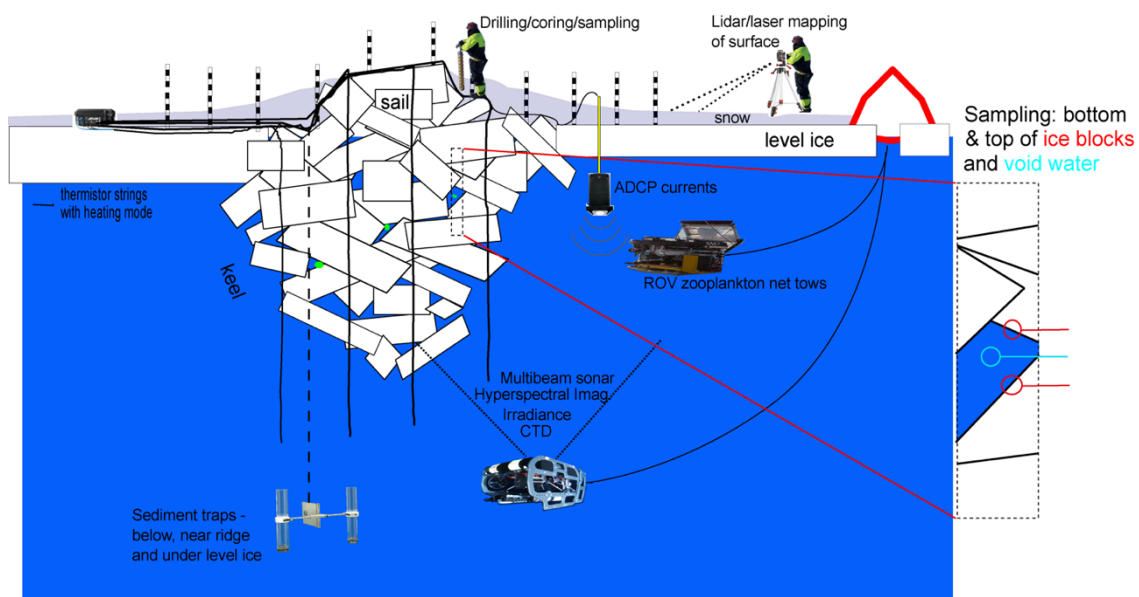
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**Figure 12. Sediment trap material from winter vs summer.** Overview images of sediment trap material from A) January 14, and B) July 21, 2020.



