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TITLE OF PROPOSED PROJECT

LTER: Seasonal controls and emergent effects of changing land-ice-ocean interactions on Arctic coastal ecosystems (BLE II)

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REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 6,375,000	60 months	09/01/2023	

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(This Certification applies to proposals submitted on or after July 31, 2023, and is not applicable to proposals for conferences, symposia, and workshops.)
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By electronically signing the certification pages, the Authorized Organizational Representative is certifying that the organization will be or is in compliance with all aspects of the United States Government Policy for Institutional Oversight of Life Sciences Dual Use Research of Concern.

Certification Requirement Specified in the William M.(Mac)Thornberry National Defense Authorization Act for Fiscal Year 2021, Section 223(a)(1) (42 USC 6605(a)(1))
By electronically signing the Certification Pages, the Authorized Organizational Representative is certifying that each individual employed by the organization and identified on the proposal as senior personnel has been made aware of the certification requirements identified in the William M.(Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021, Section 223(a)(1) (42 USC 6605(a)(1)).

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LTER: Seasonal Controls and Emergent Effects of Changing Land-Ice-Ocean Interactions on Arctic Coastal Ecosystems (BLE II)

Overview:
The Beaufort Lagoon Ecosystems (BLE) LTER program, founded in 2017, focuses on six semi-enclosed estuaries within three distinct geographic domains of the Alaska Beaufort Sea coast. These estuaries host productive, biologically complex assemblages of biota that are inherently shaped by extreme seasonal variations in physical-chemical conditions and increasingly challenged by shifts in seasonality as well as other climate change impacts in the rapidly warming Arctic. Higher level consumers in these systems include resident and anadromous fishes and migratory birds that serve important cultural and subsistence roles in the lives of native Alaskans living along the Beaufort Sea coast. Proposed research for BLE II includes continuation of Core Program measurements, next steps toward answering long-term questions established during BLE I, and exploration of new ideas. The pivotal role of sea ice is a common thread throughout this proposal, connecting our work through effects on physical, chemical, and biological components of the system. The guiding questions for BLE II are: 1) *How and in what forms do freshwater inflows, land-derived nutrients, and sediments arrive in the lagoons?* 2) *How does connectivity between lagoon and coastal shelf water vary over seasonal to interannual timeframes, and how will connectivity change in response to a shorter ice growth season and longer open water season?* 3) *How are nutrient cycling and greenhouse gas exchanges within the lagoons controlled by variations in organic matter inputs and local production (phytoplankton, ice algae, and benthic microalgae) over seasonal to multi-decadal timeframes?* 4) *How do climate forcing and seasonal drivers influence biological processes in lagoon ecosystems and the humans that depend on them?* These questions will be addressed with a suite of thematic research activities as well as overarching experimental, remote sensing, and modeling efforts.

Intellectual merit:
BLE is working to advance fundamental understanding of coastal ecosystems in the Arctic, quantify ongoing impacts of climate change, and support better prediction of future changes that are locally and globally relevant. The BLE lagoons serve as model systems to study how seasonal variations in physical conditions and food resources control stability and resilience of biotic communities, and how directional shifts driven by climate change alter community composition, trophic relationships, and biogeochemical cycling. While continuing to pursue founding objectives, BLE II places a greater emphasis on the roles of ice algae and benthic microalgae as sources of production within the lagoons; expands work on higher trophic level organisms, including linkages to human populations related to food safety and security; begins to address how saltwater intrusion is altering land-lagoon boundaries and biogeochemical fluxes; and works toward improved understanding of temporal and spatial variability across scales.

Broader Impacts:
This project will achieve broader impacts through continuation and enhancement of education and outreach programs that were established during BLE I as well as new initiatives to expand participation and strengthen connections with local communities on the North Slope of Alaska. Training of graduate students, undergraduates (Research Experiences for Undergraduates), and teachers (Research Experiences for Teachers) will continue to be an integral part of BLE. The Kaktovik Oceanography Program, offered in late summer to K-12 students and recent high-school graduates, will also be continued. New education efforts include 1) a partnership with Iḷisaġvik College, located in Utqiaġvik, to provide REU opportunities to Iḷisaġvik students, integrate BLE science and guest presenters into select college courses, and contribute to summer camps for teens, and 2) expanded Schoolyard activities with students at the Harold Kaveolook School in Kaktovik. These Schoolyard activities involve visits from BLE PIs, graduate students, and staff to conduct classroom and field activities twice during each school year. BLE also aims to increase local involvement in research and provide opportunities for REU participants to attend annual Alaska Marine Science Symposium meetings in Anchorage. BLE is strongly committed to Diversity Equity, and Inclusion (DEI), and will continue to foster and expand DEI at the project level and beyond.

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*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

LTER: Seasonal Controls and Emergent Effects of Changing Land-Ice-Ocean Interactions on Arctic Coastal Ecosystems (BLE II)

INTRODUCTION

Alaska's northern-most coastline runs along the Beaufort Sea for ~500 km between Point Barrow and the US-Canada border (Fig. 1). Approximately half this coastline is skirted by discontinuous barrier islands that enclose numerous shallow (< 7 m) lagoon ecosystems. These ecosystems host productive, biologically complex assemblages of biota that are inherently shaped by extreme seasonal variations in physical-chemical conditions and increasingly challenged by shifts in seasonality as well as other climate change impacts in the rapidly warming Arctic. Higher level consumers in these systems include resident and anadromous fishes as well as migratory birds that serve important cultural and subsistence roles in the lives of native Alaskans living along the Beaufort Sea coast.

Fig. 1. *Map depicting the BLE LTER sites along the Beaufort Sea coast. Site names are in yellow text and node names are in black text.*

The Beaufort Lagoon Ecosystems (BLE) LTER program focuses on six semi-enclosed estuaries within three distinct geographic domains (nodes) of the Alaska Beaufort Sea coast (Fig. 1). These estuaries vary in terrestrial inputs, ocean connectivity, and geomorphology. The western node includes eastern and western sections of Elson Lagoon, which lies adjacent to the native Inupiat village of Utqiaġvik. The central node, based in Deadhorse, includes Simpson Lagoon (east of the Colville River and the village of Nuiqsut) and the more open system of Stefansson Sound. The eastern node includes Kaktovik Lagoon and Jago Lagoon, directly adjacent to the native Inupiat village of Kaktovik on Barter Island.

Sea ice cover in the lagoons (and Stefansson Sound) reaches a thickness of ~1.5 to 1.8 m by early May each year. The Polar Night occurs for ~60 days, but widespread turbid ice can restrict light penetration to the seabed for the entire 8-9-month period of ice cover. During this period, salinity in bottom waters can range from near-oceanic (~32) to hypersaline (45 to 93), driven by brine rejection from sea ice formation, with water temperatures that range from -1.8 to -5.9°C.

Sea ice break-up occurs in June-July, facilitated by spring runoff from the North Slope (land area extending from the Brooks Range to the Beaufort Sea coast). Snowmelt delivers a large pulse of relatively warm, sediment-laden water from land into the coastal environment from late May to early June that accelerates thaw. At the same time, this runoff 1) mixes with salty lagoon winter water, causing rapid changes in coastal salinity conditions, and 2) delivers a large pulse of land-derived organic matter that fuels biogeochemical cycling and subsidizes food webs.

As the open water season continues into the summer, water temperatures increase to between 6 and 14 °C, and salinity fluctuates between brackish and oceanic as storm/wind events enhance or impede ocean exchanges. Open water conditions also facilitate coastal erosion. Erosion along the Alaska Beaufort Sea coast averaged ~2 m yr^{-1} between the late 1940s and early 2000s and has more than doubled during recent years at some locations (Bristol et al., 2021; Gibbs & Richmond, 2015; Jones et al., 2018;). This land loss contributes ~2100 Tg yr^{-1} of sediment and ~150 Gg yr^{-1} of organic carbon to coastal waters of the Alaska Beaufort Sea (Ping et al., 2011).

BLE foundation – BLE was founded upon a conceptual framework that emphasizes the intersection between extreme seasonal variations that inherently define Arctic coastal ecosystems and the relentless pressure of climate change that is forcing these ecosystems toward new states (Fig. 2). While interactions between seasonality and climate change are an important consideration globally, the sharp seasonal contrasts and amplified effects of climate change that Arctic coastal systems experience make them ideal testing grounds for hypotheses about how climate forcings and seasonal drivers interact to control ecosystem properties. The biota inhabiting these systems are adapted to strong seasonality, but changes in seasonality (e.g., shifts of timing or extremes) from climate forcing create disturbances.

In our first proposal we asked: *How do variations in terrestrial inputs, local production, and exchange between lagoon and ocean waters over seasonal, inter-annual, inter-decadal, and longer timeframes interact to control food web structure through effects on carbon and nitrogen cycling, microbial and metazoan community composition, and trophic linkages?* Work was then organized thematically around the following sub-questions:

Terrestrial inputs (Theme 1) – How and in what form do nutrients and water arrive in the lagoon systems?

Sea ice and ocean exchange (Theme 2) – How do changes in ice, freshwater discharges, and circulation influence the connectivity between lagoons and shelf water of the Beaufort Sea?

Lagoon biogeochemistry (Theme 3) – How are biogeochemical processes within the lagoons linked to inputs of terrestrial organic matter, autochthonous production, and inorganic carbon and nitrogen cycling?

Communities and trophic linkages (Theme 4) – How do changes in land-ocean connectivity, water residence times, and sea ice persistence influence benthic and pelagic community structure, resilience, and trophic linkages?

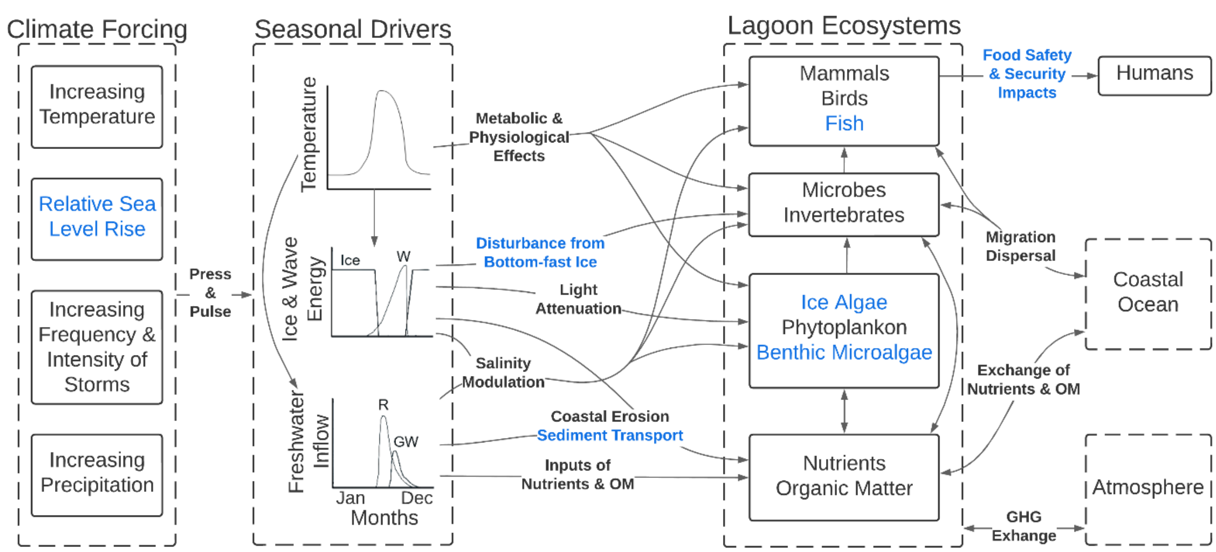

Fig. 2. *Conceptual framework for the BLE LTER program, emphasizing linked effects of seasonal drivers and climate forcing that control lagoon ecosystem dynamics in the rapidly changing Arctic. Text in blue typeface represents components receiving elevated focus in BLE II. Abbreviations are: W, wave energy; R, river. GW, groundwater; OM, organic matter; GHG, greenhouse gases.*

These questions, with some refinement (see Proposed Research), will remain central to our program during BLE II. New elements will also be embraced as we move forward (Fig. 2). Details about the new elements are provided in the Proposed Research section.

BLE study sites are representative of shallow semi-enclosed estuarine environments that fringe the convoluted Arctic coastline and our research is providing a fundamental understanding of land-sea coupling in these understudied environments. At the same time, there is an urgent need to project how climate change is altering Arctic coasts that ultimately affect their indigenous residents. Warming is occurring about four times faster in the Arctic than globally (Rantanen et al., 2022), and estuaries are particularly vulnerable because they are influenced by both terrestrial and oceanic changes.

On the land side, we are studying linkages between permafrost thaw, watershed hydrology, and coastal erosion that alter the timing, magnitude, and composition of terrestrial inputs (including freshwater, organic matter, and inorganic nutrients) to the lagoons. On the ocean side, we are examining how warming-induced changes in sea ice may directly (e.g., via effects on light availability and bottom-fast ice disturbance) and indirectly (e.g., via effects on mixing between lagoons and the open ocean) influence lagoon ecology (Fig. 2). Residents of Inupiat communities on the Beaufort coast that rely on the lagoons for hunting and fishing have a strong interest in how these ecosystems are changing. The lagoons are also recognized as potential hotspots for decomposition of land-derived organic matter (Connolly et al., 2021), a topic of broader scientific interest with respect to carbon-climate feedbacks in the Arctic.

From a basic ecological perspective, these lagoons serve as ideal model systems to study how temporal variations in food resources control trophic linkages, stability, and resilience of food webs. In particular, we are exploring how the differential availability of temporally distinct resources (e.g., fresh phytoplankton vs. detritus) alter bottom-up trophic processes to regulate consumer populations critical for indigenous users (McMeans et al., 2013; 2015). Temporal variations are inherent to most ecosystems, yet food web structure is often defined as a static property. Food webs change as habitats change over space or time (e.g., when seagrass meadows are replaced by bare sediments), but temporal variations are not typically considered a cornerstone of food web structure. Lagoons along the Alaska Beaufort Sea coast are ideal for testing effects of temporally distinct resources on trophic linkages, stability, and resilience of foods webs because they experience extreme variability in food resources over seasonal cycles and because they are experiencing rapid directional shifts driven by climate change.

BLE research is divided into "Core Program" activities and "PI-driven" work. The major distinction between these categories is that BLE is committed to maintaining Core Program measurements (Table 1) regardless of personnel changes over time, whereas PI-driven components require contributions/commitments by specific investigators or lab groups. Core Program measurements have stand-alone value for tracking basic system properties over long time frames and provide context for a range of PI-driven efforts. They also contribute to cross-LTER and broader community synthesis objectives. BLE ecosystem modeling leverages data from the Core Program as well as PI-driven efforts, providing an integrative framework for exploring our understanding of seasonal drivers and ecological responses as well as testing potential climate change effects.

Field work to support Core Program and PI-driven research is conducted during ice-cover, ice break-up, and open water periods, typically April, June, and August, respectively. During the ice-covered period, stations are accessed via snow machines and samples are retrieved from auger holes drilled through the sea ice. During break-up and open water, stations are accessed via small outboard-equipped inflatable vessels (e.g., 10-18' Achilles) and medium-sized aluminum vessels (~ 30 ft hulls). Six rivers/streams that drain into the study lagoons are also sampled routinely during this period.

BLE maintains a series of permanent stations that are seasonally reoccupied and/or host moorings with sensors that collect continuous (hourly) hydrographic measurements. Our Elson West, Elson East, Simpson, Stefansson, Kaktovik, and Jago sites each host two shallow stations (with bottom-fast ice during winter, < 1.5 m deep) and two deep stations (with liquid water under ice during winter, > 2 m deep). Deep and shallow

Table 1. *List of BLE Core Program measurements. DON = dissolved organic nitrogen. DOC = dissolved organic carbon. CDOM = chromophoric dissolved organic matter. GPP = gross primary production. R = respiration. NEP = net ecosystem production. NEM = net ecosystem metabolism. PAR = photosynthetically active radiation. Chl-a = chlorophyll-a. ^ denotes a parameter measured by seafloor moorings.*

Physical	Chemical	Biological
• Sea ice thickness • Pressure (sea level)^ • Temperature^ • Conductivity (salinity)^ • Current velocity^ • pH^ • PAR^ • Total suspended solids • Surface weather • Coastal imagery	• Dissolved inorganic nutrients in water column and porewaters • DON, DOC, CDOM • $\delta^{18}O$ • Dissolved oxygen^ • pCO_2 • Ecosystem metabolism (GPP, R, NEP, and NEM)	• Infaunal diversity and biomass • Microbial DNA & RNA in sediment and water column • Chl-a and other pigment concentrations in surface sediment and water column • $\delta^{13}C$, $\delta^{15}N$, & C:N for food web end-members and consumers

stations have been further designated as either "primary" or "secondary" to guide prioritization of sampling efforts that ensure continuous timeseries measurements are collected within each lagoon site, as unexpected logistical constraints (e.g., foul weather; ice) can reduce planned sampling efforts of all stations. Occupation of permanent stations is particularly challenging during the ice break-up period. Areas of open water typically develop near the shoreline first, making access to shallow sites more reliable than deep sites. However, variability in patterns of open water development from year to year has necessitated a more flexible sampling approach during the ice break-up period, with field efforts targeting accessible locations wherever they develop.

Impacts from COVID-19 – All field operations for 2020 were cancelled due to the COVID-19 pandemic. This was necessary for the safety of our team members as well as the communities that we work from on the North Slope. Lab operations, modeling, and other computer-oriented efforts were also slowed as we adjusted to university closures and working from home. BLE personnel were successful in finding ways to make progress during 2020 despite the pandemic. For example, students took advantage of historical datasets and incorporated new synthesis activities into their research plans. We also used the downtime to refine field and lab protocol documents, update our Code of Conduct and Sexual Misconduct policies, improve data management work-flows, and develop our Field Safety Plan and Diversity Equity and Inclusion (DEI) policies and goals. While these pandemic-born efforts cannot replace the lost field time, BLE is stronger and better prepared for the future because of them.

BLE resumed field operations out of Deadhorse and Utqiaġvik in April 2021. Field operations out of Kaktovik have taken longer to recommence because that community remained closed to visitors until August 2022. We were able to conduct limited vessel-based field campaigns at Kaktovik during August 2021, April 2022, and August 2022, but full field operations will not resume until April 2023.

RESULTS FROM PRIOR SUPPORT

This section presents 1) thematic research accomplishments, 2) data products and availability, 3) results of supplementary support, 4) cross-LTER and broader synthesis work, 5) education and outreach, and 6) the 10 most significant publications for BLE I.

Terrestrial inputs (Theme 1) – While datasets from BLE's field efforts are still nascent, we have made substantial progress on characterization of river, groundwater, and erosional inputs to the lagoons through leveraging of existing datasets, modeling, and remote sensing.

Rivers – Given BLE's large geographic domain, it is not practical to directly measure all fluvial inputs to our study sites. Thus, while we are conducting field work on select streams and rivers at each project node, we are also developing and applying a variety of tools to support input estimation over broader areas. We used a hydrological model tailored to permafrost environments to quantify discharge from the North Slope between 1981 and 2010 (Rawlins et al., 2019). Discharge averaged 31.9 $km^3 yr^{-1}$ and more than doubled during the cold season (Nov-Apr) over this timeframe (Fig. 3). We also developed model components to simulate dissolved organic carbon (DOC) leaching from soils into surface and subsurface runoff (Rawlins et al., 2021a). This DOC-enabled model captures seasonal cycles in concentrations and loadings and provides a basis for assessing impacts of changing hydrology and permafrost thaw on DOC export. For example, application to the Elson Lagoon watershed showed major increases in water and DOC export over 1981-2020 (Rawlins, 2021b). Alongside these modeling efforts, we used historical data from streams/rivers in northern Alaska, as well as other places around the Arctic, to explore relationships between water chemistry and catchment characteristics. This exploration revealed that watershed slope is a strong predictor of DOC and dissolved organic nitrogen (DON) concentrations in Arctic rivers (Connolly et al., 2018). The slope-concentration relationships will be refined with new BLE data over time, but even now we have a powerful regression-based tool to estimate DOC and DON concentrations that can be applied independently or in combination with hydrologic modeling.

