

Figure 1. Schematic of major lagoon system components (labeled black) and tools (labeled red) that will be used to support Beaufort Lagoon Ecosystems (BLE) LTER research. Note that maximum depths in the proposed study lagoons are 4-7 m.

SECTION 1: PROPOSED RESEARCH

1.1 INTRODUCTION

Temporal variations are inherent to most ecosystems on Earth, yet food web structure is often defined as a static property of a given habitat type. 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. McMeans et al. (2013; 2015), however, argue that temporal variations play a central role in determining trophic linkages, stability, and resilience of food webs. In particular, they hypothesize that differential availability of seasonally-distinct resources (e.g., fresh phytoplankton vs. detritus) is a critical factor. We propose to establish and sustain an LTER program focusing on lagoon ecosystems along the Alaskan Beaufort Sea coast (Fig. 1) to test this concept across multiple timeframes. The Beaufort lagoons are ideal for testing this concept because they experience extreme variability on seasonal cycles and because they are experiencing rapid directional shifts driven by climate change. Specific study sites (Fig. 2) will be located in Elson Lagoon (western Beaufort), Simpson Lagoon and Stefansson Sound (central Beaufort), and Kaktovik and Jago lagoons (eastern Beaufort).

Our overarching question is: *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?* The Beaufort lagoons provide a unique opportunity to study these interactions in the absence of fringing wetlands (e.g., salt marshes and mangrove stands) that often modulate land-ocean interactions in other lagoon systems. In addition, barrier island geomorphology, which exerts a strong control on water exchange between lagoons and the open ocean, is highly dynamic in the Arctic because the effects of sea-ice are superimposed on the influences of currents and waves (Reimnitz et al., 1990). Thus, connections between inputs from land and lagoon ecosystems are more direct, and water exchanges between lagoons and the open ocean are more variable