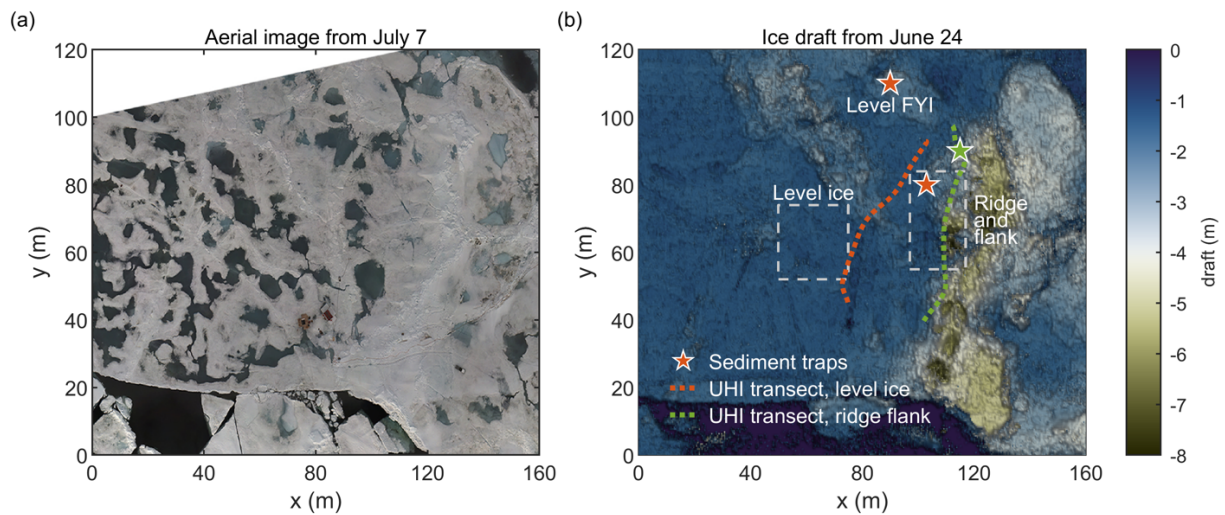


2284 **Figure 13. A variety of different seawater and sea ice habitats sampled over the**  
2285 **drift year.** A) Frost flowers developing on a refrozen lead on March 11, 2020; B)  
2286 Sampling an open lead on 22, 2020; C) New ice formation on a lead located near  
2287 ECO Lodge 2 on September 07, 2020; D) Sampling new ice and direct under-ice  
2288 waters from a lead located near ECO Lodge 2 on September 12, 2020; E)  
2289 Underwater photos of ice blocks within an open lead from July 01, 2020 and F) from  
2290 the same location on 29, 2020, showing the development of thin, stratified fresh and  
2291 brackish layers within leads. G) Jaridge Observatory from the surface with piled up  
2292 ice blocks on June 26, 2020; H) Underwater photo of ice blocks in Jaridge  
2293 Observatory with strands of Melosira; I) Refrozen surface of a melt pond showing  
2294 large aggregate material through the ice surface from Aug 21, 2020; and J) Melt  
2295 pond sampling from August 31, 2020.



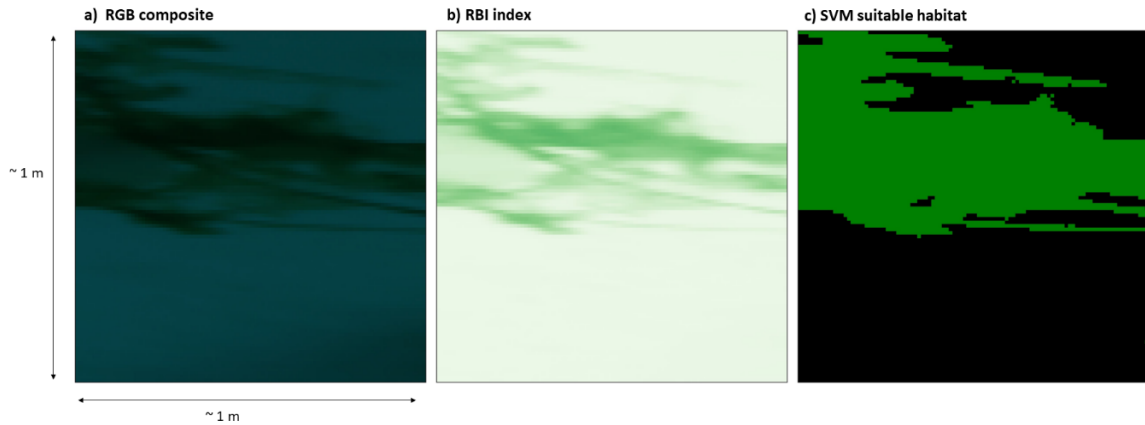
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**Figure 14. Components of the multidisciplinary ridge sampling strategy during MOSAiC.** Schematic representation of the sampling strategy of sea ice ridges developed by the HAVOC project-, including autonomous systems (e.g. thermistor strings), coring and drilling, sampling of ice and void water in the ridge keel, as well as ROV- and sediment trap-based measurements, with the former including zooplankton net tows and various sensor-based measurements (including hyperspectral imager mapping of the ice underside, see Figure 16).



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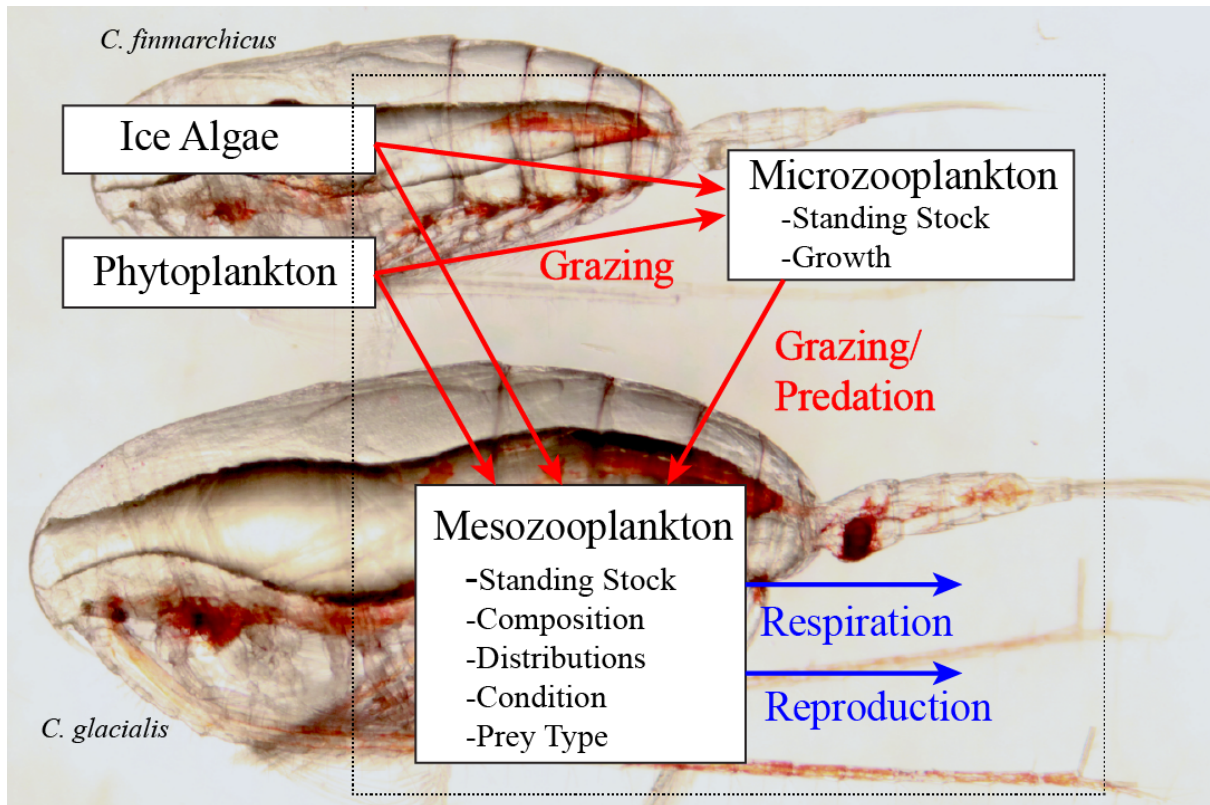
**Figure 15. The Jaridge ridge sampling areas during summer 2020.** A) Shows an aerial image of the study area with ponded level ice and the Jaridge ridge sampling site. Shading in B) indicates ice draft from the ROV multibeam sonar with keel depths of the pressure ridge exceeding 7 m, and red stars indicate locations of deployed sediment traps, and the blue star the location of underwater hyperspectral imager (UHI) data collection shown in Figure 16.