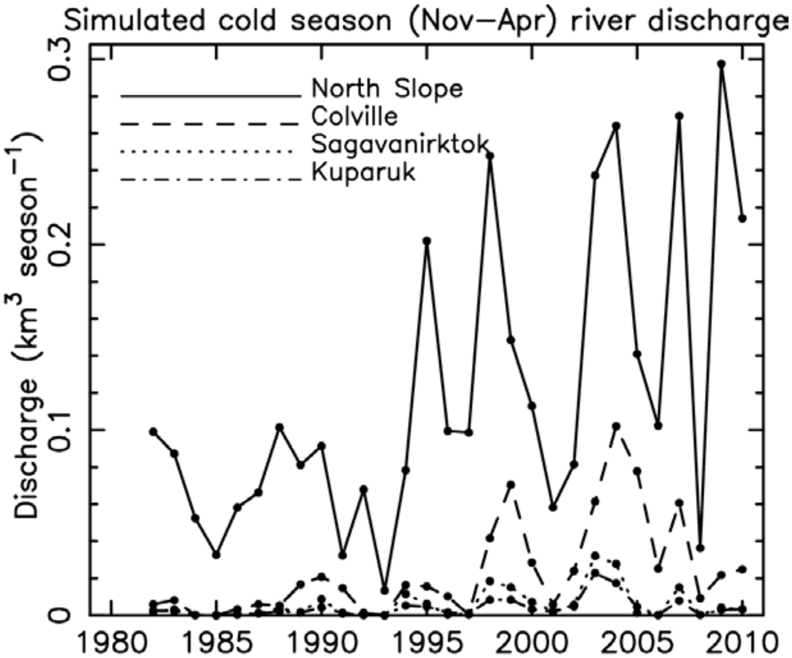

Fig. 3. *Simulated cold season discharge for the full North Slope region and for the three largest rivers draining the North Slope (Colville, Sagavanirktok, and Kuparuk).*

Groundwater – Work focusing on the Kaktovik region during BLE I showed that inputs of dissolved organic matter (DOM) to lagoons via supra-permafrost groundwater may exceed inputs from rivers during late summer (Connolly et al., 2020), and that taliks (layers of year-round unfrozen sediment) spanning the land-lagoon interface, may provide conduits for deeper groundwater exchange throughout the year (Pedrazas et al., 2020). These early advances leveraged graduate student projects that began during proposal development and were supported by the BLE from 2017-2019. We established new groundwater study sites at Simpson Lagoon in 2021 to expand on this work.

Coastal erosion – Work focusing on the shoreline of Elson Lagoon showed that mean erosion rates of 2.1 m yr^{-1} from 2000-2018 were 133% greater than mean rates over 1979-2000 (Jones et al., 2020). Since 1955 more than 80 ha of coastal landscape has been lost to erosion, equating to ~136 $m^3 m^{-1}$ and ~ 5 t soil C m^{-1} of eroding coast. Data from the USGS was used to develop semi-automated workflows from multi-temporal high-resolution imagery for processing change across the broader BLE domain. Results show Elson Lagoon to have the highest rates of erosion followed by Simpson, Kaktovik, and Jago Lagoons. Wave-energy driven by prevailing E/NE winds appears to control erosion in Elson Lagoon, but not in Simpson Lagoon where erosion occurs on west-facing bluffs exposed to warm Colville River water. To further streamline data acquisition and processing, we are exploring machine learning approaches. Results suggest that Random

Forest approaches perform shoreline mapping better than XG-Boost or a Deep Neural Network U-Net architecture (Aryal et al., 2021).

In addition to our erosion work on lagoon shorelines, we conducted work at Drew Point. This study site, which lies between our western and central research nodes, provides an open coastal reference for comparison with lagoon sites. Permafrost cores at Drew Point were used to document geochemical profiles of eroding bluffs and quantify inputs of organic carbon and nitrogen to adjacent coastal waters (Bristol et al., 2021). Erosional fluxes of organic carbon into the ocean averaged 1,369 kg C m^{-1} $year^{-1}$ during 2002–2018, approximately double the average flux of the previous half-century (1955-2002).

Sea ice and ocean exchange (Theme 2) – Through a program of buoys, moorings, field surveys, and remote sensing analyses, we are quantifying growth and melt of sea ice, extent of bottomfast ice formation, and circulation and hydrographic properties of the water below.

Sea ice – Primary observations of sea ice during BLE I included *in situ* measurements of sea-ice mass-balance (i.e., changes in the ice thickness associated with growth and melt) and satellite-based mapping of bottomfast ice extent validated by *in situ* measurements. Automated seasonal ice mass-balance buoys (SIMBs) have provided data for two seasons in both Elson Lagoon (2019 and 2022) and Stefansson Sound (2018 and 2019), allowing us to quantify the timing of key events such as melt onset and complete removal of snow in these years (e.g., Fig. 4). SIMB data also quantify the annual maximum thickness of ice, which is a critical parameter to measure since it regulates light availability to lagoon primary producers during spring, determines the volume of unfrozen water remaining in the lagoon, and alludes to the potential extent of bottomfast ice. In early 2020, we installed equipment for a community-based program of sea ice mass-balance observations in Kaktovik and Jago Lagoons (following the work of Mahoney et al., 2009; 2021), but scheduling conflicts and subsequent travel restrictions prevented adoption by community members.

In areas shallower than ~1.8 m, the entire water column can freeze allowing the sea ice to become bottomfast, which has significant implications for the thermal regime of the seafloor and associated benthic organisms (see cross-cutting experiment section). Using interferometric synthetic aperture radar (InSAR) techniques, we mapped the seasonal development of bottom-fast ice extent at all three BLE nodes from

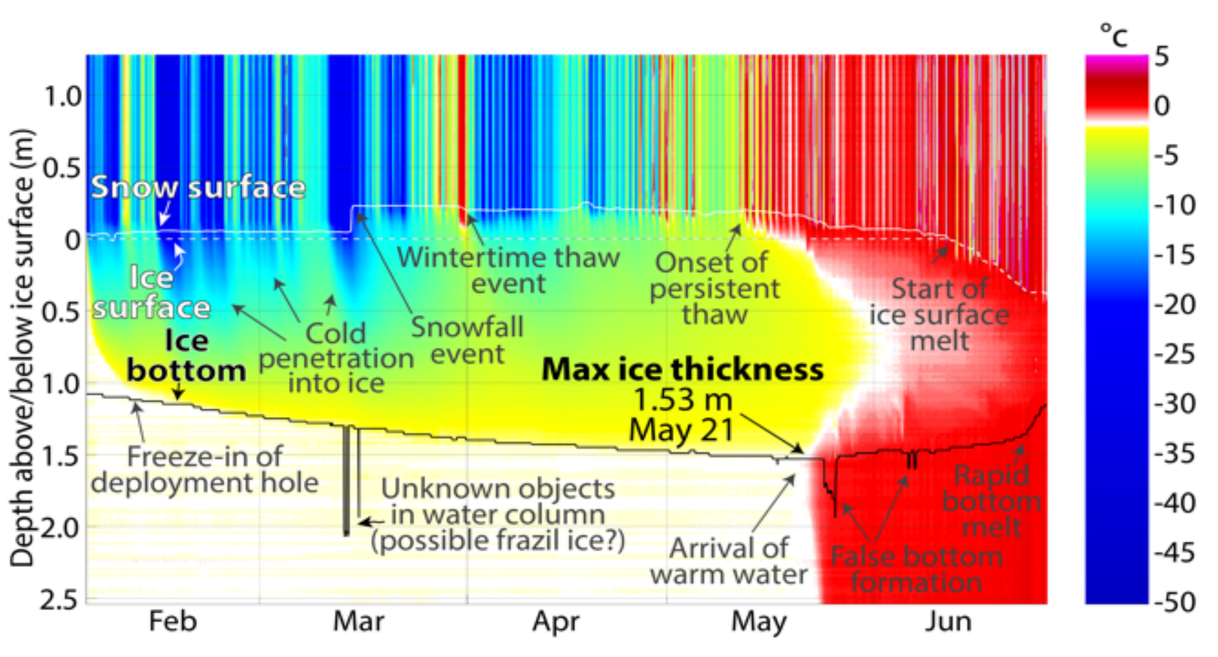

Fig. 4. *Sea ice mass-balance buoy data from Stefansson Sound in 2019 showing key seasonal events.*

2016-2021, validating our results with drill-hole surveys in western Elson Lagoon. This work formed the basis of a MS geophysics thesis for recently graduated UAF student Jacob Pratt (Pratt, 2022). We also started a program of multi-frequency electromagnetic (EM) surveys that we anticipate will allow us to map both ice thickness and the depth of unfrozen water beneath, potentially offering a way to expand our bathymetric measurements of the lagoons.

Ocean exchange – As described in the Introduction, the BLE Core Program maintains moorings at each research node that measure a variety of physical and chemical parameters year-round (Table 1). Physical data on current speed and direction, temperature, salinity, water column height, and non-directional wave spectra (wave height and period) from the moorings allow us to quantify transport of water, heat, and salt. Use of these data is highlighted in the lagoon ecosystem modeling section below.

The mooring data are supplemented by point-based measurements routinely collected in conjunction with other sampling efforts during field excursions. These include conductivity, temperature, depth (CTD) casts and measurements of suspended matter, nutrients, and stable isotopes from water samples. These observations provide additional information on water mass origin and can be used in conjunction with our transport measurements to infer information about residence times and lagoon-ocean exchange rates. In 2021, we extended our routine sampling activities during late winter by making transect measurements of velocity, salinity, and temperature through a series of holes in the ice. Data from these transects will allow us to quantify fluxes along the transects during the under-sampled period when lagoons are ice covered. Additionally, we piloted the use of a Sofar "smart mooring" through the ice in Stefansson Sound in April 2021. The mooring includes a surface float to measure waves and thermistors to measure surface and sub-surface water temperatures to provides unique water column information during the critical period of the spring freshet, when northern rivers discharge >90% of their volume into these lagoon systems.

Lagoon biogeochemistry (Theme 3) – Results from water column and sediment studies have greatly advanced our understanding of seasonal and spatial patterns in lagoon biogeochemistry. Experimental results have also shed light on organic matter lability and nutrient limitation.

Water column nutrients and organic matter – Results from Core Program sampling showed that seasonal patterns in water column nutrients and organic matter, first documented at sites along the eastern Alaska Beaufort Sea coast (Connelly et al., 2015; Connolly et al., 2021; Kellogg et al., 2019), are consistent across the entire BLE domain. Most notably, dissolved and particulate organic matter were highest during ice break-up, intermediate during open water, and lowest under ice. In contrast, inorganic nutrients were highest under ice. These patterns correlated with seasonal variations in salinity and associated changes in water sources (Harris et al., 2017). We also see emerging evidence of geographic gradients. For example, DOC in lagoon water increases from west to east across the BLE domain, which, interestingly, is opposite to the DOC gradient in watershed runoff (see Terrestrial inputs section). We hypothesize that ocean mixing and *in situ* processing effects override the effect of terrestrial input gradients during summer.

Porewater nutrients and benthic metabolism – Nutrient concentrations in sediment porewater were generally higher than in overlying water and showed less consistent seasonal variations. N_2 fluxes across the sediment-water interface, on the other hand, varied seasonally. N_2 fluxes into the water column were moderately positive during the ice-covered period and became more positive during break-up, but were negative during the open water period. Positive N_2 fluxes indicated net denitrification, which is a critical removal mechanism for bioavailable N, potentially reducing fuel for primary production in the lagoons.

Measurements of O_2 fluxes from sediment cores maintained under light and dark conditions were used to quantify benthic respiration (R), gross primary production (GPP), and net ecosystem metabolism (NEM) at the sediment-water interface (GPP + R = NEM). Our results show that benthic R was very low during the ice-covered period and ramped up during the other periods, likely reflecting increasing temperatures (Fig. 5). NEM showed a seasonal shift from net heterotrophic (CO_2 released from sediments) under ice to net autotrophic (CO_2 uptake) during break-up and open water. Shallow stations exhibited markedly high GPP during break-up and open water. These seasonal shifts in benthic metabolism may be tightly coupled with

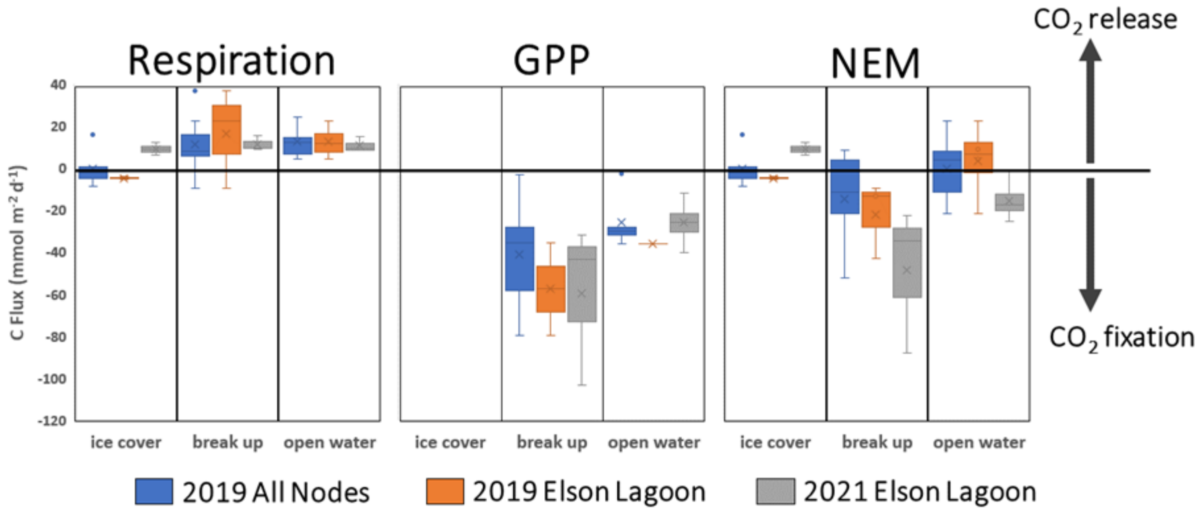

Fig. 5. *Benthic metabolism metrics derived from net O_2 fluxes from sediment batch incubations. Negative y-axis values represent carbon fixation. Units of C were derived using a -1:1 C:O_2 ratio. GPP = gross primary production. NEM: net ecosystem metabolism. GPP+R=NEM.*

microalgae production in surface sediments (Proposed Research for Themes 3 and 4).

Water column CO_2 – Measurements of pCO_2 in the water column showed evidence of seasonally varying uptake and release within the lagoons. Average concentrations of pCO_2 in bottom waters were higher than average concentrations in surface waters during ice-cover and break-up, suggesting strong coupling with benthic metabolism. Patterns in pCO2 also varied among lagoons. Jago and Kaktovik Lagoons exhibited the highest bottom water pCO_2 values, reaching three-times atmospheric levels during ice cover. We also saw that pCO_2 correlated with total organic C concentration and $\delta^{13}C$ of particulate organic carbon across all lagoons, suggesting a link between organic carbon lability, quantity, and source, and the accumulation of CO_2 during ice-cover and break-up periods.

Organic matter lability and nutrient limitation – Water incubation experiments examining the role of light and microbes on dissolved organic matter lability in Elson Lagoon revealed that sunlight significantly alters DOC, particularly in water collected from deeper sites. Furthermore, degradation is enhanced by the addition of freshwater microbes, suggesting a possible effect of microbial dispersal on lagoon carbon cycling. Nutrient limitation experiments in Elson Lagoon also point to the importance of river inflows as a control on primary production. In late summer, phytoplankton in the largest river inflows of the eastern portions of Elson Lagoon were co-limited by N and P (as seen in tundra ponds; Lougheed et al., 2015), while algae in the lagoon itself were largely N-limited.

Communities and trophic linkages (Theme 4) – Water column microbial assemblages changed seasonally but reformed similarly each year (i.e., resiliency to change), whereas the benthic microbial and macrofaunal assemblages changed little between seasons (i.e., resistance to change). The benthic food web exhibited differential trophic niche size between seasons, suggesting trophic plasticity in many consumers in response to autogenous production, despite year-round availability of terrestrial organic C.

Microbial communities, metagenomics, and metatranscriptomics – Our surveys of microbial community composition over four years found that pelagic communities were similar among lagoons but differed substantially across seasons, and that this seasonal shift reoccurs annually (Kellogg et al., 2019). Metagenome sequencing revealed a similar seasonal pattern in the genomic potential of planktonic microbes (Baker et al., 2021), suggesting that planktonic communities are not resistant to seasonally changing conditions, but are resilient because they reassemble predictably every year. In contrast, sediment

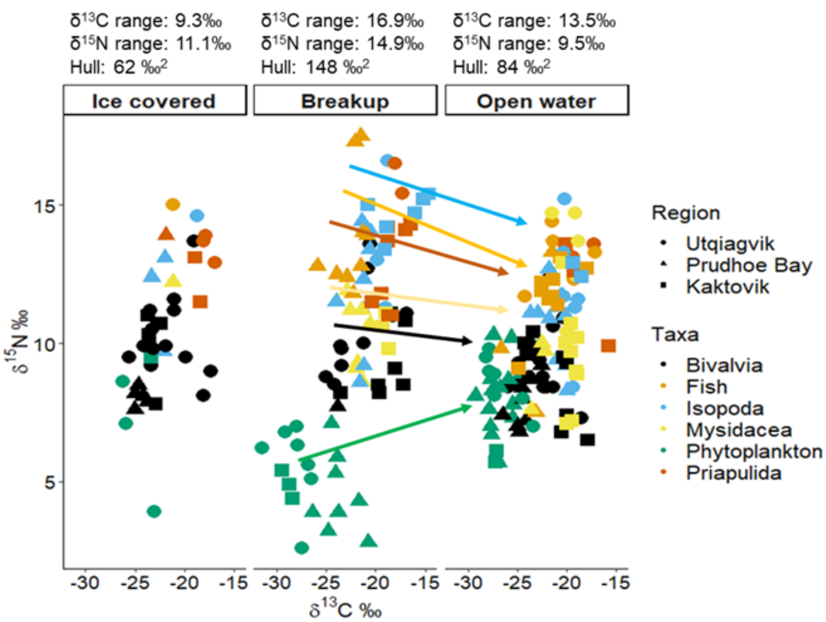

***Fig. 6**. Carbon and nitrogen isotope values of common consumers across all lagoon systems for ice covered (April), break-up (June), and summer (August) seasons. Various trophic metrics were calculated that describe the trophic niches of consumers during each season.*

microbial communities were highly similar across seasons and years, meaning that, unlike plankton communities, they are resistant to the seasonal changes. In this context, we define resistance as the ability to withstand change and resilience as the speed of recovery from change (Pimm 1984). Our results suggest fundamentally different processes driving microbial community dynamics in lagoon sediments and waters. Metagenome sequencing demonstrated that these patterns in microbial diversity reflect patterns in microbial ecosystem function. During ice-cover, gene abundances revealed elevated levels of autotrophic bacterial metabolism, chemoautotrophic carbon fixation, methane metabolism, and nitrification, consistent with our observation that water column nitrification was only measurable during ice cover, and inhibited by sunlight (Griffin, 2022). These findings suggest that high latitude estuarine microbial communities shift metabolic capabilities as they change phylogenetic composition between seasons.

<u>Benthic macrofauna</u> – Similar to sediment microbial communities, benthic macrofauna communities appear to vary primarily by location in estuaries, and not by season. Specifically, pronounced differences were detected between shallow (<2 m) and deep (>3 m) communities that may be caused by bottom-fast ice formation and sediment freezing at shallow sites. Oligochaetes common at shallow stations are known to be more freeze tolerant than other common lagoon benthos (Slotsbo et al., 2008). We collected frozen sediment cores from shallow lagoon sites and upon thawing, found that oligochaetes within became active. In contrast, polychaetes fluctuated seasonally at shallow sites with lowest abundance in April. These differences represent two modes of survival for benthos: resistance by oligochaete-dominated communities to seasonal drivers like freezing, and resilience by polychaete-dominated communities to these same drivers. These differences in resistance and resilience of benthic communities may be important local drivers of food resource availability for migratory birds and other megafauna.

<u>Food web structure</u> – We also investigated seasonal patterns in food web structure with stable carbon and nitrogen isotope measurements of animal biomass. Across all lagoon systems, $\delta^{13}C$ and $\delta^{15}N$ was most variable during the break-up period (Fig. 6), suggesting broad trophic niches for lagoon plankton and benthos. These trophic niche ranges expanded during break-up, due to major trophic shifts for phytoplankton, benthic deposit feeders (*Priapulus* and *Saduria*), and fish. Relatively higher niche diversification during break-up (i.e., larger hull size; Fig. 6) may indicate lower resource availability during ice-cover and open water, forcing taxa to use less desirable resources such as terrestrial organic matter (low $\delta^{13}C$ values) and reworked detritus (high $\delta^{15}N$ values). The shift in trophic structure between break-up and summer illustrates high trophic plasticity in many consumers and is likely an important strategy in the resilience of these taxa to the highly seasonal food supply of the lagoons. Further evidence of this trophic

plasticity comes from ^{14}C abundance measurements, which showed that many invertebrates assimilate older terrestrial organic C. For example, the ^{14}C ages of chironomids was 1,380 years BP and estuarine polychaetes was 3,580 years BP. Also, many benthic invertebrates that appear to rely on terrestrial carbon are resistant to low temperatures and high salinities typical of sediment in bottom-fast ice zones (-6 °C and of 90 PSU). These invertebrates are key prey species for anadromous fish and ducks, which in turn are common Inupiat subsistence food sources.