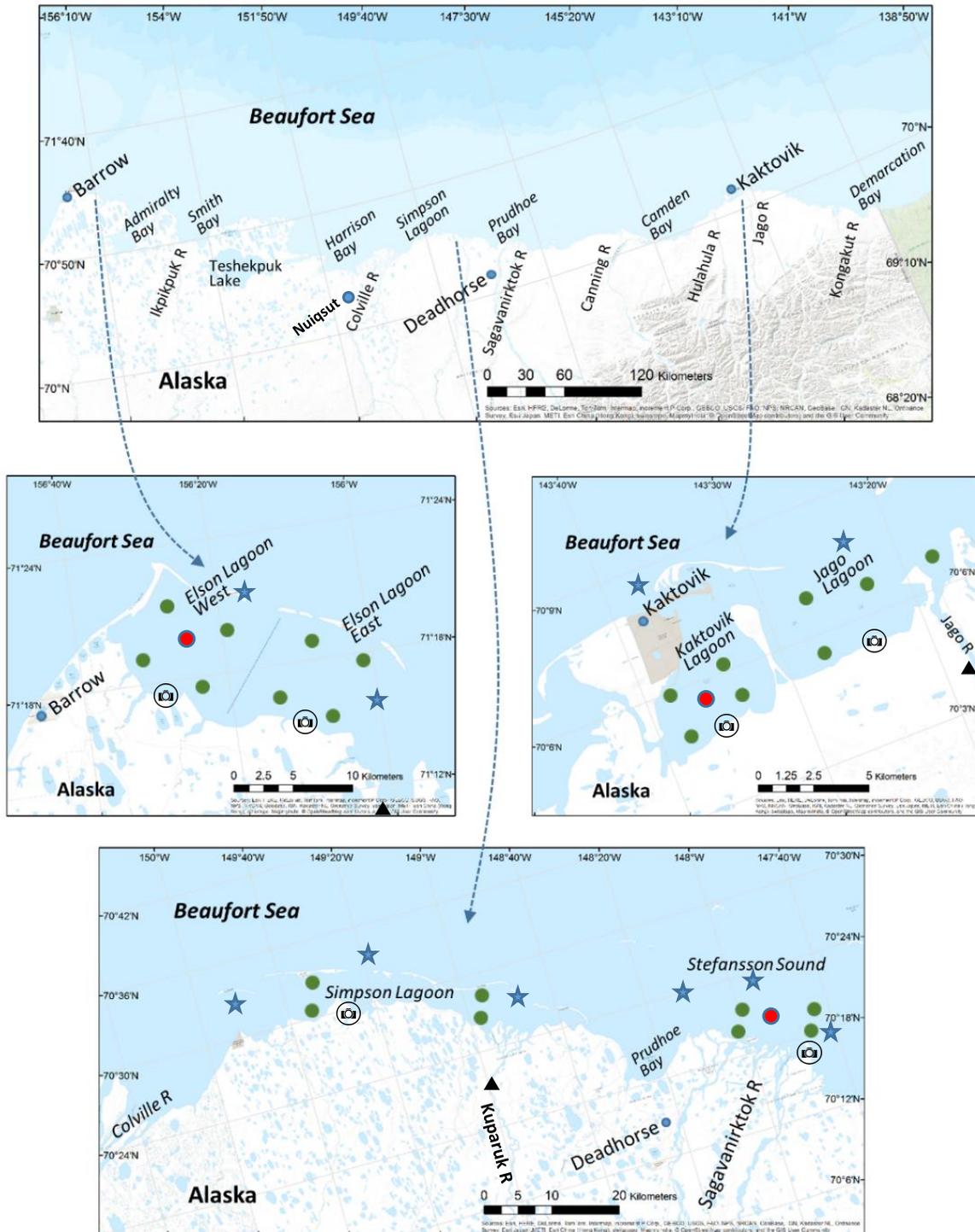


Figure 2. Proposed station located in three domains extending from Barrow (East and West Elson Lagoon), to the central (Simpson Lagoon and Stefansson Sound), and eastern (Kaktovik and Jago Lagoons) Alaska Beaufort Sea coast. Green circles mark paired shallow and deeper stations for measurement of a full suite of linked physical-chemical-biological measurements. Blue stars mark additional tilt current meter (TCM) and bottom pressure recorder (BPR) stations, red circles mark sea-ice mass balance (SIMB) stations, camera symbols mark time-lapse camera and climate stations, and black triangles mark locations for recurring river measurements. The North Slope villages of Barrow, Nuiqsut and Kaktovik are depicted by blue dots (top panel).

than is typical of lower latitude systems. Seasonality of terrestrial inputs and water exchange with the open ocean is also more extreme. Over 50% of annual discharge from rivers on the North Slope of Alaska occurs during two weeks of high flow associated with snowmelt in the spring (McClelland et al., 2014), and water exchange between the lagoons is greatly reduced – even eliminated in some cases – by sea-ice formation during the winter (Harris et al., 2016). While this LTER program will be able to begin addressing hypotheses linked to seasonality and inter-annual variability relatively quickly, it will also provide a much needed mechanism for tracking and understanding 1) how modes of climate variability such as the Pacific Decadal Oscillation and the Arctic Oscillation influence the lagoon ecosystems, and 2) how climate change impacts such as permafrost thaw, changes in terrestrial productivity and phenology, shifting hydrologic regimes, and reductions in sea ice thickness, extent and persistence alter carbon and nitrogen cycling, microbial and metazoan community composition, and trophic linkages.