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**Figure 16. Determination of ice algal habitable space in pressure ridges and level sea ice using underwater hyperspectral image (UHI) information.** A) An example of composite RGB (red, green, and blue) image of one area along the ridge flank transect (blue star in Figure 15b) compared to model results to estimate B) relative algal quantity estimated via the Relative ice algal Biomass Index (RBI), and C) inhabited area based on support vector machine (SVM) machine learning approaches of sea ice using the signature of the spectral light transmitted through the ridge (Lange et al., submitted).





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**Figure 17. Transformations of energy, carbon and nitrogen by mesozooplankton in the upper water column and near the sea ice-ocean boundary.** Arrows indicate transformation rates and component linkages that were quantified; red arrows show incorporation of carbon/nitrogen while blue arrows show export of carbon/nitrogen from the organisms. Characteristics of each ecosystem component that were measured indicated inside boxes.

2329 **Supplementary Information**

2330

2331 **Table S1. Project-specific contributions to the ECO work program. Information**  
2332 **on Project Title, PI, involved institutions, funding agencies, and science foci.**

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2334 **Table S2. List of ECO sampling events based on rosette casts and optical**  
2335 **particle profiling.** Event Operation IDs, date and time, location and bottom depth for  
2336 PS-CTD rosette, OC-CTD rosette and LISST casts as well as UVP profiles.

2337

2338 **Table S3. Overview on sample processing and applied methods.** Detailed  
2339 overview of sampled parameters, applied methods, responsible PIs, coverage, and  
2340 estimated number of samples. The table represents an extended version of Table 1  
2341 from the main document.

2342

2343 **Table S4. Overview of quantitatively analyzed zooplankton sampling events and**  
2344 **collected samples.** Samples were collected via LOKI (up to 20 frames sec<sup>-1</sup>), UVP,  
2345 multinet (MN), ring nets (RN), Nansen net (NCN) and a net mounted on an ROV  
2346 (ROVN), from Nov. 2019 to Oct. 2020. For each month, the number of samples is  
2347 given; depth strata MN: 2000-1000-500-200-50-0 m; depth strata NCN: 1000-200 m  
2348 & 200 - 0 m.

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2350 **Table S5. List of ECO sampling events for zooplankton and fish sampling.**  
2351 Event Operation IDs, date and time, location (of *RV Polarstern*), and bottom depth  
2352 for all zooplankton and fish sampling events for multinet (NM), Light-frame On-sight  
2353 Key species Investigation system (LOKI), Ring nets, Nansen Nets, long lines,  
2354 remotely operated vehicle nets (BEAST), finish rods and Gill nets.

2355

2356 **Table S6. List of ECO sampling events for first and second year ice.** Event  
2357 Operation IDs, date and time, location and bottom depth for all common time-series  
2358 ice coring activities at the first and second year ice (FYI and SYI) coring sites.

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2360 **Table S7. List of ECO sampling events for event driven sampling and intense**  
2361 **observation periods (IOPs).** Event Operation IDs, date and time, location and  
2362 bottom depth for event-driven sampling of direct under ice water, leads, melt ponds,  
2363 new ice formation as well as high frequency IOP sampling.