Lagoon ecosystem modeling – During BLE I, we configured a coupled circulation/ice/biogeochemical model and calibrated it with data from Elson Lagoon.

Coupled circulation and ice model – The circulation/ice components are based on the Regional Ocean Model System (ROMS) (Shchepetkin & McWilliams, 2005) with the ice model derived from Durski and Kurapov (2019). Utilizing high-resolution bathymetry, freshwater inputs, wind stress, and water exchange through the lagoon's major pass (Fig. 7a-b), this coupled model is able to reproduce the timing of water temperature and salinity fluctuations associated with the formation and melting of sea ice and sea surface height (Fig. 7c-d). However, we are still exploring the sources of freshwater during spring as the model shows slower and less desalination than the observations. The inputs due to precipitation and river discharge are not sufficient to account for the freshening of the water column after ice melts. Model outputs of sea surface height tightly agree with observations (Fig. 7c).

Lagoon-shelf exchanges were addressed with our model. We found that the transport through Eluitkak Pass is out of Elson Lagoon more than 70% of the time (Fig. 7b), which is consistent with the findings of Li et al. (2019). Sensitivity analyses with various depths for the Pass show that in addition to the local wind, flow through Eluitkak Pass strongly modifies circulation in the western lagoon. It is, therefore, imperative to have an accurate volume of the Pass to model lagoon circulation correctly. Tracer tracking simulations were used to assess the river transport of nutrients and dissolved organic matter, then determined where in the lagoon they have the largest impacts. We are currently working on computing residence time of these tracers in the lagoon.

Biogeochemical model – The biogeochemical model for the water column and the benthic layers includes nutrients, plankton, heterotrophic bacteria, dissolved and detrital organic matter, and oxygen. It is coupled to the 3D-circulation/ice model. A 1D Matlab version, with mixing following the PWP mixing model (Price et al., 1986), an ice thickness growth model based on Anderson (1961), and snow from atmospheric reanalysis (ERA5; Hersbach et al., 2017) to limit light for photosynthesis showed that the model can project mean chlorophyll-*a* (hereafter, chlorophyll) concentrations in Elson Lagoon. This approach allows us to

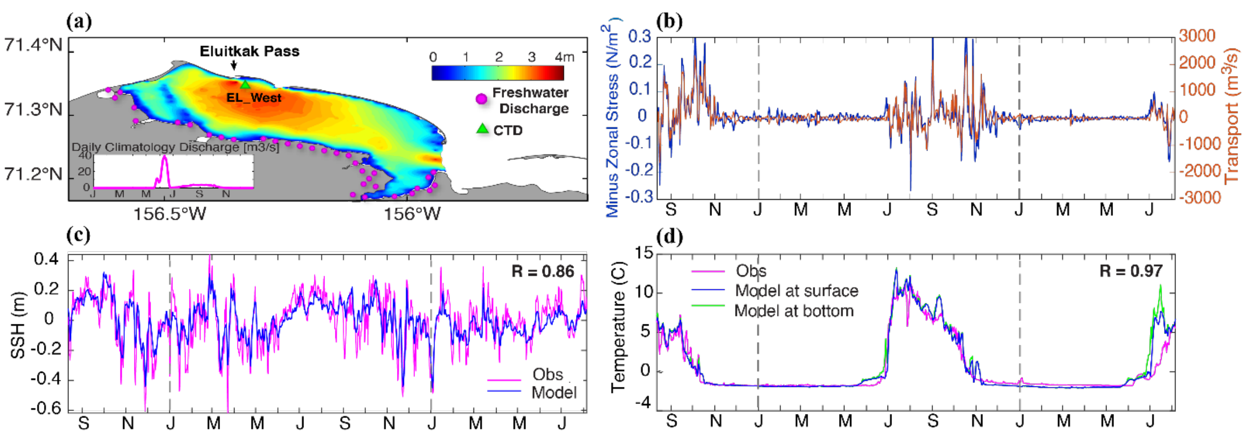

Fig. *7. a) Elson Lagoon bathymetry (m), location of the observation site (EL_West), and freshwater discharge (m^3/s) inset; b) Minus zonal wind stress (N/m^2) (positive westward) and Eluitkak Pass transport (m^3/s) (positive=outward); c) modeled and observed sea surface height (m) at EL_WEST; d) modeled and observed temperature (^{o}C).*

run the model quickly and test effects of model parameterizations and changes in the forcing for multiple years. For example, we found that the modeled particulate organic nitrogen (PON) in the water column deviates from the measured PON if the benthic detritus pool is not added to the water column pool. Based on this finding, we can now assess the possibility of sediment resuspension and the addition of other material, including terrestrial organic carbon contributions to the particulate pool. Based on isotopic data, it is possible that some non-marine components make up a large percentage of the PON pool.

Summary of BLE Products – Since its founding in 2017, the BLE LTER has published 23 peer-reviewed articles; supported 22 graduate students, 1 postdoctoral researcher, 7 REUs, and 2 RETs; and produced 28 datasets that have been downloaded 2,731 times.

BLE's 10 most significant publications – Full bibliographic information can be found in References section. Letters designate LTER Core Research Areas: A) primary production; B) population dynamics and trophic structure; C) movement of organic matter; D) movement of inorganic matter; E) disturbance patterns. An asterisk denotes student first authors. BLE Themes are denoted by number.

1. **Baker* et al., 2021.** *This study shows that microbial assemblages in Arctic lagoons shift metabolic capabilities as they change phylogenetic composition during extreme seasonal changes in the lagoons.* B, E. Theme 4.
2. **Bonsell* and Dunton, 2021.** *This study demonstrates that kelp community development in the nearshore Beaufort Sea occurs over decades, responding to combinations of recruitment limitation, primary disturbance, and abiotic stressors.* A, B, E. Theme 4.
3. **Bristol* et al., 2021.** *This study quantifies recent increases in coastal erosion and demonstrates that erosional inputs are a major source of permafrost carbon and nitrogen to Arctic coastal waters.* C, D. Theme 1.
4. **Connolly* et al., 2020.** *This study quantifies substantial groundwater inputs of freshwater, dissolved organic carbon, and dissolved organic nitrogen to the lagoon and coastal ocean environments; these inputs are predicted to increase as permafrost thaw accelerates.* C. Theme 1.
5. Ducklow et al., 2022. *This cross-LTER synthesis paper compares five marine pelagic sites across the globe in terms of primary producer and consumer responses to climate change forcings.* A, B. Theme 3, 4.
6. **Lougheed et al., 2020.** *This study examines CO_2 fluxes from ubiquitous Arctic aquatic ecosystems – ponds, lakes, rivers, lagoons, and coastal ocean – to assess their relationship to dissolved organic carbon and abiotic drivers.* C, D. Theme 3.
7. **Miller* et al., 2021.** *This study uses BLE Core Program high-frequency (hourly) time series data (pH, salinity, temperature, PAR) to estimate lagoon CO_2 fluxes through seasonal changes over the course of a year.* D. Theme 3.
8. **Rawlins et al., 2021.** *This study quantifies model-simulated estimates of dissolved organic carbon concentrations and loadings to western Arctic rivers as a basis for understanding carbon export to coastal waters.* C. Theme 1.
9. **von Biela et al., 2023.** *This study compares summer fish species assemblage, catch rate, and size distribution among three periods that span a 30-year record to illustrate the borealization of an Arctic nearshore fish community during a period of rapid warming.* B. Theme 4.
10. **Zimmermann et al., 2022.** *This paper examines patterns of nearshore bathymetry change from post-WWII era to recent observations and relates them to coastal erosion and seabed resuspension, both of which are more pronounced as sea ice extent decreases.* D, E. Theme 2.

Data availability – To date, BLE has published 28 datasets. Most of these are archived at the Environmental Data Initiative (EDI) with metadata replicated at the Arctic Data Center (ADC) to enhance discoverability. Two datasets include genomics data and are archived at NIH GenBank which specializes in such data. Datasets with partial funding from BLE may be archived in other repositories but are cataloged on the BLE website under Data > Find Data > Related Data. All BLE datasets published at EDI include Ecological Metadata Language (EML) metadata and are also discoverable from the BLE website.

Published BLE datasets are listed in Table S1 of this document. These data cover the five LTER core areas and are all available for public access and use. Most datasets are published as in the public domain, for example, using a CC0 license. Datasets published outside of EDI may have other licenses such as CC BY 4.0 license. Note that some datasets from work conducted during BLE I have yet to be archived because they are still in progress; these will be archived within the two-year window required of LTER data.

Results of supplemental support – BLE received supplemental support through the NSF Non-Academic Research Internships for Graduate Students (**INTERN**) and Research Experiences for Teachers (**RET**). The INTERN supplement provided an internship for a graduate student (Craig Connolly) at the US Geological Survey Alaska Science Center during summer 2019. Craig worked with USGS colleagues on a study of surface and groundwater hydrology and biogeochemical transport in the Canning River watershed. In addition to supporting advancement of scientific knowledge, this internship provided Craig with valuable experience working with a non-academic agency and fostered collaborative ties between the USGS and BLE. The RET supplement supported involvement of two female Hispanic science K-12 teachers in BLE research in summer 2022. One teacher deployed to Utqiaġvik and one to Prudhoe Bay. In partnership with BLE scientists, both teachers are producing "Arctic Data Nugget" lesson plans following the *Data Nugget* format developed by Michigan State University. We also received supplemental support to extend funding for the BLE program. The global pandemic resulted in the loss of an entire year of field work (2020). Supplemental support was provided to extend BLE I to a sixth year to ensure data continuity and completion of studies initiated by PIs and graduate students as described in the Results.

LTER and other cross-site synthesis accomplishments/findings – A recent cross site synthesis incorporated five LTER marine coastal ecosystems (BLE, CCE, NES, NGA, and PAL). The resultant paper "Marine pelagic ecosystem responses to climate variability and change" (Ducklow et al., 2022) was one of several papers published in a special issue of *BioScience* on long-term ecosystem response to climate change and variability. BLE PI Dunton contributed to the pelagic synthesis paper which summarizes how well-known climate modes, which effect marine ecosystems through the geophysical system of atmospheric and ocean currents, provide insights into the effects of longer term, unidirectional climate trends. The authors examined effects of climate forcing on physical and ecological processes from the poles to mid-latitudes, developing new ideas on ecosystem response to climate forcing. A second paper, "*Monitoring Alaskan Arctic shelf ecosystems through collaborative observation networks"* (Danielson et al., 2022) summarized the extensive ongoing scientific programs in the western American Arctic. Dunton provided input for this synopsis, which illustrated the critical role of BLE in providing the only long-term integrated autonomous measurements along the Beaufort Sea coast.

BLE is also involved in international projects aimed at pan-Arctic synthesis. Dunton is a co-PI on the TerrACE (*Terrestrial inputs as a key driver of Arctic Coastal biogeochemistry, Ecology, and contamination*) project, funded by the Norwegian Research Council. This research effort is focused on the role of terrestrial inputs to coastal waters (in this case, Svalbard). Both Dunton and Iken are co-PIs on an international program involving five countries entitled "*De-icing of Arctic Coasts: Critical or new opportunities for marine biodiversity and Ecosystem Services (ACCES)?*" funded by the NSF Belmont Forum Collaborative Research (BiodivERsA) program. This research effort is focused on how increased coastal erosion and sediment loads are physically changing nearshore bottom habitats, biodiversity, and trophic dynamics in the High Arctic. Long-term irradiance data collected in the Beaufort Sea by Dunton before the founding of BLE and continued as part of the LTER program was featured in a recent ACCES modeling paper on the availability of light on the Arctic seabed (Singh et al., 2022).

Broader Impacts – Broader impacts accomplishments during BLE I included successful implementation of schoolyard efforts as well as offering Research Experiences for Undergraduates (REU) and Research Experiences for Teachers (RET) opportunities. See the "Results of supplemental support" section above for more information on the RETs. In addition, we worked to strengthen ties with residents of Kaktovik through the distribution of newsletters (see BLE website), participation in community activities, and the establishment of a Traditional Knowledge (TK) panel that meets regularly (the panel includes PI Dunton and several Inupiat hunters and fishers).

Schoolyard ecology program: in-person Kaktovik Oceanography Program (KOP) – The Schoolyard Program builds on the long-standing summer KOP which Dunton started in 2017. The 5-day KOP learning opportunity takes place annually in mid-August in collaboration with Harold Kaveolook School and the U.S. Fish and Wildlife Service. Other contributing partners include the Bureau of Ocean Energy Management (BOEM) and the US Geological Survey (USGS). Formal classes at Kaveolook School begin on the latter two days of KOP, allowing us to help teachers engage older students in a variety of field activities, including learning research techniques aboard our 30-foot research vessel. Such activities significantly increased the participation by middle school and high school youth. Students explore a range of disciplines that include local ecology and geology, environmental chemistry, and climatology. The program is led by BLE researchers, graduate students, staff, and experienced K-12 science teachers.

Other Schoolyard Activities – Secondary students from Harold Kaveolook School joined researchers on the ice in Kaktovik Lagoon in April 2019 and 2022. Both field experiences were extremely successful with the Inupiat mayors of the village (Amanda Kaleak and Flora Rexford) joining us on both expeditions with their snowmachines. In 2019, we were joined by Dr. Matthew Burtner, a contemporary award-winning American composer and professor at the University of Virginia (who also works with the Virginia Coastal Reserve LTER). Kaktovik students excitedly joined Dr. Burtner and the BLE team on the ice where he established a temporary interactive acoustic laboratory. Dr. Burtner sonified the first year of BLE data into *Sonification of an Arctic Lagoon*, an ecoacoustic sound artwork which was published on the musical album *Icefield* (2022, Ravello Records RR8066 Parma Recordings/Naxos, Boston, MA). The piece was also released as a music video on YouTube. *Sonification of an Arctic Lagoon* converts one year of water velocity, salinity, temperature, and light data into contrapuntal sonic voices, synthesizing these data sets across a four-minute duration so that a listener can hear the dramatic interaction of these environmental parameters unfolding as music.

The KOP was cancelled from 2020-2022 due to COVID-19 closures and travel restrictions. In response, BLE pivoted to distance-delivered lessons and activities during that timeframe. Guided by our education and outreach coordinator Katie Gavenus (Center for Alaskan Coastal Studies) and PI Dunton, BLE graduate students and research staff developed thematic ideas for virtual education. These ideas were distilled into four topics that maximized student interest and relevance to age-appropriate experiential science learning: (1) microbes & DNA, (2) coastal invertebrates, (3) owls, tundra habitats, and ecosystems, and (4) coastal erosion. All grades of Harold Kaveolook School participated in these "Arctic Nuggets" distance-delivered learning opportunities. Our education partner at the U.S. Fish and Wildlife Service educator (Allyssa Morris) led additional virtual presentations about owls and owl pellet dissection labs with all the four 5th grade classes of Fred Ipalook Elementary School in Utqiaġvik, Alaska.

REUs – Despite the loss of two summer field seasons from COVID-related closures and quarantine restrictions, we recruited seven REU students and expect to recruit three more in summer 2023 under BLE I funding (10 students total). Of the seven REU students sponsored to date, four were Hispanic women from UTEP and UT-Austin, one was a male Hispanic student from UTEP, and one was an Army veteran. These students (with the one exception during COVID) joined researchers in the field in Utqiaġvik and Kaktovik. In addition to conducting research, the REUs participated in virtual professional development seminars, shared online lab notebooks, online data analysis video tutorials (developed by PI Lougheed), and virtual meetings two to three times per week.

RESPONSE TO THE MIDTERM REVIEW

The midterm review for BLE I was conducted September 2021. We met with the review panel and NSF representatives virtually over a 2.5-day period spanning September 7-9. The panel was strongly supportive of BLE's ongoing work and accomplishments and provided four recommendations for action during the remainder of the grant period. Two of these recommendations focused on information management, one focused on access to digital products associated with our education and outreach efforts, and one focused on REU support. These recommendations were addressed as described below.

Information management and sample archival – The review committee recommended that we **(1)** *"develop an explicit policy and plan for information transfer before a researcher leaves the group"*, and **(2)** *"develop and make discoverable a description of physically-archived samples"*. These two recommendations were addressed by updating our Policy on Data Stewardship, Use, and Access document to include guidance on information transfer for departing personnel and sample archiving. A link to this document is provided in the Policies section of our website (subsection of Project Overview). We also added information to the Data section of our website describing physical samples, specimen vouchers, genetic materials, and soil cores, that are archived for community use. Samples for these archives are maintained by individual BLE investigators, but we are pursuing longer-term solutions.

One solution is our initiation of a partnership with the University of Alaska Museum of the North (UAMN) to archive specimen vouchers. We will deposit vouchered (identified, preserved in molecular-grade ethanol and/or frozen, georeferenced, including full metadata) invertebrates collected across all sampling seasons and lagoon systems. Multiple individuals from each site and season will be included to capture morphological and genetic variation. In addition, multiple individuals of Arctic fish species from the lagoon systems are included (images, physical frozen specimen, and frozen tissue samples). UAMN archives these samples for a one-time cost (allocated in the UT-Austin budget), maintains the samples (preservative levels, frozen tissue at -80 °C), and makes the collection available and discoverable through their web site. The UANM website also provides an online form for other researchers to request sample loans. We are also working with UAMN to develop a strategy for archiving and sharing e-DNA samples.

Digital products associated with education and outreach – The review committee recommended that we **(3)** *"post relevant digital products from education and outreach actives on the BLE website"*. The Outreach section of our website now includes links to lesson plans, community newsletters, and activities developed for K-12 education programs.

REU support – The review committee recommended that we **(4)** *"identify ways to support two REU students annually"*. REU involvement was intentionally limited during project spin-up, then due to COVID-19 restrictions, but we made up for it in later years (see Results of Prior Support). We are committed to supporting at least two REU students annually as we move forward. In fact, we have budgeted to support the involvement of three undergraduates each year for BLE II.

Other adjustments - In addition to recommendations, the review committee provided several optional suggestions to consider. These included refining our conceptual model; thinking about how our methods for measuring primary production compare with other sites; showcasing links to ecological theory; formalizing partnerships that support BLE's higher trophic level work; seeking more opportunities for cross-LTER work; improving data query capabilities on our website; involving our IMs in all stages of data life cycles; providing a more comprehensive list of collaborators on our website; thinking about leadership transitions; establishing an external advisory committee, and continuing to strive for diversity, equity, and inclusion within BLE. While we do not have space to address each suggestion individually here, we embraced and acted upon *all* of them. This should be apparent throughout the proposal, from our refined conceptual framework diagram (Fig. 2) to our data management plan.

PROPOSED RESEARCH

Planned research for BLE II includes continuation of Core Program measurements (Table 1), next steps toward answering BLE's founding questions, and exploration of new ideas that emerged from BLE I. Updated questions, revised in parallel with our conceptual diagram, are provided along with guiding hypotheses for BLE II. Hypotheses emphasizing continuity from BLE I are shown in black, and hypotheses emphasizing new components are shown in blue. Our description of proposed work begins with thematic research activities, then delves into cross-theme work and lagoon ecosystem modeling advances.

How and in what forms do freshwater inflows, land-derived nutrients, and sediments arrive in the lagoons? (Theme 1: Lougheed, McClelland, Rawlins, Tweedie)

H1a. Freshwater inflows from surface runoff are the primary source of new nutrients (predominantly organic) to lagoons during spring, with inputs from coastal erosion and groundwater becoming important secondary sources in late summer.
H1b. Runoff pulses associated with precipitation events account for a large proportion of riverine nutrient inputs to the lagoons during summer, and these pulses are enriched in organic matter relative to baseflow conditions.
H1c. Lagoons receiving inputs from catchments where ice-wedge polygons occupy a larger proportion of the landscape will experience greater increases in freshwater and nutrient inputs, due to warming and associated permafrost degradation, compared to areas where they are less prominent.
H1d. Nutrient inputs from land will increase in the future, and proportional contributions from coastal erosion and groundwater will become greater.
H1e. Storm events and associated changes in lagoon water-level drive extensive saltwater intrusion in low elevation areas, facilitating subsidence, erosion, and changes in water-borne nutrient fluxes.