This LTER will benefit significantly from the long-standing partnerships that several of the senior scientists have developed with the North Slope Borough (NSB), the City of Kaktovik, and the USFWS, which manages the Arctic National Wildlife Refuge (see letters of collaboration). Our research will also connect with and leverage local, regional, and pan-Arctic environmental observing initiatives. These include the International Tundra Experiment (ITEX), Circumarctic Active Layer Monitoring (CALM) program, Circum-Arctic Coastal Communities Knowledge Network (CACCON), Distributed Biological Observatory (DBO), Arctic Coastal Dynamics (ACD), and Arctic Great Rivers Observatory (Arctic-GRO) efforts. Last but not least, this LTER will foster collaboration with native villagers on the North Slope who have a keen understanding of the Arctic coastal environment and a strong interest in how climate change is impacting natural resources (such as subsistence fisheries) that they rely on.

1.2 LTER STUDY AREA

The proposed study area comprises the lagoons and sounds in three geographic domains on the coast of the Alaskan Beaufort Sea. Each domain differs in the relative contribution it receives from terrestrial inputs, circulation and oceanic exchange, and sea ice dynamics. Although the Beaufort Sea extends from Point Barrow, Alaska to Banks Island in Canada, nearly one-half of the Alaskan Beaufort Sea coast is skirted by an irregular and discontinuous chain of barrier islands that enclose numerous shallow (< 7 m) lagoons and sounds (Fig. 2). Freezing of Beaufort Sea coastal waters begins as early as October, though there is evidence of a trend toward later freeze-up in recent years (Mahoney et al., 2014). Ice forms first on sheltered and brackish lagoons and typically reaches a maximum thickness of between 1.5 and 2 m in late April (Johnson and Richardson, 1981; Eicken et al., 2012). Peak runoff and discharge from the many small to medium sized streams/rivers that feed these lagoons occurs during late May and early June, before ice break-up. While freshwater inflow facilitates ice break-up, the lagoons remain largely ice-covered until late June / early July. This lag between the spring freshet and ice break-up promotes retention and biological processing of river-borne materials, including vast inputs of dissolved and particulate organic matter (McClelland et al., 2012). During ice-free months, exchange between lagoons and the Beaufort Sea varies substantially depending on local geomorphology, but is much less restricted than during ice-covered months. Variation in exchange causes lagoons to have a wide range of salinities and temperatures during the open-water period (Griffiths et al., 1977; Harris et al., 2016).

Despite extreme seasonal variations in physical conditions, the benthic biota in these shallow waters is remarkably abundant and diverse, including a variety of infaunal and epifaunal organisms that represent nearly every major invertebrate taxonomic group, from sponges to ascidians, along with several species of fishes, including Arctic cod (Dunton et al., 2012). The seabed is often littered with terrestrial debris, and zooplankton tows produce assemblages of copepods, mysids, and pteropods. Nearshore estuarine environments in the Arctic are also critical to vibrant coastal fisheries (von Biela et al., 2012) and serve as habitat for hundreds of thousands of birds representing over 157 species that breed and raise their young over the short summer period (Brown, 2006). In fact, with warming waters and reductions in summer sea-ice cover in Arctic Ocean environments in recent years, some have suggested that Pacific salmon (*Oncorhynchus* spp.) might colonize drainages in Beaufort Sea estuarine systems of northern Alaska and northwest Canada and eventually become viable fisheries for local communities (Nielsen et

al., 2013). Popular accounts suggest that Pacific salmon are already becoming more common in the region (Dunmall et al., 2013), although Stephenson (2006) pointed out that this perception might be the result of improved communications systems and not necessarily an increase in fish abundance.

Erosion along the Alaskan Beaufort Sea coast averages 2.5 m yr^{-1} with significant sediment release (estimated $5 \times 10^6 \text{ t yr}^{-1}$) into nearshore systems including Prudhoe Bay (Reimnitz et al., 1988). Some areas have undergone as much as 0.9 km of erosion in the past 50 years due to doubling of the coastal erosion rate from $0.48 \text{ km}^2 \text{ yr}^{-1}$ during 1955–1985 to $1.08 \text{ km}^2 \text{ yr}^{-1}$ during 1985–2005 (Mars and Houseknecht, 2007; Gibbs et al., 2015; Gibbs and Richmond, 2015). Although strong seasonal variations in terrestrial inputs and water exchange dynamics are defining features of all lagoons in the study region, we selected sites along the western, central, and eastern portions of the Alaskan Beaufort Sea coast to capture differences in relative amounts of freshwater inflow and ocean connectivity among lagoons. This distribution of domains (Fig. 2) also facilitates engagement of scientists with local communities that are situated directly on the Beaufort Sea coast at Barrow (western Beaufort) and Kaktovik (eastern Beaufort).

1.2.1 The Western Beaufort (Elson Lagoon): The Barrow Peninsula borders both the Chukchi Sea to the west and the Beaufort Sea to the north. To the southeast lies Elson Lagoon, the largest lagoon in the Beaufort Sea. It is delimited by a 55 km chain of barrier islands and receives substantial freshwater inputs from many streams (Lewellen, 1972). Exchange between Elson Lagoon and the Beaufort Sea occurs through several and sometimes intermittent channels within the barrier island chain (see Fig. 2). Under prevailing conditions, with wind from the east-northeast, currents are forced in a north to north-westerly direction within Elson Lagoon prompting strong outflow in the northwest and strong inflow in the eastern channels of the lagoon (Okkonen, 2008). Coastal erosion within Elson Lagoon is significant. Estimates calculated from annual surveys between 2003 and 2015 show annual variability of areal loss between 0.7 and 2.8 m yr^{-1} , and volumetric loss between 0.8 - $3.5 \text{ m}^3 \text{ m}^{-1} \text{ yr}^{-1}$ (Aguirre, 2011; Tweedie et al., 2012; Tweedie et al., 2016), which equates to a contribution of 53 - $220 \text{ kgC m yr}^{-1}$ to Elson Lagoon.

1.2.2 The Central Beaufort (Simpson Lagoon and Stefansson Sound): These two large semi-enclosed systems border the western and eastern portions of Prudhoe Bay, respectively, and are unique in their juxtaposition to the largest oil reservoir in North America and the first offshore production of oil in the Arctic (in 1985 by BP in eastern Stefansson Sound). Simpson Lagoon, located between Oliktok Point and Point McIntyre (Fig. 2), is approximately 35 km long and 3-6 km wide with depths to 4 m (Craig and Haldorson, 1981; Craig et al., 1984). Exchanges with offshore waters are mainly limited to two channels on the western end of the lagoon and via an opening at Gwyder Bay in the east. The Kuparuk River discharges directly into Gwydyr Bay at the eastern end of Simpson Lagoon. On the western end, Simpson Lagoon receives discharge from the Colville River, the largest river on the North Slope of Alaska. In winter, lagoon waters freeze to approximately 2 m, locking 90% of the lagoon volume in ice, leaving isolated pockets of hypersaline waters (up to 60) in deeper areas that quickly dissipate during breakup in early July (Craig and Haldorson, 1981). Intensive studies of biological and physical processes in Simpson Lagoon began in 1971 and continued through 1979 with the culmination of a dedicated volume (Craig and Haldorson, 1981) and a synthesis paper on the lagoon's trophic ecology (Craig et al., 1984).

In contrast to Simpson Lagoon, Stefansson Sound is deeper (4-7 m) and extends from Prudhoe Bay east to the Sagavanirktok River. This area has been the focus of extensive biological studies since 1978 owing to the presence of the only known kelp bed community on the Alaskan Arctic coast north of the Bering Strait (Dunton et al., 1982). Long-term studies of this area include continuous measurements of bottom water temperatures and salinity collected from 1987 to 1988 (Sellmann et al., 1992), year round hydrography from bottom mounted conductivity-temperature-depth (CTD) and acoustic doppler current profiler (ADCP) measurements from 2001 to 2007 (Weingartner et al., 2009), and measurements of bottom water temperatures and salinity since 2012 (Dunton, unpub. data). Although Stefansson Sound is largely protected from ice scours by barrier islands and shoals, it has relatively open exchange with the Beaufort Sea. Our strategic selection of stations in Stefansson Sound takes advantage of existing historical data and the changes in epilithic biota that occur with increasing distance from the shore, possibly in response to salinity (Sellmann et al., 1992; Dunton and Schonberg, 2000; Dunton et al., 2009).