Freshwater inflows – Daily freshwater inflows to all lagoons (and Stefansson Sound) will be modeled from 1980-present during BLE II. This work will make use of the 1-km digital river network derived during BLE I. Model calibration and validation will leverage USGS data for larger drainage areas as well as new BLE data for smaller drainage areas. USGS gauges provide discharge data for most of the Kuparuk River drainage and substantial sub-basins of the Colville and Sagavanirktok. Since discharge data for smaller drainage areas are lacking, our efforts will focus on the No Name River and Mayoeak River in the eastern node and the Putuligayuk River in the central node, where we already collect BLE Core Program chemistry samples and higher temporal resolution water sampling is planned for BLE II. New model simulations will be made after implementation of a lateral subsurface flow sub-model within the Permafrost Water Balance Model (PWBM). We also plan to incorporate new model process representations that will capture dynamics of runoff emanating from ice-wedge polygons (Liljedahl et al., 2016; Rettelbach et al., 2021). Subsurface flow rates will be parameterized as a function of the local slope gradient and model-simulated water table depth and calibrated based on measurements of hydraulic head, hydraulic conductivity, and saturated thicknesses in active layers (e.g., O'Connor et al., 2019), as well as data emerging from BLE's groundwater work (Connolly et al., 2020).

We will also run simulations out to 2100 during BLE II using atmospheric forcings from two coupled GCMs (MPI-ESM2-HR and IPSL-CM6A-LR). The models were selected based on the magnitude of future climate changes, relative to the distribution of all IPCC models participating in CMIP6, with one model near the middle of the distribution and one model near to the upper end. Our future model simulations will capture strong positive trends in air temperature, rainfall, and active-layer thickness (Arp et al., 2020; Rawlins, 2021b). Leveraging a NASA grant, the UMass team is working with staff at the National Center for Supercomputing Applications (NCSA) at the University of Illinois to upgrade the PWBM to make use of parallel processing. These model improvements will enable higher resolution (nominally 1 km) model simulations across the entire North Slope.

Coastal erosion – During BLE II, the 20-year annual survey record of our ~11 km study of coastline position along Elson Lagoon will be sustained and surveys in other BLE lagoons, including barrier islands, will be conducted at least once. We will transition from using survey-grade differential GPS to UTEP's new Trinity F90+ vertical takeoff and landing (VTOL) drone equipped with high a resolution digital camera, thermal sensor, and multispectral sensor. Drone-based surveys can derive a broader range of products spanning the coastal zone (*sensu* Clark et al., 2021, 2022; Cunliffe et al., 2019). These include the horizontal and vertical position of the waterline, coastal bluff, creeks/rivers, and thermokarst pits ponds and lakes; thermal profiles of land and water bodies; and spectral indices that serve as proxies for vegetation biomass/productivity (e.g., NDVI, EVI), surface water (NDSWI; Goswami et al., 2011), and a range of nearshore ocean color parameters (e.g., sea surface temperature, turbidity, chlorophyll, etc.) for Arctic waters (Lewis & Arrigo, 2020). Structure from Motion (SfM) approaches will be used to model land surface elevation (*sensu* Clark et al., 2021). Where appropriate, we will apply machine learning approaches to enhance shoreline classification (e.g., Aryal et al., 2021). Derived products will include estimates of aerial and volumetric losses/gains to the lagoon derived from the Digital Shoreline Analysis System to ensure inter-comparison with other studies in the Arctic (Jones et al., 2020), change in surface greenness and thermokarst ecohydrology, and variability in ocean color indices. Raw and derived products will be shared with the High Latitude Drone Ecology Network to enhance cross-site inter-comparison and synthesis. High spatial resolution satellite data (MAXAR, Planet) will be acquired annually through NextView licensing requests to the Polar Geospatial Consortium to complement drone-based sampling and assessment of inter-annual variability.

<u>Biogeochemistry of terrestrial inputs</u> – New work supporting estimation of nutrient and organic matter fluxes into the lagoons via rivers, groundwater, and coastal erosion will include 1) efforts to enhance datasets for model calibration and validation, and 2) further characterization of organic matter composition/lability. Growing datasets associated with river sampling at Core Program stations are capturing seasonal differences in water chemistry and contributing to time series that will become increasingly valuable in the future. However, higher frequency sampling is needed to better understand and represent short-term (i.e., event scale) concentration-discharge dynamics that may strongly influence watershed export estimates. We will capture these dynamics by deploying autosamplers at Core Program stream/river sites for days to weeks (with sampling frequencies of hours to days) during spring-summer, and moving samplers among sites from year to year. We will have 2-3 autosamplers at our disposal and will conduct spring and summer deployments at all 6 of our Core Program river sites. CO_2 and DO sensors will be deployed simultaneously with auto-samplers to allow continual logging and determination of carbon flux and net ecosystem metabolism (NEM). As mentioned in the freshwater inflows section above, discharge will be measured at a subset of BLE's Core Program sites to facilitate flux estimation.

Groundwater sampling for BLE I initially focused on inputs to Kaktovik and Jago lagoons and then shifted to Simpson Lagoon. Groundwater sampling for BLE II will focus on inputs to Elson Lagoon. In contrast, sampling of eroding soils will shift from an emphasis on Elson Lagoon during BLE I to sampling of central and eastern sections of the Beaufort Sea coastline during BLE II. Water samples (river and groundwater) will be analyzed for inorganic nutrient and dissolved organic C and N concentrations as well as composition/lability indicators such as CDOM and amino acid composition. Incubation assays will also be used to assess DOM lability. Likewise, eroding soils will be analyzed for organic matter content and lability assays will be run on bulk soils (tracking CO_2 production) and DOM leachates (tracking DOC loss). These soils will also be analyzed for grain size and salinity to enhance linkages between with new work proposed for Themes 1 and 2. Work focusing on the fate of terrestrial inputs after delivery to the lagoons is addressed below in Theme 3.

<u>Saltwater intrusion</u> – While BLE's conceptual framework emphasizes inputs from land to coastal waters, we recognize that land-sea interactions work in both directions and are excited to incorporate new work addressing effects of inundation and saltwater intrusion on coastal tundra and freshwater environments (including groundwater and surface waters). Sea level rise and increasing storm events associated with climate change are pushing seawater into terrestrial environments world-wide, catalyzing land loss as well as changes in biogeochemistry. High-latitude coastlines are no exception to this ocean encroachment, as

evidenced by drowning tundra and wrack deposition kilometers from the coast (Arp et al., 2010), yet studies quantifying saltwater intrusion along Arctic coastlines have been scarce.

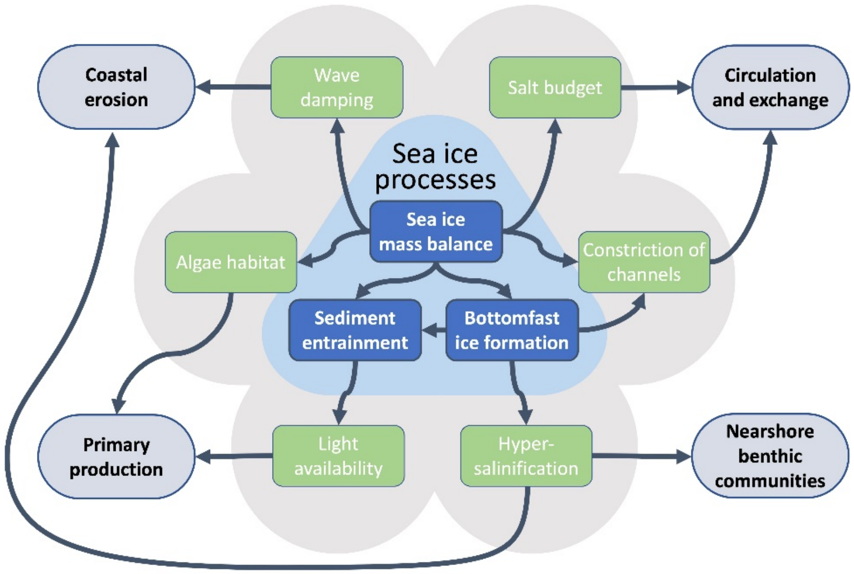

***Fig. 8**. Illustration of relationships between sea ice, and other physical, chemical, and biological components of Arctic lagoon ecosystems.*

During BLE II, we will establish stations for tracking water level and saltwater intrusion at focal sites along the shorelines of Elson, Simpson, and Kaktovik lagoons. We will also leverage water level data from a broader network of sensors associated with the growing Alaska Water Level Watch. Isostatic change in land surface elevation will be derived from long term GPS base stations maintained by UNAVCO and/or associated with the Earthscope Plate Boundary Observatory. Elevation change resulting from permafrost degradation and other near-surface processes will be derived through inter-comparison and vertical differencing high spatial resolution drone/SfM-derived Digital Elevation Models of coastal landscapes. Soil porewater will be sampled from grids that span inland to shore-adjacent tundra to map and track saltwater intrusion. Water from the grids will be collected with pushpoint samplers and analyzed for conductivity. In addition, conductivity sensors will be installed in groundwater wells and nearby surface waters to continuously record temporal variations in salinization, and time lapse cameras will be installed to track associated vegetation characteristics. These data will be related to broader patterns captured by drone and satellite-derived spectral greenness.

How does connectivity between lagoon and coastal shelf water vary over seasonal to interannual timeframes, and how will connectivity change in response to a shorter ice growth season and longer open water season? (Theme 2: Eidam, Mahoney, Tweedie)

H2a. Seasonal, annual, and multi-decadal dynamic interactions between river discharge, sea ice duration, and inlet geometry control connectivity during both ice-cover and open water.
H2b. Reduced winter ice growth will lead to reduced bottomfast sea ice extent, reduced salt influx, and greater wintertime ocean exchange.
H2c. Freeze-up period will become stormier, leading to increased sediment entrainment in ice and increased surface roughness and reduced light availability below.
H2d. The overall kinetic energy of the lagoon systems will increase leading to greater ocean exchange, bed disturbance, sediment export, and reduced light availability.

Sea ice – Seasonal formation and decay of sea ice plays a definitive role in a number of different physical processes that affect lagoon chemistry and biology (Fig. 8). For BLE II, our sea ice observing plan will focus on three processes that are especially important in sheltered, shallow-water environments: (i) mass balance (i.e., growth and melt), (ii) bottomfast ice formation, and (iii) sediment entrainment.

In early winter, we will deploy Cryosphere Innovations' Mark 3 Seasonal Ice Mass balance Buoys (SIMB3; Planck et al., 2019) to measure the change in ice thickness, snow depth, and the ocean-to-atmosphere

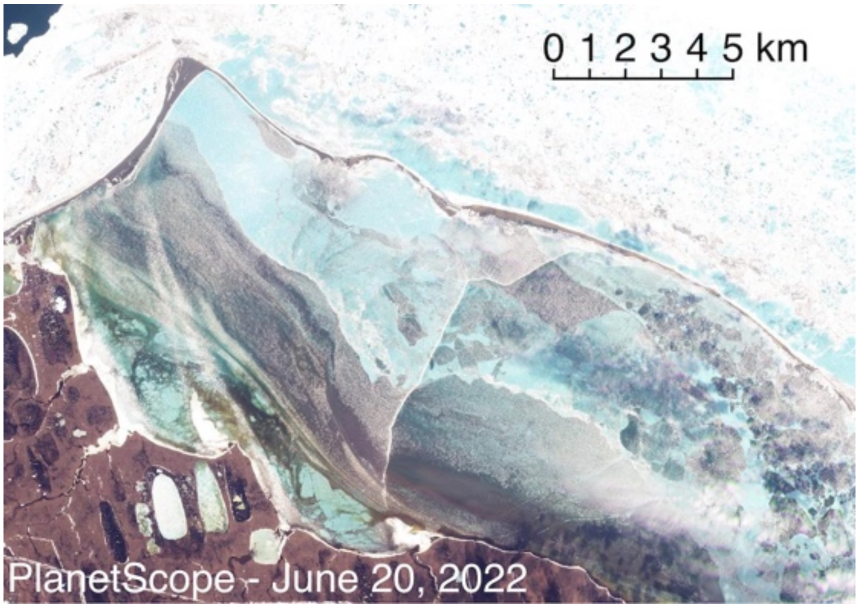

***Fig. 9**. Elson Lagoon after snow melt showing distribution of sediment laden ice that typically develops earliest in shallow nearshore waters adjacent to the mainland down-wind coast.*

temperature profile during the growth and early melt seasons. Together with lagoon bathymetry, measurements of ice growth and the salinification of the water beneath will allow us to estimate a salt budget for each lagoon, which will provide an independent means for deriving winter residence times and exchange rates of lagoon waters. Ice thickness m easurements from the SIMB will also allow us to accurately model restriction or closure of channels during winter.

In the bottomfast ice zone, the entire water column freezes and the ice makes contact with the seafloor. This can allow the benthic environment to become frozen or cooled below the typical freezing point of seawater. Any seawater remaining unfrozen becomes hypersaline in a process likely important for the formation of ancient cryopegs (Iwahana et al., 2021), which may leave coastal permafrost more susceptible and predisposed to coastal erosion (Gilbert et al., 2019) and could serve as a subsurface conduit for exchange of water and dissolved carbon between the land and ocean (Pedrazas et al., 2020). The spatial extent of bottomfast sea ice (BSI) is strongly linked to thickness of ice that grows each winter and, with continued thinning of Arctic first year landfast sea ice (e.g., Mahoney, 2018), we expect to observe a long-term decrease in BSI extent. We will continue the work led by UAF MS geophysics student Jacob Pratt during BLE I (Pratt, 2022), to map bottomfast sea ice (BSI) extent in the BLE lagoons using synthetic aperture radar (SAR) interferometry (InSAR) techniques. Building on Pratt's (2022) work, we will carry out in situ surveys in spring to identify regions of bonded and unbonded BSI and collect benthic core samples from the underlying seafloor to better understand the impact of BSI on shallow water benthos.

Delayed onset of ice formation and associated increases in coastal erosion may be accompanied by greater sediment entrainment in the ice (e.g., Eicken et al., 2005). If multiple storms occur before the ice is landlocked, the sediment distribution in the ice can become highly heterogeneous, (see Fig. 9) and we speculate this is the primary source of spatial variability in water column light availability prior to break-up. We will measure sediment load in ice cores collected at our primary observing locations in each lagoon. We will also estimate sediment load from remote sensing techniques and use this information to target additional ice core collections to better characterize the spatial variability in sediment content.

<u>Physical oceanography</u> – Proposed work during BLE II will build on data collected during BLE I to quantify residence times of lagoon waters and rates of exchange with water from outside the barrier islands at different times of year. This will involve a network of year-round and short-term moorings supported by targeted water sampling, boat-based surveys, and remote sensing data. These observations will be designed to inform and test the performance of our lagoon ecosystem model. We are also planning new work focusing on sediment transport during open water, sediment entrainment in sea ice during freeze up, and the fate of sediment during break-up.

We will deploy a network of year-round bottom-mounted moorings equipped with sensors for measuring bottom pressure (i.e., local sea level), salinity, temperature, and current velocity. Current meters will be placed near channels between barrier islands to measure the inflow and outflow from lagoons, while bottom pressure recorders (BPRs) will allow us to measure relative changes in sea surface slope, a principal driver of lagoon-ocean exchange (Okkonen, 2016), especially when landfast ice decouples lagoon waters from direct wind forcing. Numerical modelling will be used to characterize fine spatial-scale circulation within lagoons and, with transport measurements at primary inflow/outflow channels (identified by satellite imagery, e.g., Fig. 10), estimate average residence times.

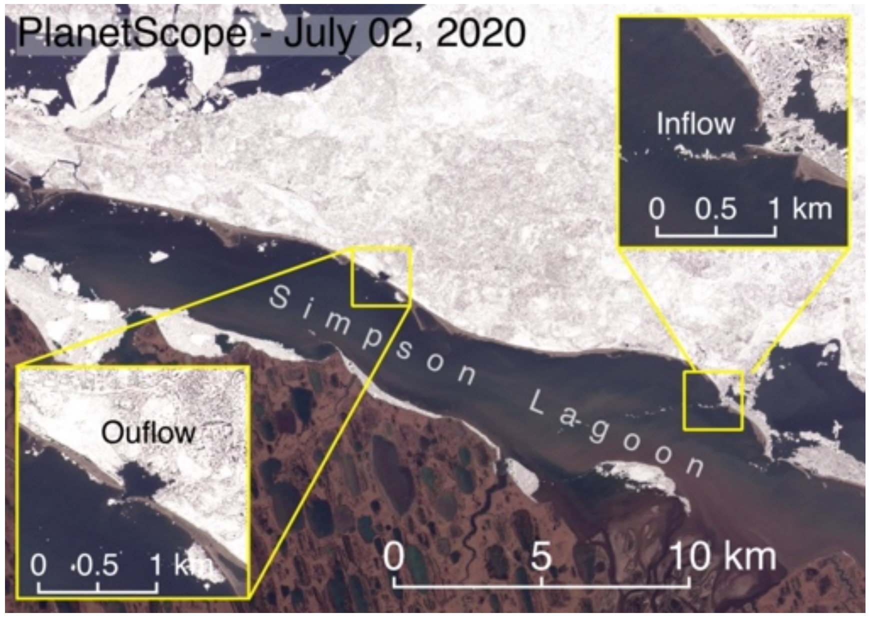

***Fig. 10**. Contrasting waters and locations of prominent exchange in and out of Simpson Lagoon.*

Sediment derived from bluff erosion is trapped in lagoons and/or exported to the continental shelf. These processes are mediated by waves, currents, and entrainment in sea ice, with impacts on substrate types, deposition or erosion depths and locations, and light attenuation in the water column and in sea ice. In order to better constrain these processes and understand their impacts on benthos, we will (1) measure seabed grain-sizes at coring sites (including down-core, to observe any changes); (2) estimate deposition or erosion using diver-installed rods (where feasible) and inter-comparison of new and existing sonar data; (3) measure near-bed sediment fluxes at primary mooring sites (using turbidity sensors paired with current meters; (4) measure turbidity, particle size, particle volume concentration, and light attenuation profiles during sampling trips, and near-bed turbidity and light attenuation throughout mooring deployments (including under ice); (5) measure the sediment concentration and sizes in sea ice (see above); and (6) use satellite imagery to qualitatively assess if ice-rafted sediment is exported from the lagoons, and where the greatest concentrations of export occur among the three sites.

How are nutrient cycling and greenhouse gas exchanges within the lagoons controlled by variations in organic matter inputs and local production (phytoplankton, ice algae, and benthic microalgae) over seasonal to multi-decadal timeframes? (Theme 3: Hardison, Lougheed, McClelland)

> *H3a. Arctic lagoons are net heterotrophic systems that serve as hotspots for decomposition of land-derived organic matter and release of CO_2 to the atmosphere, with peak CO_2 production rates in spring and early summer, and slower but cumulatively significant production in winter.*
> *H3b. Inorganic nutrients supporting primary production in the lagoons are chiefly supplied by decomposition of sediment organic matter, with proportional contribution from external versus internal organic matter sources varying strongly among seasons.*
> *H3c. Subterranean mixing zones between inflowing groundwater and sediment porewaters are sites of enhanced nutrient cycling within the lagoons, with net consumption of DOM and ammonium production.*
> *H3d. Stocks of DOM in sea-ice are small relative to water column DOM within the lagoons but serve*

as a significant source of labile, ice-algae derived organic matter to the water column.
H3e. As permafrost thaws, coastal erosion accelerates, and groundwater inputs to lagoons increase in the future, nutrient stocks and cycling rates will be enhanced, and the lagoons will become increasingly important sources of CO_2 to the atmosphere.

Lagoon ecosystem metabolism – Sensor-based dissolved oxygen (DO) time series have been used to determine net ecosystem metabolism (NEM) – the sum of gross primary production (GPP) and respiration (R)- at multiple LTER sites including PIE (Hopkinson & Weston, 2020), GCE (Wang et al., 2018), and VCR (Hume et al., 2011). This approach was used to monitor ecosystem metabolism in surface and bottom waters across Elson Lagoon and its inflowing rivers during BLE I. We will apply this approach more broadly during BLE II, conducting measurements at one core site per node for 3-5 days per year during the open water season. We will also leverage DO data from our year-round bottom-mounted moorings (Core Program) to explore seasonality. Data from these moorings do not always integrate formation from the complete water column, particularly during periods of stratification, but they do provide a year-round view of the lower strata that is most tightly coupled with the benthos.