1.2.3 The Eastern Beaufort (Kaktovik and Jago Lagoons): Kaktovik and Jago Lagoons are relatively small, shallow systems east of Barter Island (Fig. 2). Freshwater enters Kaktovik Lagoon from tundra streams and via diffuse runoff and groundwater seepage from the surrounding tundra. No large streams flow directly into the lagoon and it is isolated from neighboring lagoons by Barter Island to the west and a peninsula to the east. In contrast, Jago Lagoon receives direct input from the Jago River. Consequently, a distinct freshet-effect is observed in Jago Lagoon during the spring, whereas salinity decreases are less precipitous in Kaktovik Lagoon (Fig. 3). The two lagoons also differ substantially in their connectivity with the Beaufort Sea. For Kaktovik Lagoon, exchange with Beaufort Sea waters is limited to two shallow (<2.5 m) and narrow (25 m) entrances. For Jago Lagoon, exchange with the Beaufort Sea occurs through a relatively broad (200 m) 3 m deep channel. Salinities in both lagoons reach hypersaline levels (relative to a marine end-member salinity of 31.6) during the ice-covered period, but maximum values vary from year to year (Fig. 3). Lagoon margins are lined with slumping 1-4 m high eroding bluffs and shorelines dominated by mixtures of sand, peat, and mud. Key prey species for upper trophic level biota (noted by Griffiths et al., 1977), including polychaetes, mysids, and amphipods, that are abundant in these lagoons may contribute to robust local fisheries. An estimated 3,000 kg of fish (Arctic Char, Arctic Cisco) were taken by Kaktovik residents in 1975 (Griffiths et al., 1977), and extensive subsistence fishing activities continue to the present day (Dunton, pers. obs.).

1.3 CLIMATE CHANGE CONTEXT

While this proposed LTER addresses fundamental ecological questions, the need to understand how climate variations and directional shifts are impacting society, biota, and the fate and transport of carbon, water, and energy in this rapidly changing region adds urgency to the work. Arctic coastal environments are recognized as some of the most threatened ecosystems on Earth (Lantuit et al., 2011), and represent an obvious nexus for examining change at the interface between marine, cryospheric, terrestrial, atmospheric and social systems. In many areas, nearshore ice conditions are changing (AMAP, 2011; Mahoney et al., 2014), erosion of coastlines is increasing (Jones et al., 2009a), permafrost is warming (AMAP, 2011), landscapes are slumping (Shiklomanov et al., 2012) and drying (Andresen and Lougheed, 2015; Lin et al., 2012) or becoming warmer and greener (Bhatt et al., 2010), and the extent, duration, and intensity of ocean acidification events are increasing (e.g., Fabry et al., 2009). Several recent studies also highlight how changes in sea ice extent can impact the depth and width of barrier island passes, the wave climate (Thomson and Rogers, 2014), and terrestrial processes (Bhatt et al., 2010; Tweedie et al., 2016). These processes control coastal erosion (e.g. Aguirre, 2011) and watershed export to the coastal ocean (Jones and Arp, 2015), with significant implications for the exchange of carbon, water and nutrients on the inner shelf (Mathis et al., 2012; Pickart et al. 2013).