During BLE I, we used sediment core incubations to measure benthic metabolism (i.e., GPP, NEM, R), N_2 gas, and inorganic nutrient (NH_4^+, NO_3^-, NO_2^-, PO_4^{3-}) fluxes during ice cover, break-up, and the open water season, primarily at Elson Lagoon. During BLE II, we plan to expand this work to our easternmost node, in Kaktovik and Jago Lagoons. Light/dark fluxes of DO and DIC will be used to quantify benthic metabolism parameters, allowing us to determine the trophic status of the sediments (i.e., net autotrophy vs. heterotrophy) for comparison with our water-column based ecosystem metabolism measurements. Net N_2 fluxes will directly quantify net sediment denitrification rates, and inorganic nutrient fluxes will show whether sediments are a net sink or source for nutrients.

BLE I quantified whole ecosystem and benthic NEM over the three sampling seasons in Elson Lagoon, but did not specifically examine production by phytoplankton or sea ice algae, even though they are likely dominant components of the ecosystem. In shallow coastal lagoons, where much of the sediments lie within the euphotic zone, benthic photoautotrophy plays an important role in carbon and nutrient cycling (McGlathery et al., 2007; Sundbäck et al., 2000; Valiela et al., 1997; Viaroli et al., 1996). Ice algae may also contribute significantly to ecosystem production, with their growth influenced by spatio-temporal changes in snow cover, nutrients, salinity, and light (Cunliffe et al., 2019; Legendre et al., 1992; Leu et al., 2015; Smith et al., 1997). During BLE II, we will determine rates of microalgal production and respiration in all three compartments (i.e., benthic microalgae, water column phytoplankton, sea ice algae) in Elson Lagoon during ice cover and open water seasons. We hope to identify a range of contributions from the different primary producers with this seasonal comparison. To understand factors driving algal production and growth, nutrient and light limitation experiments will be performed in laboratory incubations at varying light levels, with additions of N, P, and Si for sea ice algae (Smith et al., 1997), phytoplankton (Lougheed et al., 2015), and benthic microalgae (Porubsky et al., 2008). We will also measure change in biomass (as chlorophyll) and metabolism, as change in DO.

Measurements of water column CO_2 will continue during BLE II, but with more attention to short-term variability in stratification. Preliminary data, including temperature and salinity profiles under sea ice, indicate substantial day-to-day movement of the pycnocline and differential contributions of moving water sources. Fresher and warmer water was associated with higher CO_2. During BLE II, temperature, salinity, and CO_2 will be logged with a vertical array of 4-5 sensors distributed evenly through the water column for 2–4-day periods to provide more context for surface and bottom water CO_2 data collected routinely during core program sampling. This work will focus on different locations over time, aiming to provide information on short-term variability at all primary Core Program stations by the end of BLE II. Water will be collected and analyzed for H_2O-^{18}O along with salinity at each sensor depth to help determine water contributions to different strata of the water column.

We will also begin measuring methane (CH_4) in the water column. Methane may be produced through microbial transformations of sediment carbon or may be trapped in submarine permafrost. Elsewhere in the Arctic, high CH_4 concentrations have been found under sea ice (Kitidis et al., 2010) and may contribute significantly to sea-air flux during ice melt (He et al., 2013). How CH_4 concentrations in Arctic waters will respond to future environmental change remains unknown (James et al., 2016). These measurements at BLE will, over the longer time frame of this program, provide datasets that track how fluxes of this potent greenhouse gas are changing and support modeling efforts that require better baseline information on CH_4 fluxes in Arctic coastal waters (Frederick et al., 2022). These measurements will be conducted alongside the CO_2 and DO measurements discussed above using a ProOceanus miniCH_4 probe.

Fate of DOM – New work addressing the fate of DOM in coastal/lagoon waters will focus on inputs from sea ice melt and groundwater. We will also expand spatial coverage of water column sampling for DOM lability assays, which largely concentrated on Elson and Simpson lagoons during BLE I but will shift eastward to Kaktovik and Jago lagoons. DOM inputs from sea ice were not considered during BLE I. However, with increasing emphasis on the role that ice algae may play as a source of production within the lagoons, it follows that sea ice melt may be a source of highly labile DOM. Thus, we will sub-sample for DOM (and nutrients) when ice cores are collected for ice algae work (see Theme 4), and complete lability assays and analysis of DOM.

Fate of groundwater inputs – Groundwater sampling for BLE I quantified concentrations and lability of DOM before entering the estuarine environment. While this end-member work will continue during BLE II (see Terrestrial inputs section), we propose here to collect groundwater samples that capture salinity gradients across the land-lagoon interface. Examination of DOM and nutrient concentration distributions relative to expectations for conservative mixing across these gradients will provide information about biogeochemical processing of the groundwater DOM as it moves through inter- and sub-tidal sediments, and thus, how groundwater inputs may be modified before delivery to the lagoon water column. A recent synthesis of groundwater data collected from subterranean estuaries throughout the world shows that, on average, groundwater DOM is consumed and NH_4^+ is produced along these gradients (Wilson et al., under review). However, patterns vary widely among geographic locations, and little is known about the fate of groundwater DOM entering Arctic estuaries. We will select three sites within the BLE domains for this proposed work. Sediment core incubations will also be employed at these sites to investigate decomposition and net nutrient fluxes across the sediment-water interface.

How do climate forcing and seasonal drivers influence biological processes in lagoon ecosystems and the humans that depend on them? (Theme 4: Crump, Dunton, Iken, McMeans, von Biela)

> *H4a. Microbial and metazoan community structure (composition and diversity) and trophic linkages differ in sensitivity to extreme and changing seasonal variations in salinity, temperature, and organic matter supply, specifically, ice algae, phytoplankton, benthic microalgae, and terrestrial organic matter.*
> *H4b. Stability and resilience to disturbances is greater with higher diversity within microbial and metazoan communities.*
> *H4c. Long-term changes in climate forcing will influence microbial and metazoan community structure and trophic linkages.*
> *H4d. Lagoon attributes (e.g., physiography, hydrography, biogeochemistry, sediment transport) play a significant role in shaping biological communities (microbes, benthos, fish) and trophic structure.*

Ecological theory – Studies proposed during BLE II will continue to emphasize our contribution to ecological theory by advancing a more dynamic perspective of communities and food webs through multi-season and multi-year sampling that includes ice-covered winter periods. Warmer winter temperatures and reductions in ice cover are strong signals of climate change across temperate and Arctic ecosystems (Bintanja & van der Linden, 2013, Gilg et al., 2012) that threaten the inherent seasonality of these systems. However, remarkably little empirical or theoretical work has focused on the consequences of winter or seasonality. Instead, ecologists tend to sample during summer and often treat the roles of organisms in communities as fixed, static traits (McMeans et al., 2015, Shogren et al., 2021). The lack of studies on ecological responses to existing seasonal signals makes it challenging to predict the consequences of altered seasonal signals arising under a changing global climate. Under BLE II, we will continue to address this knowledge gap by quantifying how populations, communities, and food webs maintain key functions in naturally variable ecosystems that are also undergoing rapid change. For example, during BLE II we will test the hypothesis that higher community diversity allows for more diverse species and trophic responses to seasonality that maintain key functions through time (i.e., energy flow, diversity, biomass stability; Gutgesell et al., 2022; Mougi, 2021).

BLE II will also more explicitly contribute to concepts in disturbance ecology. Using a recent synthetic framework (Graham et al., 2021), we will distinguish between disturbance drivers (i.e., abiotic forces that deviate from local, prevailing background conditions such as sea ice cover and freshwater input) and disturbance impacts (i.e., social and ecological responses to disturbance drivers, including changes in habitat and resource availability, community, and trophic structure). These drivers and impacts are not unique to Beaufort Sea lagoons and are signals of climate change disturbance across the Arctic (Walsh et al., 2011), giving broad relevance to our findings. BLE I provided sufficient information to establish disturbance drivers and impacts from background conditions. Inter-annual variation in our system will allow us to directly observe how communities respond to both average and more extreme years, including a potential future with complete loss of ice cover, with the expectation being that communities with high diversity suffer fewer negative disturbance impacts.

We are also interested in the role of physiologically tolerant taxa for resistance and resilience to disturbance, and whether physiologically sensitive species can act as indicators of shifting communities under climate change. We will integrate disturbance drivers and impacts across multiple spatial and temporal scales (i.e., pulse disturbances overlaid across press disturbances) and address several research areas of need recently identified in disturbance ecology (Graham et al., 2021).

Microbial communities – Microbial communities are the most rapidly cycling communities in the Lagoons, with the potential to respond to disturbance drivers on the scale of weeks to months. During BLE I, we found evidence that benthic microbes are resistant to seasonal change and planktonic microbes are resilient. This contrast reflects patterns in invertebrate communities, but we do not yet know if they will persist over time, or how they will respond to major disturbances. Other long-term studies of microbial diversity show gradual change over multiple years (Fuhrman et al., 2015), variability due to microbial dispersal (Cram et al., 2015), and sudden change in response to disturbance (Walsh et al., 2016). BLE II will test long-term persistence of microbial community resistance and resilience with continued seasonal surveys of microbial taxonomic and functional diversity. We will seek explanations for these patterns with a new effort to track sources of microbes by investigating microbial dispersal via water, sea ice, and sediment transport and potential microbial seed-banks in sea ice, tundra soils, and deposit-feeding infauna.

Metagenomic surveys during BLE I focused on planktonic communities, revealing seasonal variation in important ecosystem functions in Kaktovik Lagoon, and investigating nitrification in detail in Elson Lagoon (via metatranscriptomics and rate measurements; Griffin, 2022). These studies developed analysis protocols that we will use in BLE II to extend this work to (a) all nodes to identify spatial variation in microbial genomic potential, and (b) to sediment communities which have not yet been analyzed. We will also continue to investigate key microbial ecological functions in detail with work at Elson Lagoon focused on denitrification and methane metabolism in water and sediment.

Sea ice-associated (sympagic) microbial communities recycle organic matter and nutrients within sea ice, supporting sea ice algal productivity, and potentially serve as seedbanks of diversity that contribute to the resilience of planktonic communities (Szymansky & Gradinger, 2016). Preliminary research on sympagic microbes during BLE I developed preservation methods for sympagic RNA and DNA, and initial analysis identified diverse communities featuring both typical planktonic microbes and specialized sympagic communities. During BLE II we will characterize sympagic microbial community composition including ice algae and compare with sediment and water datasets to track dispersal patterns of microbial communities. We will also use metagenomics and metatranscriptomics to explore the genomic potential and active gene expression of these communities.

Benthic communities and trophic structure – Trophic interactions are a powerful way of connecting community dynamics based on energy supplies to the system as driven by the availability of various food resources. In Arctic lagoons, the delivery of marine phytoplankton is mainly restricted to the 3-mo open water period, yet terrestrial organic matter (denoted by ^{14}C abundances) is available as a "carbon subsidy" year-round. Seasonal patterns of expansion or contraction of trophic niches suggest that many taxa exhibit opportunistic feeding behavior. Under BLE II, we will examine the increasing evidence of seasonal resource switching, which may be related to the availability of alternate sources of autogenous production. These include sea ice algae and benthic microalgae, both important energy contributors to food webs in the Arctic, as described in Theme 3, but whose contributions to Beaufort lagoon food webs are poorly known.

Under BLE II, we will also make efforts to define the role of benthic microalgae as a distinct carbon source to food webs. Assimilation of benthic microalgae across trophic levels was noted by Harris et al. (2018). During BLE I, we found sediment chlorophyll stocks exceeded that of open water integrated chlorophyll by an order of magnitude (Ducklow et al., 2022). The shallow nature of the lagoons allows sufficient light to reach the sediments to support primary production for several months annually, including the ice-covered period (Singh et al., 2022). *In situ* observations by divers and ROV imagery also clearly denote the occurrence of benthic microalgae on the seabed. BLE II will focus on identifying the seasonal and spatial contribution of benthic microalgae to lagoon food webs using a variety of stable isotope and fatty acid biomarker approaches (Budge et al., 2008; North et al., 2014; Wainwright et al., 2000) in concert with the analysis of degraded chlorophyll products (e.g., pheophorbide and pheophytin; McTigue et al., 2015).

On an ocean basin scale, sea ice algae contribute substantially to primary production and can be significant seasonal contributors to Arctic food webs (Kohlbach et al., 2016; Wang et al., 2014). Ice algae have occasionally been associated with physiological fitness and reproductive events in Arctic invertebrates (Reed et al., 2021). The role of sea ice algae in Beaufort lagoon ecosystems is not yet well defined, especially in relation to other sources such as phytoplankton or terrestrial production (e.g., Stanek et al., 2022). Under BLE II, we will make a more concerted effort to understand the factors contributing to the substantial spatial and interannual variability in lagoon sea ice algae through increased sampling and ROV videography. We will complement the proposed sea ice microbial work and investigate the importance of ice algae to lagoon metazoan food webs (benthic invertebrates to fish) by employing a variety of biomarkers, including sea ice-specific highly-branched isoprenoids (HBI) (Amiraux et al., 2023) to better assess the importance of an ice algal carbon subsidy to these shallow lagoon ecosystems, especially over longer time frames as sea ice becomes more ephemeral.

Fishes and birds – Under BLE II, we plan to expand our trophic studies to include upper trophic predators common to lagoons (specifically fishes and birds). These linkages to our goals and hypotheses provide a more complete ecosystem picture that also connects our research to the substantial dependence on estuarine lagoons by our indigenous Inupiat hosts, particularly at the villages of Utqiaġvik and Kaktovik for their subsistence needs (Fig. 2).

During BLE II, we will continue collaborations with USGS to understand whether changes in prey fish communities with climate forcing have contributed to decline in a loon species. The focal loon species is one of two species with evidence of long-term population decline among birds breeding on the Arctic Coastal Plain (Amundson et al., 2019) and both declining species are closely associated with lagoon ecosystems. Loon breeding success will be compared between two study areas with different fish communities in a space for time substitution. During BLE I, we collaborated with the USGS to confirm long-term change in fish communities concurrent with climate forcing via warming water temperature and ice declines (von Biela et al., 2023).

We will also continue our efforts to understand differences in fish trophic structure among lagoons during

BLE II. During BLE I, we expected to find greater contributions of terrestrial carbon to fish biomass in lagoons with greater freshwater inflow (Stanek et al., 2022). Instead, differences were related to niche partitioning that could be explained by differences among lagoons in the degree of protection from barrier islands. Less protected lagoons likely have more wind-mixing and homogenization of organic matter sources and lower variability among fishes. In contrast, protected lagoons featured greater variability in terrestrial contributions related to niche diversification (Stanek et al., 2022). This finding contributed to our decision to add a fourth hypothesis in BLE II, which focuses on lagoon attributes such as their unique physiography and hydrography. More diverse fish feeding niches within protected lagoons are expected to promote stability and resilience to disturbances within fish communities (Stanek et al., 2022).

Food security and human health – Subsistence practices constitute important socio-environmental systems that are intrinsically linked to community resilience and underpinned by generationally preserved knowledge of spatial and seasonal trends (Gadamus, 2013; Green et al., 2021). Historically, seasonal cues have been sufficiently reliable to inform decisions about resource allocation and harvest site selection, thereby allowing Arctic communities to maximize harvest yields and maintain high levels of food security. However, climate forcing is rapidly altering these once-predictable processes, with downstream implications for the timing and availability of subsistence fishes and marine mammals (Gadamus, 2013). As the success of subsistence harvests declines, food insecurity is escalating in these communities, necessitating adaptive dietary practices that include targeting alternative species and increasing consumption of shelf-stable processed foods (Green et al., 2021; Kuhnlein, 2015). These dietary shifts correspond with concerning public health trends in rural Alaska, including a rise in the prevalence of diseases-of-poor-nutrition and mental health disorders (Bridges et al., 2020; Kuhnlein, 2015).

During BLE I, community members repeatedly relayed their climate change-related food safety concerns to investigators, particularly regarding increased exposure to dietary methylmercury (MeHg) in fish (due to dietary shifts). The global biogeochemical cycle of mercury (Hg) is tightly coupled to climate and many of the abiotic and biotic factors investigated in BLE I and proposed for BLE II (e.g., terrestrial inputs, microbial community composition, lagoon attributes, composition/trophic structure of biological communities) can meaningfully alter human dietary exposure to MeHg. During BLE II, we propose to evaluate the impact of adaptive subsistence practices on dietary MeHg exposure, across seasons, years, and lagoons in the context of relative public health risks (Bridges et al., 2020). This work will be done in collaboration with BLE Affiliated Investigator Kristin Nielsen (née Bridges). We plan an integrated evaluation of existing and newly-collected community-specific data describing subsistence trends, Hg in abiotic and biotic environmental media, and disease surveillance data. We will also evaluate the links between/impacts of climate forcing on human health risks related to changes in dietary MeHg exposure in response to adaptive subsistence practices across seasons, years, and lagoons.

Multi-theme efforts – Alongside the thematic research activities described above, we will initiate a benthic recolonization field experiment and perform overarching remote sensing activities during BLE II.

Benthic recolonization experiment – This experiment will focus on ecological consequences of bottom-fast sea ice (BSI) on benthic communities. We ask: *What physical, chemical, and biological factors influence seasonal re-establishment of the nearshore (shallow) benthos?* Seasonally, fishes and birds avoid harsh winter conditions by migrating each winter (Carey et al., 2021), leading to a dramatic seasonal decrease in predation for invertebrates. But after sea ice break-up in May, shallow lagoon sediments (< 2 m water depth) are a major source of food for anadromous fish and migrating waterfowl that begin feeding within the fringe of open water along lagoon shorelines. During the ice-cover period, these typically frozen sediments are inhabited by one species of Polychaeta, *Pygospio elegans*, but over the following months as sediments thaw, they are quickly recolonized by many marine worms, bivalves, crustaceans, and other fauna as reflected in a 5-7-fold seasonal increase in species richness and diversity (Fig. 11). Do these species arrive as immigrants (meroplankton released by gravid adults) from adjacent deeper waters that remained unfrozen? Or have these organisms survived the winter as young freeze-resistant larvae that pass through 0.5 mm sieves undetected? To explore the ecological mechanisms of recolonization in shallow Arctic

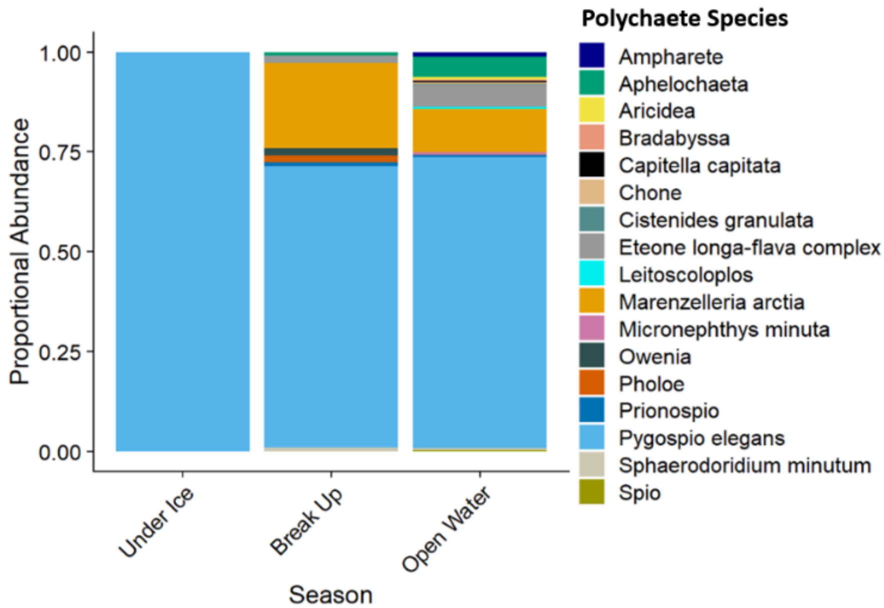

Fig. 11. *The proportional abundance of polychaete species from shallow stations and seasons across nodes for the period 2019-2022. Margalef species richness and Shannon Diversity increases from 0.17 and 0.16 to 1.16 and 0.91, respectively, from under ice to open water conditions on an annual basis.*

lagoon sediments, we propose a larval settlement field experiment coupled with meroplankton surveys. We will install predator-exclusion cages (following Diaz et al., 2023) during ice break-up in June to create treatments to reduce the effects of epibenthic or benthic grazing activity on larval recruits with appropriate replicates for cage effects and controls. Benthos in the top 6 cm of sediment retrieved with a corer will be sieved through 150 µm and 63 µm screens and preserved in 100% ethanol for later identification. Since larval identification is notoriously difficult, we plan to use high-throughput metabarcoding which has recently shown great promise as a tool to identify larvae in ethanol-preserved collections (Descôteaux et al., 2021) in combination with microscopic analyses (Bowden 2005; Kuklinski et al., 2013; Snelgrove et al., 1999).