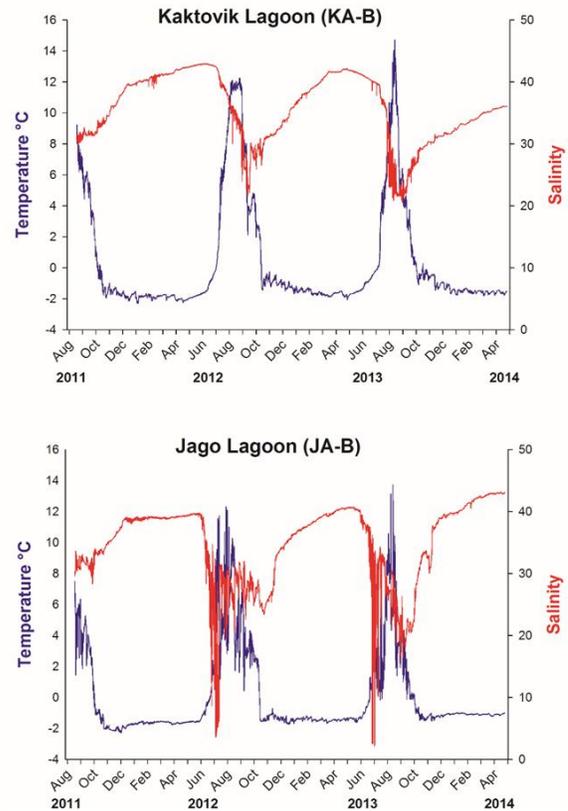


Figure 3. Variations in temperature and salinity from two adjacent eastern Beaufort Sea lagoons (Kaktovik, top; Jago, bottom) illustrate differences in freshwater inflow and exchange with the Beaufort Sea (adapted from Harris et al. 2016). Continuous records of temperature and salinity were collected using ten HOBO data loggers deployed in five lagoons from 2011-2014 (adapted from Harris et al., 2016).

Arctic estuarine systems are primed to undergo dramatic state changes in functionality in the next few decades because of the enormous changes taking place on their landward and seaward margins, including shifts in carbon and nitrogen cycling, trophic linkages, and faunal diversity, driven by changes in freshwater inflow, coastal erosion, ice cover, and exchange with the coastal ocean. LTER sites have proven capacities and efficiencies in polar regions, as exemplified by the Arctic LTER at Toolik Lake and the Palmer Station and McMurdo Dry Valleys LTERs in Antarctica, but no such efforts have been employed in the coastal zone of the US Arctic, despite the nature and potential implications of observed changes that have taken place in this region over the past decade and the presence of the three largest US Inupiat communities (Barrow, Nuiqsut, and Kaktovik) in this focal area.

1.4 CONCEPTUAL FRAMEWORK

Our research is organized into four synthetic and integrated themes (articulated as questions) that collectively represent the conceptual framework for this LTER. The first three address physical and biogeochemical questions that are essential building blocks for reaching our ultimate goal of understanding the role that differential availability of seasonally-distinct resources plays in defining trophic linkages and maintaining stability and resilience of food webs. These themes address questions of ecosystem connectivity, stability, and resilience in an environment structured by highly dynamic, seasonally-driven physical forces along a coastline that is being profoundly impacted by climate change:

Theme 1. *How and in what form do nutrients and water arrive in Beaufort Coast lagoon systems?*

Theme 2. *How do changes in ice, freshwater discharges, and circulation influence the connectivity between lagoons and shelf waters of the Beaufort Sea?*

Theme 3. *How are biogeochemical processes within the lagoons linked to inputs of terrestrial organic matter, autochthonous production, and inorganic carbon and nitrogen cycling?*

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?*

1.5 CORE ENVIRONMENTAL MEASUREMENTS

In support of our hypothesis-driven work, we will establish time-series observations that (1) are representative of ice-covered, ice break-up, and open-water seasons, (2) can involve the participation of local citizen-scientists, and (3) are baseline measurements critical to a sustained science program.