Forecasting long-term change to this potentially important larval supply for lagoon communities depends on understanding long-term variations in the magnitude and composition of source populations and larval dispersal trajectories. To investigate planktonic and demersal larval recruitment patterns, we will perform quantitative 20 µm phytoplankton net tows equipped with flowmeters in the deeper (> 2 m water depth) lagoon regions during our April, June, and August surveys. All net samples will be preserved in 100% molecular-grade ethanol for later identification and enumeration to examine evidence for sources of new recruits to shallow sediments. Meroplankton sampling in tandem with benthic larval sampling will allow comparison of pelagic versus demersal larval strategies (Kuklinski et al., 2013) and spatial differences in larval supply (Snelgrove et al., 1999). Sampling over extended time frames will also capture changes that reflect borealization of the nearshore Beaufort, already noted in one fish species (von Biela et al., 2023).

These experimental studies are planned for the western, central, and eastern Beaufort Sea nodes. Our multi-year interdisciplinary approach will include mapping of BSI (Theme 2) at the experimental sites, collection of sediments for grain size, benthic microalgae, microbiology, porewater nutrients, and measurement of biogeochemical processes that may affect re-establishment of these highly perturbed communities. Our investigation into under ice larval activity would add to a growing body of research into winter reproduction of polar invertebrates (Berge et al., 2015; Bowden 2005; Kuklinski et al., 2013). We will also complement our taxonomic diversity data with a functional diversity analysis to determine vulnerability and resilience to disturbances.

Overarching remote sensing work – Near surface to satellite remote sensing approaches will be used to enhance cross-theme integration and improve the spatiotemporal scaling of process level studies, drawing on our experience with multiple sonar, radar, optical, and thermal sampling and analytical approaches and near-surface, drone, and satellite platforms (e.g., Aryal et al., 2021; Dammann et al., 2023; Jensen et al., 2023; Johnson et al., 2020; Lougheed et al., 2020; Zimmermann et al., 2022). Relative to *in situ* measurements, remote sensing offers a well-recognized capacity as a low-cost approach to improving spatiotemporal scaling, will enhance the development of decadal to half century time scale observations using historic imagery, and likely increase the impact of our research publications. The inclusion of remote sensing also offers graduate students an opportunity to develop geospatial and other skillsets recognized as being next-gen training priorities. The development of scaled products will also improve our preparedness to link with emerging research efforts such as NASA-COLORS, an effort within NGA to improve mapping of coastal elevation change in Alaska, storm surge modeling and coastal change research within the USGS, and aerial surveys being conducted by NEON over Elson Lagoon and Germany's Alfred Wagner Institute along the Beaufort Sea Coastal zone.

Measurements will focus on the development and testing of algorithms suitable for scaling from imagery acquired from drone and satellite sensing platforms (e.g., Plane, Maxar, Sentinel, Landsat, SeaWifs, Modis, SAR, IceSat II) for the remote derivation of primarily SST, turbidity, chlorophyll, and ice cover; and other variables as required to advance PI and graduate student research. Development of algorithms for scaling will be developed from spot measurements coupled to core measurements and relevant PI-driven science; systems onboard UTEP's RV *Aliuq* in Elson Lagoon that can provide synoptic physical and hydrographic data (survey grade sonar, high speed water intake system, forward boom for ocean color sampling of reflectance), and drone-based sampling conducted concomitantly with field measurements. Derived products will be scaled to satellite platforms to develop high spatial resolution time series mapping products of BLE lagoon ecosystems and adjacent waters that will be validated against independent field-based sampling and used in analyses that address hypotheses across all four themes.

Lagoon ecosystem modeling - During BLE II, we will focus on further developments of our modeling tools and perform coupled circulation/ice/biogeochemical simulations for all three nodes. Offshore boundary and initial biogeochemical conditions will continue to be explored with new databases such as the Arctic Ocean Biogeochemistry Analysis and Forecast Product available from Copernicus in addition to BIOMAS outputs (Jin et al., 2016; Zhang et al., 2014) that we presently use. Running fully coupled 3D circulation/ice/biogeochemical model in high spatial and temporal resolution is very costly even on high performance computers. We are currently exploring techniques to speed up the runs by omitting the biological forcing at the time step needed for advection (40 s) or by using some statistical methods based on short time simulations. We will also continue to utilize the MATLAB/Python 1D framework that we used in BLE I to develop and refine the various pathways of the water column and benthic biogeochemical model and ice algae model.

<u>*Circulation/ice/wave/sediment development and simulations*</u> – While a more complex state-of-the-art ice model such as the Los Alamos Sea ice model version 6 (CICE6) might show better success in simulating desalination of the water column in late spring/early summer, the computing cost of such a model coupled to the circulation and biogeochemical model is prohibitive. Consequently, we will continue to use our simpler model developed in BLE I with the following modifications. Several factors impact ice melting and freshening of the water column in late spring-early summer that can be included in our model (snow coverage, melt ponds, late winter sea ice salinity, and river/groundwater discharge). Moon et al. (2019) observed large variations of snow thickness with formation of snow dunes in Elson Lagoon due to wind forcing. We will explore the possibility of adding a simple model for snow dune formation to simulate snow thickness. This will lead to better modeling of melt pond formation, ice melt, and freshwater input and is important in accurately simulating the start of the phytoplankton bloom in response to local light availability. Our present ice model does not include temporal and spatial variability of sea ice salinity, but we plan on adding that component. While our model simulations include river discharge, we will add groundwater discharge from Theme 1 model results. We will perform tracer tracking simulations to assess how the spatial influence of river, groundwater, and catchment discharge impacts lagoon salinity. Similarly, we will perform some tracer simulations to track oceanic influence through the passes. In years 4 and 5 of

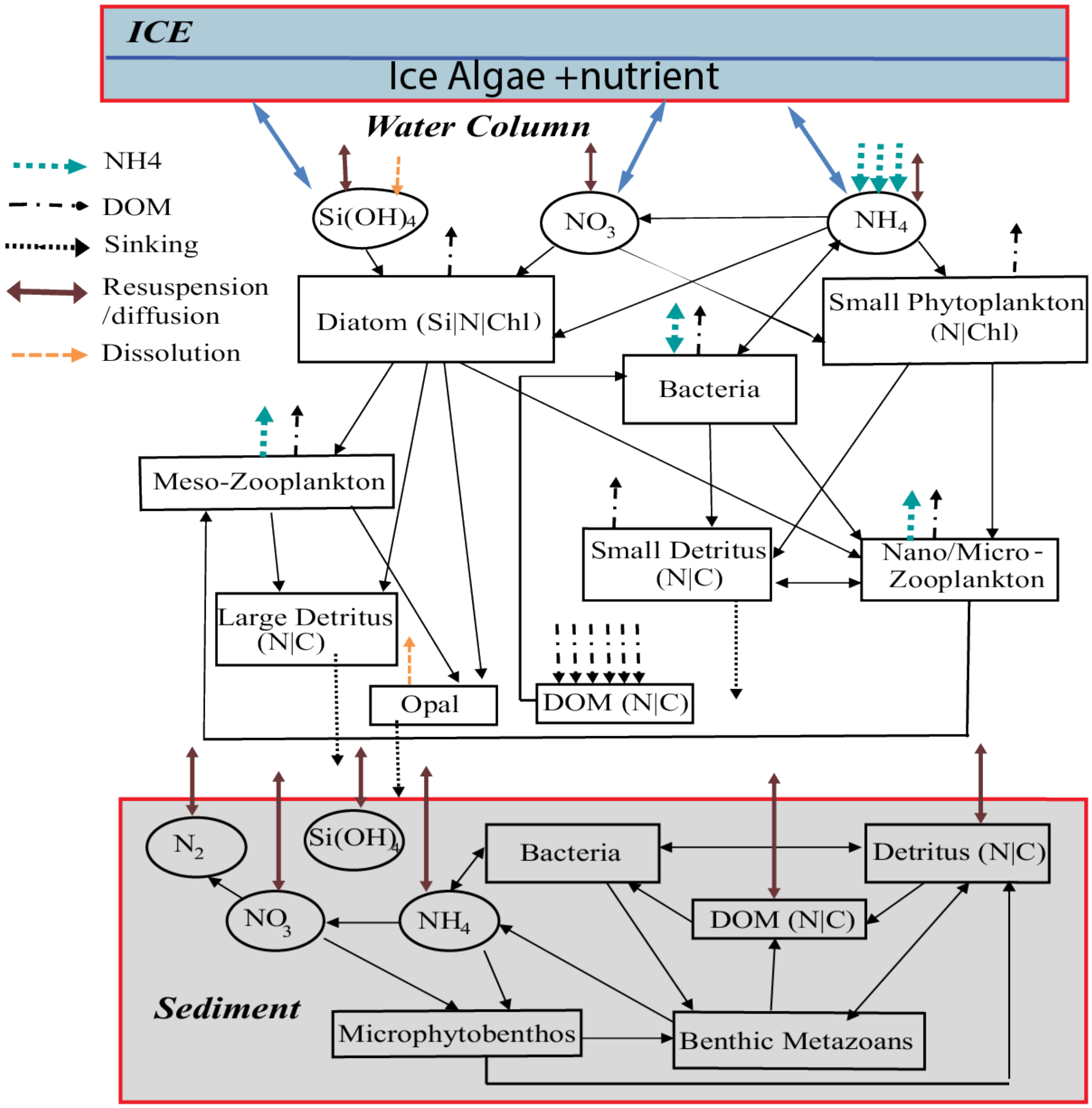

Fig. 12. *Schematic of the biogeochemical model. The red boxes (sediment and sea ice) indicate the two components that will receive focus for further development during BLE II.*

BLE II, we will use a wave model and sediment transport model as used in COWAST (Warner et al., 2010). To assess the processes of entrainment of sediment in ice and its influence on timing of ice melt, we will perform targeted simulations for short periods from ice formation to melt which can be validated by work proposed in Theme 2.

<u>Biogeochemical and ice algae model development and simulations</u> – During BLE I, we focused our effort on the development of the biogeochemical model for the water column (Fig 12) and used a simple remineralization parameterization of sinking detrital matter nutrient flux for the benthos. We added a benthic infauna (e.g., bivalves, amphipods, polychaetes) component following Gibson and Spitz (2011) and Kearney et al. (2020). In BLE II, we will complete and calibrate the development of the benthic component

of the model by adding a microbial component and DOM (Fig. 12). We will add an oxygen module for the water column and benthos. We will fully calibrate the new model outputs based upon data collected in BLE I-II and data available from other projects accessible via the Arctic Data Center, NOAA, and USGS. We will add an ice algae component based on BIOMAS (modified from Jin et al., 2006) with additional data produced from Theme 3. We anticipate that starting in year 3, we will be able to compute NEM and compare model estimates with field measurements and determine the seasonal and interannual drivers (physical and biological) that influence spatial and temporal NEM variability.

INTEGRATED SUMMARY OF PROPOSED RESEARCH

Proposed research for BLE II includes the continuation of Core Program measurements (Table 1), next steps toward answering long-term questions established during BLE I, and exploration of new ideas. The pivotal role of sea ice is a common thread, connecting much of our proposed work through effects on physical, chemical, and biological components of the system (Fig. 8). BLE II places a greater emphasis on the roles of ice algae and benthic microalgae as sources of production within the lagoons; expands work on higher trophic level organisms, including linkages to human populations related to food safety and security; begins to address how intrusion of saltwater into tundra and freshwater environments as a consequence of storm surges and sea level rise is altering land-lagoon boundaries and biogeochemical fluxes; and works toward improved understanding of temporal and spatial variability across scales. While our thematic research is inherently interconnected, we have planned a cross-cutting field experiment for BLE II that investigators from all thematic groups will work on together. This experiment will quantify the physical, chemical, and biological factors that influence seasonal re-establishment of shallow benthic communities in the bottomfast ice zone. Our lagoon ecosystem modeling efforts, expanded to include new sea ice and benthic components and applied across all BLE nodes, will also facilitate integration across thematic components.

CROSS-SITE SYNTHESIS ACTIVITIES

As BLE continues, our maturing datasets will become increasingly valuable for cross-site synthesis work. Topics of particular interest stemming from the 2022 LTER All Scientists Meeting are: 1) food webs, trophic plasticity, community composition, and isoscapes; 2) human-environment interactions and feedback; 3) how environmental forcings driven by climate change, such as increases in temperature, precipitation, and sea-level rise, affect ecosystem function; and 4) examining the role of regular and irregular pulses (e.g., seasonality, extreme events) in disturbance ecology and organismal feedback. BLE investigators are engaged in these ongoing efforts, and we intend to foster the development of new efforts through workshops at LTER All Scientists' Meetings, leadership in LTER synthesis working groups, the sharing of information with other cold region LTER programs, and facilitating graduate student field opportunities among LTER networks. In 2022, a BLE graduate student participated in an NGA LTER fall research cruise. BLE and NGA plan to continue to partner to build upon this successful test of concept. Both BLE and NGA have been sharing the same education coordinator, Katie Gavenus (Center for Alaskan Coastal Studies), which has enabled both programs to coordinate our Schoolyard programs, provide cross-site educational opportunities for graduate students, and potentially develop other joint outreach activities.

RELATED RESEARCH PROJECTS

Work proposed for BLE II is not dependent on funding from related research projects, but we will leverage other projects to enhance research and education outcomes. Funded projects that dovetail with BLE II include: remote sensing of nearshore environments along the Alaska Beaufort Sea coast supported by the NOAA Center for Earth System Sciences and Remote Sensing Technologies (ongoing-2028) and the NSF International Tundra Experiment (ongoing-2025); study of sea ice stability and trafficability funded by the Cold Regions Research and Engineering Laboratory (ongoing-2024); study of polygon-scale hydrology and biogeochemical mobilization in North Slope tundra supported by NSF-ARCSS (2023-2026); development and application of techniques for metatranscriptomics to investigate functional gene expression patterns of microbial communities in sea-ice (ongoing-2024); study of disturbance driven trophic level effects on red-throated loon productivity in the Central Beaufort Sea (ongoing-2025); and study of algal communities in the Boulder Patch kelp bed in Stefansson Sound supported by the Bureau of Ocean Energy Management (ongoing-2025). The International Tundra Experiment and the boulder patch project are both long-term efforts that will likely continue beyond their current funding cycles. We also have several shorter-term proposals under review that complement BLE II. These include: a planned research effort focused on drivers and biogeochemical implications of saltwater intrusion along Arctic coastlines (NSF-ANS); work on integrating water and renewable energy infrastructure on the North Slope of Alaska (NSF-NNA); development of mechanisms for knowledge coproduction with indigenous communities on the North Slope (NSF-NNA); and two NSF Research and Mentoring for Postbaccalaureates in Biological Sciences (RaMP) proposals that aim to expand BLE's educational reach.

BROADER IMPACTS

Fig. 13. *Students from the 2nd and 3rd grade classroom in Harold Kaveolook School in Kaktovik, AK watch as Ken Dunton shares a video taken by BLE's ROV that shows ice algae growing beneath the ice in Kaktovik Lagoon. Graduate student Sydney Wilkinson and research assistant Kaylie Plumb have just completed a show-and-tell of the ROV and a plankton net which are visible in front of the classroom. (Photo credit: Flora Rexford; 26 April 2022).*

We will pursue broader impacts during BLE II through continuation and enhancement of our education and outreach programs and implementation of new initiatives to expand participation and strengthen local connections.

Schoolyard classroom and field activities – In BLE II, we plan to budget more time to support the teachers and students at the Harold Kaveolook School in Kaktovik. We have allocated time and travel for a group of BLE researchers, graduate students, and/or staff to plan and implement school-based activities (Fig. 13) and/or field trips (Fig. 14) in conjunction with our April and August field campaigns and, when possible, the annual Alaska Marine Science Symposium (AMSS) held in January in Anchorage. We include an LTER data analysis component to these Schoolyard activities, where students and teachers use our data to understand the ecology of their lagoons and how ecosystem properties are changing with time. Students will have opportunities to collect and analyze their own samples as well as design experiments, building their familiarity with scientific practices. A focus on observation and storytelling, alongside quantitative data, are included to create more culturally relevant learning opportunities. Through these activities, including NSF approval for Inupiat teacher-artist Flora Rexford to paint a mural with students that features the local ecosystem on the exterior wall of our new lab, local students will gain an appreciation for the scientific research ongoing on their Native-owned and managed lands. At the same time, BLE scientists will gain valuable insight on how traditional knowledge can complement our research efforts. We will mentor and encourage high school students to actively join our field efforts and provide them with opportunities to present their work to the community or at regional symposia. Curriculum materials are created to highlight BLE science and processes and align with Next Generation Science Standards and the Iñupiaq Learning Framework developed by the North Slope Borough School District. Creation of BLE-specific lesson plans and activity guides will also support emerging outreach and education opportunities, such as a nascent partnership with the Boys & Girls Club of Utqiaġvik. In addition, the BARC Science Fair, hosted by UIC Science in Utqiaġvik, is returning after a 3-year hiatus. The BLE has been invited to participate in all years of BLE II, drawing on materials created for KOP and Kaveolook School visits. We are also pursing plans to involve students directly in our research in concert with the Alaska Arctic Observatory and Knowledge Hub (AAOKH) to document environmental changes.

Kaktovik Oceanography Program (KOP) – The KOP program provides students ages 6-18 an opportunity to become immersed in a combination of field, laboratory, and classroom activities to stimulate their interest in science and discovery. Activities focus on meaningful, hands-on learning with an emphasis on place-based learning that helps students draw connections between their lived experience, BLE LTER research, and science practices and knowledge. This is a successful program that the community of Kaktovik has grown to know and support since 2008, and we propose to continue offering the KOP every summer in BLE II.

BLE soundscapes – Through continued partnership with Matthew Burtner, we plan to deploy underwater microphones and audio recorders that can collect data for extended periods of time during BLE II, ideally for an entire year along with other environmental sensors. Such recorders will enable better integration of environmental sound into our *in situ* continuous data sets, producing the living dynamic resonance of Beaufort Lagoons year-round as a tool for public engagement. This activity also serves as another way to engage Kaveolook High School students to participate in our science, but through an interactive acoustic laboratory of musical expression.

Partnership with Iḷisaġvik College – Iḷisaġvik College is Alaska's only Tribal College. Located in Utqiaġvik (formerly Barrow), Alaska, the college provides an education based on the Iñupiaq cultural heritage. In BLE II, we propose to partner with Iḷisaġvik College and Dr. Linda Nicholas-Figueroa to integrate BLE science and guest presenters into both college courses and summer camps for teens. Twice during BLE II, researchers will present a module within Nicholas-Figueroa's course on climate change, culminating in an on-ice field trip during the April field campaign. As part of this partnership, we will reserve four of our budgeted REU positions for applicants from Iḷisaġvik College. Students can also receive independent research credit through Iḷisaġvik.

Fig. 14. *High school students from Harold Kaveolook School in Kaktovik, AK help BLE scientists deploy two remotely operated vehicles (ROVs) in Kaktovik Lagoon to observe the under-ice environment. The equipment used for BLE research is repurposed for in-field, hands-on lessons with students. Students in the background are learning how to take ice cores with a SIPRE coring device. (Photo credit: Flora Rexford; 26 April 2022).*

Research Experience for Teachers (RET) – In BLE II, we plan to expand our RET efforts to recruit indigenous teachers working in Alaska, and especially those working within the North Slope Borough School District (particularly Inupiat teachers working in Utqiaġvik and Kaktovik). One major goal is to link Inupiat students and teachers under REU and RET programs with BLE scientists in addressing questions of major concern to indigenous communities of the Beaufort Sea coast. Hunters and fishers in Kaktovik have asked about changes in subsistence fishery harvests, water quality, loss of cultural sites from shoreline erosion, and mercury levels in birds, fish, and marine mammals. As with BLE I, funding for RETs will be requested as supplementary support.

Research Experience for Undergraduates (REU) – We plan to support three students annually from different BLE institutions; we will prioritize that 50% of all REUs will come from groups underrepresented in the sciences. In addition, we aim to support 4 REUs from Iḷisaġvik College within the 5-year grant cycle (see above).

As a multi-institution LTER, with research teams located across the country, our REU program requires a combination of virtual and in-person activities. We will implement an REU program modelled after our Summer 2022 program, which supported five REUs at three BLE institutions; two of these REUs were selected to present their research projects at the ASM. To promote team-building and consistency across institutions, we will host twice weekly team meetings on Zoom with organization and team communication on a digital platform (e.g., Slack). Each week, one meeting will be focused on sharing the process of scientific research (e.g., developing a question, methods, presenting results) and giving REUs time to present five-minute update talks about their research and receive feedback. The second weekly meeting will focus on supplementary professional development activities (e.g., career panel, applying to graduate school), as well as lightening talks by BLE PIs and graduate students. Additional resources will be provided virtually to students to watch on their own. Each host lab is tasked with individual-based mentoring, such as lab safety, lab protocols and relevant analytical techniques, in addition to providing guidance through the process of completing their research project. The REU experience will culminate in final virtual presentations made to the entire BLE team.

Diversity Equity and Inclusion (DEI) – Ensuring a safe and inclusive environment for all BLE team members is a top priority. In 2020, the entire BLE team of PIs, students and staff worked to develop a DEI plan which strives to 1) ensure the BLE is a welcoming and inclusive environment, 2) promote recruitment, retention, and support of a more diverse team of students, faculty, staff and collaborators, and 3) build meaningful and lasting collaborations with local communities on the North Slope of Alaska.

Field safety is a related and important part of these efforts, and the BLE Field Safety Manual includes recommended risk assessment and mitigation strategies. In particular, all field team members are given the opportunity to attend Arctic Field Training and small boat training (AMSEA) provided by BLE logistics partners. In addition, BLE personnel are expected to abide by our Code of Conduct and Sexual Misconduct policies. These policies, as well as our Field Safety Manual and DEI Plan are all posted and publicly available on the BLE website.

Our ongoing efforts to promote DEI include:

- Emphasizing DEI as a priority during monthly team meetings through a DEI moment and ensuring time for all participants, regardless of position, to speak
- Giving graduate students space and time to be heard through the appointment of two PI liaisons, a graduate student representative on the Executive Committee (see Project Management Plan) and bi-weekly virtual meetings for team-building, professional development and journal discussions
- Offering climate surveys and field season reporting mechanisms and debriefing protocols, so multi-institution teams build and maintain positive relationships in the field, lab and online
- Promoting responsiveness to North Slope community needs and interests. For BLE II, this includes greater emphasis on study of higher trophic level organisms and links to food security and human health, as well as the education and outreach efforts listed above.

References Cited

Amiraux, R., Mundy, C. J., Pierrejean, M., Niemi, A., Hedges, K. J., Brown, T. A., Ehn, J. K., Elliott, K. H., Ferguson, S. H., Fisk, A. T., Gilchrist, G., Harris, L. N., Iken, K., Jacobs, K. B., Johnson, K. F., Kuzyk, Z. A., Limoges, A., Loewen, T. N., Love, O. P., Matthews, C. D., Ogloff, W. R., Rosenberg, B., Søreide, J. E., Watt, C. A., & Yurkowski, D. J. (2023). Tracing carbon flow and trophic structure of a coastal Arctic marine food web using highly branched isoprenoids and carbon, nitrogen and sulfur stable isotopes. *Ecological Indicators*, *147*, 109938. https://doi.org/10.1016/j.ecolind.2023.109938

Amundson, C., Flint, P., Stehn, R., Platte, R., Wilson, H., Larned, W., & Fischer, J. (2019). Spatio-temporal population change of Arctic-breeding waterbirds on the Arctic Coastal Plain of Alaska. *Avian Conservation and Ecology*, *14*(1). https://doi.org/10.5751/ACE-01383-140118

Anderson, D. L. (1961). Growth Rate of Sea Ice. *Journal of Glaciology*, *3*(30), 1170–1172. https://doi.org/10.3189/S0022143000017676

Arp, C. D., Jones, B. M., Schmutz, J. A., Urban, F. E., & Jorgenson, M. T. (2010). Two mechanisms of aquatic and terrestrial habitat change along an Alaskan Arctic coastline. *Polar Biology*, *33*, 1629–1640.

Arp, C. D., Whitman, M. S., Kemnitz, R., & Stuefer, S. L. (2020). Evidence of Hydrological Intensification and Regime Change From Northern Alaskan Watershed Runoff. *Geophysical Research Letters*, *47*(17), e2020GL089186. https://doi.org/10.1029/2020GL089186

Aryal, B., Escarzaga, S. M., Vargas Zesati, S. A., Velez-Reyes, M., Fuentes, O., & Tweedie, C. (2021). Semi-Automated Semantic Segmentation of Arctic Shorelines Using Very High-Resolution Airborne Imagery, Spectral Indices and Weakly Supervised Machine Learning Approaches. *Remote Sensing*, *13*(22), Article 22. https://doi.org/10.3390/rs13224572

Baker, K. D., Kellogg, C. T. E., McClelland, J. W., Dunton, K. H., & Crump, B. C. (2021). The Genomic Capabilities of Microbial Communities Track Seasonal Variation in Environmental Conditions of Arctic Lagoons. *Frontiers in Microbiology*, *12*. https://doi.org/10.3389/fmicb.2021.601901

Berge, J., Daase, M., Renaud, P. E., Ambrose, W. G., Darnis, G., Last, K. S., Leu, E., Cohen, J. H., Johnsen, G., Moline, M. A., Cottier, F., Varpe, Ø., Shunatova, N., Bałazy, P., Morata, N., Massabuau, J.-C., Falk-Petersen, S., Kosobokova, K., Hoppe, C. J. M., Węsławski, J. M., Kukliński, P., Legeżyńska, J., Nikishina, D., Cusa, M., Kędra, M., Włodarska-Kowalczuk, M., Vogedes, D., Camus, L., Tran, D., Michaud, E., Gabrielsen., T. M., Granovitch, A., Gonchar, A., Krapp, R., & Callesen, T. A. (2015). Unexpected Levels of Biological Activity during the Polar Night Offer New Perspectives on a Warming Arctic. *Current Biology*, *25*(19), 2555–2561. https://doi.org/10.1016/j.cub.2015.08.024

Bintanja, R., & van der Linden, E. C. (2013). The changing seasonal climate in the Arctic. *Scientific Reports*, *3*(1), 1556. https://doi.org/10.1038/srep01556

Bonsell, C., & Dunton, K. H. (2021). Slow Community Development Enhances Abiotic Limitation of Benthic Community Structure in a High Arctic Kelp Bed. *Frontiers in Marine Science*, *8*. https://www.frontiersin.org/articles/10.3389/fmars.2021.592295

Bowden, D. (2005). *Benthic assemblage development and larval ecology of marine invertebrates at Adelaide Island, Antarctica*. Open University (United Kingdom).

Bridges, K. N., Furin, C. G., & Gerlach, R. F. (2020). Subsistence fish consumption in rural Alaska: Using regional monitoring data to evaluate risk and bioavailability of dietary methylmercury. *Science of The Total Environment*, *736*, 139676. https://doi.org/10.1016/j.scitotenv.2020.139676

Bristol, E. M., Connolly, C. T., Lorenson, T. D., Richmond, B. M., Ilgen, A. G., Choens, R. C., Bull, D. L., Kanevskiy, M., Iwahana, G., Jones, B. M., & McClelland, J. W. (2021). Geochemistry of Coastal Permafrost and Erosion-Driven Organic Matter Fluxes to the Beaufort Sea Near Drew Point, Alaska. *Frontiers in Earth Science*, *8*, 598933. https://doi.org/10.3389/feart.2020.598933

Budge, S. M., Wooller, M. J., Springer, A. M., Iverson, S. J., McRoy, C. P., & Divoky, G. J. (2008).Tracing carbon flow in an arctic marine food web using fatty acid-stable isotope analysis. *Oecologia*, *157*(1), 117–129. https://doi.org/10.1007/s00442-008-1053-7

Carey, M. P., Biela, V. R. von, Brown, R. J., & Zimmerman, C. E. (2021). Migration strategies supporting salmonids in Arctic Rivers: A case study of Arctic Cisco and Dolly Varden. *Animal Migration*, *8*(1), 132–143. https://doi.org/10.1515/ami-2020-0115

Clark, A., Moorman, B., Whalen, D., & Fraser, P. (2021). Arctic coastal erosion: UAV-SfM data collection strategies for planimetric and volumetric measurements. *Arctic Science*, *7*(3), 605–633. https://doi.org/10.1139/as-2020-0021

Clark, A., Moorman, B., Whalen, D., & Vieira, G. (2022). Multiscale Object-Based Classification and Feature Extraction along Arctic Coasts. *Remote Sensing*, *14*(13), Article 13. https://doi.org/10.3390/rs14132982

Connelly, T., McClelland, J., Crump, B., Kellogg, C., & Dunton, K. (2015). Seasonal changes in quantity and composition of suspended particulate organic matter in lagoons of the Alaskan Beaufort Sea. *Marine Ecology Progress Series*, *527*, 31–45. https://doi.org/10.3354/meps11207

Connolly, C. T., Cardenas, M. B., Burkart, G. A., Spencer, R. G. M., & McClelland, J. W. (2020). Groundwater as a major source of dissolved organic matter to Arctic coastal waters. *Nature Communications*, *11*(1), 1479. https://doi.org/10.1038/s41467-020-15250-8

Connolly, C. T., Crump, B. C., Dunton, K. H., & McClelland, J. W. (2021). Seasonality of dissolved organic matter in lagoon ecosystems along the Alaska Beaufort Sea coast. *Limnology and Oceanography*, *66*(12), 4299–4313. https://doi.org/10.1002/lno.11962

Connolly, C. T., Khosh, M. S., Burkart, G. A., Douglas, T. A., Holmes, R. M., Jacobson, A. D., Tank, S. E., & McClelland, J. W. (2018). Watershed slope as a predictor of fluvial dissolved organic matter and nitrate concentrations across geographical space and catchment size in the Arctic. *Environmental Research Letters*, *13*(10), 104015. https://doi.org/10.1088/1748-9326/aae35d

Cram, J. A., Chow, C.-E. T., Sachdeva, R., Needham, D. M., Parada, A. E., Steele, J. A., & Fuhrman, J. A. (2015). Seasonal and interannual variability of the marine bacterioplankton community throughout the water column over ten years. *The ISME Journal*, *9*(3), Article 3. https://doi.org/10.1038/ismej.2014.153

Cunliffe, A. M., Tanski, G., Radosavljevic, B., Palmer, W. F., Sachs, T., Lantuit, H., Kerby, J. T., & Myers-Smith, I. H. (2019). Rapid retreat of permafrost coastline observed with aerial drone photogrammetry. *The Cryosphere*, *13*(5), 1513–1528. https://doi.org/10.5194/tc-13-1513-2019

Dammann, D. O., Johnson, M. A., Mahoney, A. R., Fedders, E. R., Ito, M., Hutchings, J. K., Polashenski, C. M., & Fahnstock, M. (2023). Ground-based radar interferometry for monitoring of landfast sea ice dynamics. *Cold Regions Science and Technology*, 103779. https://doi.org/10.1016/j.coldregions.2023.103779

Danielson, S. L., Grebmeier, J. M., Iken, K., Berchok, C., Britt, L., Dunton, K. H., Eisner, L., Farley, E. V., Fujiwara, A., Hauser, D. D. W., Itoh, M., Kikuchi, T., Kotwicki, S., Kuletz, K. J., Mordy, C. W., Nishino, S., Peralta-Ferriz, C., Pickart, R. S., Stabeno, P. S., … Woodgate, R. (2022). Monitoring Alaskan Arctic Shelf Ecosystems Through Collaborative Observation Networks. *Oceanography*, *35*(3/4), 198–209.

Descôteaux, R., Ershova, E., Wangensteen, O. S., Præbel, K., Renaud, P. E., Cottier, F., & Bluhm, B. A. (2021). Meroplankton diversity, seasonality and life-history traits across the Barents Sea Polar Front revealed by high-throughput DNA barcoding. *Frontiers in Marine Science*, *8*, 677732.

Díaz, M. J., Buschbaum, C., Renaud, P. E., Valdivia, N., & Molis, M. (2023). Limited predatory effects on infaunal macrobenthos community patterns in intertidal soft-bottom of Arctic coasts. *Ecology and Evolution*, *13*(1), e9779. https://doi.org/10.1002/ece3.9779

Ducklow, H., Cimino, M., Dunton, K. H., Fraser, W. R., Hopcroft, R. R., Ji, R., Miller, A. J., Ohman, M. D., & Sosik, H. M. (2022). Marine Pelagic Ecosystem Responses to Climate Variability and Change. *BioScience*, *72*(9), 827–850. https://doi.org/10.1093/biosci/biac050

Durski, S. M., & Kurapov, A. L. (2019). A high-resolution coupled ice-ocean model of winter circulation on the bering sea shelf. Part I: Ice model refinements and skill assessments. *Ocean Modelling*, *133*, 145–161. https://doi.org/10.1016/j.ocemod.2018.11.004

Eicken, H., Gradinger, R., Gaylord, A., Mahoney, A., Rigor, I., & Melling, H. (2005). Sediment transport by sea ice in the Chukchi and Beaufort Seas: Increasing importance due to changing ice conditions? *Deep Sea Research Part II: Topical Studies in Oceanography*, *52*(24), 3281–3302. https://doi.org/10.1016/j.dsr2.2005.10.006

Frederick, J., Conley, E., Nole, M., Marchitto, T., & Wagman, B. (2022). *Quantifying the Known Unknown: Including Marine Sources of Greenhouse Gases in Climate Modeling.* (No. SAND2022-13028). Sandia National Lab. (SNL-NM), Albuquerque, NM (United States). https://doi.org/10.2172/1889332

Fuhrman, J. A., Cram, J. A., & Needham, D. M. (2015). Marine microbial community dynamics and their ecological interpretation. *Nature Reviews Microbiology*, *13*(3), Article 3. https://doi.org/10.1038/nrmicro3417

Gadamus, L. (2013). Linkages between human health and ocean health: A participatory climate change vulnerability assessment for marine mammal harvesters. *International Journal of Circumpolar Health*, *72*(1), 20715. https://doi.org/10.3402/ijch.v72i0.20715

Gibbs, A. E., & Richmond, B. M. (2015). *National Assessment of Shoreline Change: Historical Shoreline Change Along the North Coast of Alaska, U.S.-Canadian Border to Icy Cape* (Open-File Report) [Open-File Report]. US Department of the Interior, US Geological Survey.

Gibson, G. A., & Spitz, Y. H. (2011). Impacts of biological parameterization, initial conditions, and environmental forcing on parameter sensitivity and uncertainty in a marine ecosystem model for the Bering Sea. *Journal of Marine Systems*, *88*(2), 214–231.

Gilbert, G. L., Instanes, A., Sinitsyn, A. O., & Aalberg, A. (2019). Characterization of two sites for geotechnical testing in permafrost: Longyearbyen, Svalbard. *AIMS Geosciences*, *5*(4), 868–886. https://doi.org/10.3934/geosci.2019.4.868

Gilg, O., Kovacs, K. M., Aars, J., Fort, J., Gauthier, G., Grémillet, D., Ims, R. A., Meltofte, H., Moreau, J., Post, E., Schmidt, N. M., Yannic, G., & Bollache, L. (2012). Climate change and the ecology and evolution of Arctic vertebrates. *Annals of the New York Academy of Sciences*, *1249*(1), 166–190. https://doi.org/10.1111/j.1749-6632.2011.06412.x

Goswami, S., Gamon, J. A., & Tweedie, C. E. (2011). Surface hydrology of an arctic ecosystem: Multiscale analysis of a flooding and draining experiment using spectral reflectance. *Journal of Geophysical Research: Biogeosciences*, *116*(G4). https://doi.org/10.1029/2010JG001346

Graham, E. B., Averill, C., Bond-Lamberty, B., Knelman, J. E., Krause, S., Peralta, A. L., Shade, A., Smith, A. P., Cheng, S. J., Fanin, N., Freund, C., Garcia, P. E., Gibbons, S. M., Van Goethem, M. W., Guebila, M. B., Kemppinen, J., Nowicki, R. J., Pausas, J. G., Reed, S. P., Rocca, J., Sengupta, A., Sihi, D., Simonin, M., Słowiński, M., Spawn, S. A., Sutherland, I., Tonkin, J. D., Wisnoski, N. I., Zipper, S. C., Staal, A., Arora, B., Oldfield, C., Dwivedi, D., Larson, E., Santillan, E., Aaron Hogan, J., Atkins, J., Zheng, J., Lembrechts, J., Patel, K., Copes-Gerbitz, K., Winker, K., Mudge, L., Wong, M., Nuñez, M., Luoto, M., & Barnes, R. (2021). Toward a Generalizable Framework of Disturbance Ecology Through Crowdsourced Science. *Frontiers in Ecology and Evolution*, *9*. https://www.frontiersin.org/articles/10.3389/fevo.2021.588940

Green, K., Beaudreau, A., Lukin, M., & Crowder, L. (2021). Climate change stressors and social-ecological factors mediating access to subsistence resources in Arctic Alaska. *Ecology and Society*, *26*(4). https://doi.org/10.5751/ES-12783-260415

Gries, C., Beaulieu, S., Brown, R. F., Elmendorf, S., Garritt, H., Gastil-Buhl, G., Hsieh, H.-Y., Kui, L., Martin, M., Maurer, G., Nguyen, A. T., Porter, J. H., Sapp, A., Servilla, M., & Whiteaker, T. L. (2021). *Data Package Design for Special Cases* [Data set]. Environmental Data Initiative. https://doi.org/10.6073/PASTA/9D4C803578C3FBCB45FC23F13124D052

Griffin, N. A. (2022). *Quantitative Metatranscriptomics and Biogeochemical Rate Measurements Reveal Microbial Pathways Driving Carbon and Nitrogen Cycles in an Arctic Lagoon* [M.S.]. Oregon State University.

Gutgesell, M. K., McCann, K. S., Gellner, G., Cazelles, K., Greyson-Gaito, C. J., Bieg, C., Guzzo, M. M., Warne, C. P. K., Ward, C. A., O'Connor, R. F., Scott, A. M., Graham, B. C., Champagne, E. J., & McMeans, B. C. (2022). On the Dynamic Nature of Omnivory in a Changing World. *BioScience*, 72(5), 416–430. https://doi.org/10.1093/biosci/biab144

Harris, C. M., McClelland, J. W., Connelly, T. L., Crump, B. C., & Dunton, K. H. (2017). Salinity and temperature regimes in eastern Alaskan Beaufort Sea lagoons in relation to source water contributions. *Estuaries and Coasts*, *40*, 50–62.

Harris, C. M., McTigue, N. D., McClelland, J. W., & Dunton, K. H. (2018). Do high Arctic coastal food webs rely on a terrestrial carbon subsidy? *Food Webs*, *15*, e00081. https://doi.org/10.1016/j.fooweb.2018.e00081

He, X., Sun, L., Xie, Z., Huang, W., Long, N., Li, Z., & Xing, G. (2013). Sea ice in the Arctic Ocean: Role of shielding and consumption of methane. *Atmospheric Environment*, *67*, 8–13. https://doi.org/10.1016/j.atmosenv.2012.10.029

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Greer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., & Thépaut, J.-N. (2017). Complete ERA5 from 1979: Fifth generation of ECMWF atmospheric reanalyses of the global climate. *Copernicus Climate Change Service (C3S) Data Store (CDS)*.

Hopkinson, C., & Weston, N. (2020). PIE LTER transects of the Parker River Plum Island Sound Estuary, Massachusetts conducted at dawn and dusk, containing dissolved oxygen, conductivity, temperature, percent saturation, pH, DIC, and pCO2 data. *Environmental Data Initiative*. https://doi.org/10.6073

Hume, A. C., Berg, P., & McGlathery, K. J. (2011). Dissolved oxygen fluxes and ecosystem metabolism in an eelgrass (Zostera marina) meadow measured with the eddy correlation technique. *Limnology and Oceanography*, *56*(1), 86–96. https://doi.org/10.4319/lo.2011.56.1.0086

Iwahana, G., Cooper, Z. S., Carpenter, S. D., Deming, J. W., & Eicken, H. (2021). Intra-ice and intra-sediment cryopeg brine occurrence in permafrost near Utqiaġvik (Barrow). *Permafrost and Periglacial Processes*, *32*(3), 427–446. https://doi.org/10.1002/ppp.2101

James, R. H., Bousquet, P., Bussmann, I., Haeckel, M., Kipfer, R., Leifer, I., Niemann, H., Ostrovsky, I., Piskozub, J., Rehder, G., Treude, T., Vielstädte, L., & Greinert, J. (2016). Effects of climate change on methane emissions from seafloor sediments in the Arctic Ocean: A review. *Limnology and Oceanography*, *61*(S1), S283–S299. https://doi.org/10.1002/lno.10307

Jensen, D. A., Nandan, V., Mahoney, A. R., Yackel, J. J., & Resler, L. M. (2023). Landfast sea ice break out patterns in the northern Bering Sea observed from C-band Synthetic Aperture Radar. *International Journal of Applied Earth Observation and Geoinformation*, *117*, 103183. https://doi.org/10.1016/j.jag.2023.103183

Jin, M., Deal, C. J., Wang, J., Shin, K.-H., Tanaka, N., Whitledge, T. E., Lee, S. H., & Gradinger, R. R. (2006). Controls of the landfast ice–ocean ecosystem offshore Barrow, Alaska. *Annals of Glaciology*, *44*, 63–72. https://doi.org/10.3189/172756406781811709

Jin, M., Popova, E. E., Zhang, J., Ji, R., Pendleton, D., Varpe, Ø., Yool, A., & Lee, Y. J. (2016). Ecosystem model intercomparison of under-ice and total primary production in the Arctic Ocean. *Journal of Geophysical Research: Oceans*, *121*(1), 934–948. https://doi.org/10.1002/2015JC011183

Johnson, M., Mahoney, A., Sybrandy, A., & Montgomery, G. (2020). Measuring Acceleration and Short-Lived Motion in Landfast Sea-Ice. *Journal of Ocean Technology*, *15*(3).

Jones, B. M., Farquharson, L. M., Baughman, C. A., Buzard, R. M., Arp, C. D., Grosse, G., Bull, D. L., Günther, F., Nitze, I., Urban, F., Kasper, J. L., Frederick, J. M., Thomas, M., Jones, C., Mota, A., Dallimore, S., Tweedie, C., Maio, C., Mann, D. H., Richmond, B., Gibbs, A., Xiao, M., Sachs, T., Iwahana, G., Kanevskiy, M., & Romanovsky, V. E. (2018). A decade of remotely sensed observations highlight complex processes linked to coastal permafrost bluff erosion in the Arctic. *Environmental Research Letters*, *13*(11), 115001. https://doi.org/10.1088/1748-9326/aae471

Jones, B. M., Irrgang, A. M., Farquharson, L. M., Lantuit, H., Whalen, D., Ogorodov, S., Grigoriev, M., Tweedie, C., Gibbs, A. E., Strzelecki, M. C., Baranskaya, A., Belova, N., Sinitsyn, A., Kroon, A., Maslakov, A., Vieira, G., Grosse, G., Overduin, P., Nitze, I., Maio, C., Overbeck, J., Bendixen, M., Zagorski, P., & Romanovsky, V. E. (2020). Coastal Permafrost Erosion. *Arctic Report Card*, *15*. https://doi.org/10.25923/e47w-dw52

Kearney, K., Hermann, A., Cheng, W., Ortiz, I., & Aydin, K. (2020). A coupled pelagic–benthic–sympagic biogeochemical model for the Bering Sea: Documentation and validation of the BESTNPZ model (v2019. 08.23) within a high-resolution regional ocean model. *Geoscientific Model Development*, *13*(2), 597–650.

Kellogg, C. T. E., McClelland, J. W., Dunton, K. H., & Crump, B. C. (2019). Strong Seasonality in Arctic Estuarine Microbial Food Webs. *Frontiers in Microbiology*, *10*. https://www.frontiersin.org/articles/10.3389/fmicb.2019.02628

Kitidis, V., Upstill-Goddard, R. C., & Anderson, L. G. (2010). Methane and nitrous oxide in surface water along the North-West Passage, Arctic Ocean. *Marine Chemistry*, *121*(1), 80–86. https://doi.org/10.1016/j.marchem.2010.03.006

Kohlbach, D., Graeve, M., A. Lange, B., David, C., Peeken, I., & Flores, H. (2016). The importance of ice algae-produced carbon in the central Arctic Ocean ecosystem: Food web relationships revealed by lipid and stable isotope analyses. *Limnology and Oceanography*, *61*(6), 2027–2044. https://doi.org/10.1002/lno.10351

Kuhnlein, H. V. (2015). Food system sustainability for health and well-being of Indigenous Peoples. *Public Health Nutrition*, *18*(13), 2415–2424. https://doi.org/10.1017/S1368980014002961

Kuklinski, P., Berge, J., McFadden, L., Dmoch, K., Zajaczkowski, M., Nygård, H., Piwosz, K., & Tatarek, A. (2013). Seasonality of occurrence and recruitment of Arctic marine benthic invertebrate larvae in relation to environmental variables. *Polar Biology*, *36*, 549–560.

Legendre, L., Martineau, M.-J., Therriault, J.-C., & Demers, S. (1992). Chlorophyll a biomass and growth of sea-ice microalgae along a salinity gradient (southeastern Hudson Bay, Canadian Arctic). *Polar Biology*, *12*(3), 445–453. https://doi.org/10.1007/BF00243115

Leu, E., Mundy, C. J., Assmy, P., Campbell, K., Gabrielsen, T. M., Gosselin, M., Juul-Pedersen, T., & Gradinger, R. (2015). Arctic spring awakening – Steering principles behind the phenology of vernal ice algal blooms. *Progress in Oceanography*, *139*, 151–170. https://doi.org/10.1016/j.pocean.2015.07.012

Lewis, K. M., & Arrigo, K. R. (2020). Ocean Color Algorithms for Estimating Chlorophyll a, CDOM Absorption, and Particle Backscattering in the Arctic Ocean. *Journal of Geophysical Research: Oceans*, *125*(6), e2019JC015706. https://doi.org/10.1029/2019JC015706

Li, C., Boswell, K. M., Chaichitehrani, N., Huang, W., & Wu, R. (2019). Weather induced subtidal flows through multiple inlets of an arctic microtidal lagoon. *Acta Oceanologica Sinica*, *38*, 1–16.

Liljedahl, A. K., Boike, J., Daanen, R. P., Fedorov, A. N., Frost, G. V., Grosse, G., Hinzman, L. D., Iijma, Y., Jorgenson, J. C., Matveyeva, N., Necsoiu, M., Raynolds, M. K., Romanovsky, V. E., Schulla, J., Tape, K. D., Walker, D. A., Wilson, C. J., Yabuki, H., & Zona, D. (2016). Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. *Nature Geoscience*, *9*(4), Article 4. https://doi.org/10.1038/ngeo2674

Lougheed, V. L., Hernandez, C., Andresen, C. G., Miller, N. A., Alexander, V., & Prentki, R. (2015). Contrasting responses of phytoplankton and benthic algae to recent nutrient enrichment in Arctic tundra ponds. *Freshwater Biology*, *60*(10), 2169–2186. https://doi.org/10.1111/fwb.12644

Lougheed, V. L., Tweedie, C. E., Andresen, C. G., Armendariz, A. M., Escarzaga, S. M., & Tarin, G. (2020). Patterns and Drivers of Carbon Dioxide Concentrations in Aquatic Ecosystems of the Arctic Coastal Tundra. *Global Biogeochemical Cycles*, *34*(3), e2020GB006552. https://doi.org/10.1029/2020GB006552

Mahoney, A. R. (2018). Landfast Sea Ice in a Changing Arctic. *Arctic Report Card 2018*.

Mahoney, A. R., Gearheard, S., Oshima, T., & Qillaq, T. (2009). Sea ice thickness measurements from a community-based observing network. *Bulletin of the American Meteorological Society*, *90*(3), 370–378.

Mahoney, A. R., Turner, K. E., Hauser, D. D., Laxague, N. J., Lindsay, J. M., Whiting, A. V., Witte, C. R., Goodwin, J., Harris, C., & Schaeffer, R. J. (2021). Thin ice, deep snow and surface flooding in Kotzebue Sound: Landfast ice mass balance during two anomalously warm winters and implications for marine mammals and subsistence hunting. *Journal of Glaciology*, *67*(266), 1013–1027.

McGlathery, K. J., Sundbäck, K., & Anderson, I. C. (2007). Eutrophication in shallow coastal bays and lagoons: The role of plants in the coastal filter. *Marine Ecology Progress Series*, *348*, 1–18.

McMeans, B., McCann, K. S., Humphries, M., Rooney, N., & Fisk, A. T. (2015). Food Web Structure in Temporally-Forced Ecosystems. *Trends in Ecology & Evolution*, *30*(11), 662–672. https://doi.org/10.1016/j.tree.2015.09.001

McMeans, B., Rooney, N., Arts, M., & Fisk, A. (2013). Food web structure of a coastal Arctic marine ecosystem and implications for stability. *Marine Ecology Progress Series*, *482*, 17–28. https://doi.org/10.3354/meps10278

McTigue, N. D., Bucolo, P., Liu, Z., & Dunton, K. H. (2015). Pelagic-benthic coupling, food webs, and organic matter degradation in the Chukchi Sea: Insights from sedimentary pigments and stable carbon isotopes. *Limnology and Oceanography*, *60*(2), 429–445. https://doi.org/10.1002/lno.10038

Miller, C. A., Bonsell, C., McTigue, N. D., & Kelley, A. L. (2021). The seasonal phases of an Arctic lagoon reveal the discontinuities of pH variability and CO_2 flux at the air–sea interface. *Biogeosciences*, *18*(3), 1203–1221. https://doi.org/10.5194/bg-18-1203-2021

Moon, W., Nandan, V., Scharien, R. K., Wilkinson, J., Yackel, J. J., Barrett, A., Lawrence, I., Segal, R. A., Stroeve, J., & Mahmud, M. (2019). Physical length scales of wind-blown snow redistribution and accumulation on relatively smooth Arctic first-year sea ice. *Environmental Research Letters*, *14*(10), 104003.

Mougi, A. (2020). Polyrhythmic foraging and competitive coexistence. *Scientific Reports*, 10(1), Article 1. https://doi.org/10.1038/s41598-020-77483-3

North, C. A., Lovvorn, J. R., Kolts, J. M., Brooks, M. L., Cooper, L. W., & Grebmeier, J. M. (2014). Deposit-feeder diets in the Bering Sea: Potential effects of climatic loss of sea ice-related microalgal blooms. *Ecological Applications*, *24*(6), 1525–1542. https://doi.org/10.1890/13-0486.1

O'Connor, M. T., Cardenas, M. B., Neilson, B. T., Nicholaides, K. D., & Kling, G. W. (2019). Active Layer Groundwater Flow: The Interrelated Effects of Stratigraphy, Thaw, and

Topography. *Water Resources Research*, *55*(8), 6555–6576. https://doi.org/10.1029/2018WR024636
Okkonen, S. R. (2016). Sea Level Measurements along the Alaskan Chukchi and Beaufort Coasts. In *OCS Study BOEM 2016-075* (p. 26).
Pedrazas, M. N., Cardenas, M. B., Demir, C., Watson, J. A., Connolly, C. T., & McClelland, J. W. (2020). Absence of ice-bonded permafrost beneath an Arctic lagoon revealed by electrical geophysics. *Science Advances*, *6*(43), eabb5083. https://doi.org/10.1126/sciadv.abb5083
Pimm, S. L. (1984). The complexity and stability of ecosystems. *Nature*, 307(5949), Article 5949. https://doi.org/10.1038/307321a0
Ping, C.-L., Michaelson, G. J., Guo, L., Jorgenson, M. T., Kanevskiy, M., Shur, Y., Dou, F., & Liang, J. (2011). Soil carbon and material fluxes across the eroding Alaska Beaufort Sea coastline. *Journal of Geophysical Research: Biogeosciences*, *116*(G2). https://doi.org/10.1029/2010JG001588
Planck, C. J., Whitlock, J., Polashenski, C., & Perovich, D. (2019). The evolution of the seasonal ice mass balance buoy. *Cold Regions Science and Technology*, *165*, 102792. https://doi.org/10.1016/j.coldregions.2019.102792
Porubsky, W. P., Velasquez, L. E., & Joye, S. B. (2008). Nutrient-Replete Benthic Microalgae as a Source of Dissolved Organic Carbon to Coastal Waters. *Estuaries and Coasts*, *31*(5), 860–876. https://doi.org/10.1007/s12237-008-9077-0
Pratt, J. W. (2022). *Mapping Bottomfast Sea Ice in Arctic Lagoons Using Sentinel-1 Interferometery* [M.S., University of Alaska Fairbanks]. https://www.proquest.com/docview/2703418056/abstract/928486E35AD247A9PQ/1
Price, J. F., Weller, R. A., & Pinkel, R. (1986). Diurnal cycling: Observations and models of the upper ocean response to diurnal heating, cooling, and wind mixing. *Journal of Geophysical Research: Oceans*, *91*(C7), 8411–8427. https://doi.org/10.1029/JC091iC07p08411
Rantanen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., & Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*, *3*(1), Article 1. https://doi.org/10.1038/s43247-022-00498-3
Rawlins, M. A., Connolly, C. T., & McClelland, J. W. (2021a). Modeling Terrestrial Dissolved Organic Carbon Loading to Western Arctic Rivers. *Journal of Geophysical Research: Biogeosciences*, *126*(10). https://doi.org/10.1029/2021JG006420
Rawlins, M. A. (2021b). Increasing freshwater and dissolved organic carbon flows to Northwest Alaska's Elson lagoon. *Environmental Research Letters*, *16*(10), 105014.
Rawlins, M. A., Cai, L., Stuefer, S. L., & Nicolsky, D. (2019). Changing characteristics of runoff and freshwater export from watersheds draining northern Alaska. *The Cryosphere*, *13*(12), 3337–3352.
Reed, A. J., Godbold, J. A., Solan, M., & Grange, L. J. (2021). Reproductive traits and population dynamics of benthic invertebrates indicate episodic recruitment patterns across an Arctic polar front. *Ecology and Evolution*, *11*(11), 6900–6912. https://doi.org/10.1002/ece3.7539
Rettelbach, T., Langer, M., Nitze, I., Jones, B., Helm, V., Freytag, J.-C., & Grosse, G. (2021). A Quantitative Graph-Based Approach to Monitoring Ice-Wedge Trough Dynamics in

Polygonal Permafrost Landscapes. *Remote Sensing*, *13*(16), Article 16. https://doi.org/10.3390/rs13163098

Shchepetkin, A. F., & McWilliams, J. C. (2005). The regional oceanic modeling system (ROMS): A split-explicit, free-surface, topography-following-coordinate oceanic model. *Ocean Modelling*, *9*(4), 347–404. https://doi.org/10.1016/j.ocemod.2004.08.002

Shogren, A. J., Zarnetske, J. P., Abbott, B. W., Iannucci, F., Medvedeff, A., Cairns, S., Duda, M. J., & Bowden, W. B. (2021). Arctic concentration–discharge relationships for dissolved organic carbon and nitrate vary with landscape and season. *Limnology and Oceanography*, *66*(S1), S197–S215. https://doi.org/10.1002/lno.11682

Singh, R. K., Vader, A., Mundy, C. J., Søreide, J. E., Iken, K., Dunton, K. H., Castro de la Guardia, L., Sejr, M. K., & Bélanger, S. (2022). Satellite-Derived Photosynthetically Available Radiation at the Coastal Arctic Seafloor. *Remote Sensing*, *14*(20), Article 20. https://doi.org/10.3390/rs14205180

Slotsbo, S., Maraldo, K., Malmendal, A., Nielsen, N. Chr., & Holmstrup, M. (2008). Freeze tolerance and accumulation of cryoprotectants in the enchytraeid Enchytraeus albidus (Oligochaeta) from Greenland and Europe. *Cryobiology*, *57*(3), 286–291. https://doi.org/10.1016/j.cryobiol.2008.09.010

Smith, R. E. H., Gosselin, M., & Taguchi, S. (1997). The influence of major inorganic nutrients on the growth and physiology of high arctic ice algae. *Journal of Marine Systems*, *11*(1), 63–70. https://doi.org/10.1016/S0924-7963(96)00028-0

Snelgrove, P. V., Grassle, J. P., Grassle, J. F., Petrecca, R. F., & Ma, H. (1999). In situ habitat selection by settling larvae of marine soft-sediment invertebrates. *Limnology and Oceanography*, *44*(5), 1341–1347.

Stanek, A. E., von Biela, V. R., Laske, S. M., Taylor, R. L., & Dunton, K. H. (2022). Barrier islands influence the assimilation of terrestrial energy in nearshore fishes. *Estuarine, Coastal and Shelf Science*, *278*, 108094. https://doi.org/10.1016/j.ecss.2022.108094

Sundbäck, K., Miles, A., & Göransson, E. (2000). Nitrogen fluxes, denitrification and the role of microphytobenthos in microtidal shallow-water sediments: An annual study. *Marine Ecology Progress Series*, *200*, 59–76. https://doi.org/10.3354/meps200059

Szymanski, A., & Gradinger, R. (2016). The diversity, abundance and fate of ice algae and phytoplankton in the Bering Sea. *Polar Biology*, *39*(2), 309–325. https://doi.org/10.1007/s00300-015-1783-z

Valiela, I., McClelland, J., Hauxwell, J., Behr, P. J., Hersh, D., & Foreman, K. (1997). Macroalgal blooms in shallow estuaries: Controls and ecophysiological and ecosystem consequences. *Limnology and Oceanography*, *42*(5part2), 1105–1118. https://doi.org/10.4319/lo.1997.42.5_part_2.1105

Viaroli, P., Bartoli, M., Bondavalli, C., Christian, R. R., Giordani, G., & Naldi, M. (1996). Macrophyte communities and their impact on benthic fluxes of oxygen, sulphide and nutrients in shallow eutrophic environments. In P. Caumette, J. Castel, & R. Herbert (Eds.), *Coastal Lagoon Eutrophication and ANaerobic Processes (C.L.E.AN.): Nitrogen and Sulfur Cycles and Population Dynamics in Coastal Lagoons A Research Programme of the Environment Programme of the EC (DG XII)* (pp. 105–119). Springer Netherlands. https://doi.org/10.1007/978-94-009-1744-6_9

von Biela, V. R., Laske, S. M., Stanek, A. E., Brown, R. J., & Dunton, K. H. (2022). Borealization of nearshore fishes on an interior Arctic shelf over multiple decades. *Global Change Biology*, gcb.16576. https://doi.org/10.1111/gcb.16576

Wainright, S., Weinstein, M., Able, K., & Currin, C. (2000). Relative importance of benthic microalgae, phytoplankton and the detritus of smooth cordgrass Spartina alterniflora and the common reed Phragmites australis to brackish-marsh food webs. *Marine Ecology Progress Series*, *200*, 77–91. https://doi.org/10.3354/meps200077

Walsh, J. E., Overland, J. E., Groisman, P. Y., & Rudolf, B. (2011). Ongoing Climate Change in the Arctic. *AMBIO*, *40*(1), 6–16. https://doi.org/10.1007/s13280-011-0211-z

Walsh, J. R., Carpenter, S. R., & Vander Zanden, M. J. (2016). Invasive species triggers a massive loss of ecosystem services through a trophic cascade. *Proceedings of the National Academy of Sciences*, *113*(15), 4081–4085. https://doi.org/10.1073/pnas.1600366113

Wang, S. R., Di Iorio, D., Cai, W.-J., & Hopkinson, C. S. (2018). Inorganic carbon and oxygen dynamics in a marsh-dominated estuary. *Limnology and Oceanography*, *63*(1), 47–71. https://doi.org/10.1002/lno.10614

Wang, S. W., Budge, S. M., Gradinger, R. R., Iken, K., & Wooller, M. J. (2014). Fatty acid and stable isotope characteristics of sea ice and pelagic particulate organic matter in the Bering Sea: Tools for estimating sea ice algal contribution to Arctic food web production. *Oecologia*, *174*(3), 699–712. https://doi.org/10.1007/s00442-013-2832-3

Warner, J. C., Armstrong, B., He, R., & Zambon, J. B. (2010). Development of a Coupled Ocean–Atmosphere–Wave–Sediment Transport (COAWST) Modeling System. *Ocean Modelling*, *35*(3), 230–244. https://doi.org/10.1016/j.ocemod.2010.07.010

Wilson, S.J. et al. (72 authors). (2023). Global subterranean estuaries modify groundwater nutrient fluxes to the ocean. *Nature Geosciences*, under review.

Yilmaz, P., (111 authors). (2011). Minimum information about a marker gene sequence (MIMARKS) and minimum information about any (x) sequence (MIxS) specifications. *Nature Biotechnology*, *29*(5), Article 5. https://doi.org/10.1038/nbt.1823

Zhang, J., Ashjian, C., Campbell, R., Hill, V., Spitz, Y. H., & Steele, M. (2014). The great 2012 Arctic Ocean summer cyclone enhanced biological productivity on the shelves. *Journal of Geophysical Research: Oceans*, *119*(1), 297–312. https://doi.org/10.1002/2013JC009301

Zimmermann, M., Erikson, L. H., Gibbs, A. E., Prescott, M. M., Escarzaga, S. M., Tweedie, C. E., Kasper, J. L., & Duvoy, P. X. (2022). Nearshore bathymetric changes along the Alaska Beaufort Sea coast and possible physical drivers. *Continental Shelf Research*, *242*, 104745. https://doi.org/10.1016/j.csr.2022.104745