1.5.1 Study domains: Our proposed study domains along western, central, and eastern sections of the Alaskan Beaufort Sea coast (**Section 1.2**; Fig. 2) represent a wide range of land-lagoon-ocean connectivity configurations, and are logistically tractable for sampling from Barrow (western), Deadhorse (central), and Kaktovik (eastern) in all seasons. These domains are also desirable because a plethora of historic and ongoing research activities (by the PIs and others) within the selected lagoons can be used to enhance analytical and interpretive power of LTER findings. With respect to broader impacts, (1) our site choices will facilitate the involvement of young citizen scientists from Barrow and Kaktovik who will be chosen to participate in field data collection efforts, and (2) the sites near Barrow and Kaktovik are important subsistence hunting areas for residents of these coastal communities who wish to know how they are responding to climate change.

1.5.2 Specific locations and timing sampling: We will occupy 12 shallow (1 – 2 m) and 12 deeper (3 – 5 m) water stations distributed across Elson Lagoon, Simpson Lagoon, Stefansson Sound, Kaktovik Lagoon, and Jago Lagoon for repeated measurements. Elson Lagoon has been separated into eastern and western sections to improve coverage of this relatively large system. Samples will be collected at these stations during ~2 week field campaigns during (a) the ice-covered period in April, (b) during and immediately following ice break-up in June, and (c) during the open-water period in July/August. The season-specific data from these field campaigns will be complemented by continuous data streams for select parameters measured with sensors (**Sections 1.5.4 and 1.5.5**).

1.5.3 General sampling strategy: Lagoon sites will be accessed using snow machines during April and outboard-equipped Zodiacs (or equivalent) during June and August. In April, ice will be removed using augers and chain saws to access underlying waters and ice-bound sediments. We will use an ROV (see

Facilities document) to enable under-ice sampling. The ROV is not powerful enough of pull trawls and plankton nets, but will be used to carry light lines between ice holes. These lines will then be used to pull heavier lines between holes that can be connected to trawls and plankton nets. This approach will allow us to use the same sampling gear during all seasons.

1.5.4 Remotely sensed parameters: We will use several remote sensing approaches to document spatiotemporal patterns and controls of coastal erosion, which are important for understanding land-lagoon-ocean carbon, water, and nutrient transfer dynamics. Satellite imagery and remote sensing image analysis will be used to define coastline position and morphology, and seasonal landscape phenology near the land-sea interface. Annually for each lagoon and once during the award period for the entire Beaufort Sea Coast, coastline and barrier island position and morphology will be digitized from high spatial resolution pan-sharpened orthorectified WorldView2 satellite imagery acquired at no cost from the Polar Geospatial Center. The Normalized Difference Vegetation Index (NDVI, an index of vegetation productivity; Walker et al., 2012) and the Normalized Difference Surface Water Index (NDSWI, an index of water cover and depth; Goswami et al., 2011) will be derived for coastal landscapes adjacent to each lagoon using 16-day MODIS satellite products from the USGS MODIS Land Products DAAC. We will also make use of open-access Synthetic Aperture Radar from the Sentinel-1a satellite to monitor ice formation and breakup conditions throughout the Alaska Beaufort Coast. Remotely sensed products, will be validated with Differential Global Positioning System (DGPS) surveys of coastline position along Elson Lagoon and near Kaktovik (coastline position) and from digital greenness (*sensu* Richardson et al. 2007) derived from fixed coastal cameras described below (phenology and surface water, **Section 1.5.5**).

1.5.5 Year-round instrument deployments: Moorings with MicroCAT data loggers for temperature, salinity, and pressure (i.e., sea level) will be deployed year-round at all of the 3-5 meter deep stations (12 total). Previous year-round deployments of temperature/salinity loggers using this approach were successful in Stefansson Sound and the lagoons east of Kaktovik. In addition, we will deploy three Satlantic SeaFETs (one in Elson, Simpson, and Kaktovik Lagoons) to collect continuous measurements of pH, 10 bottom mounted tilt current meters (TCMs), and 10 inexpensive bottom pressure recorders (BPRs, e.g., HOBOS) in the passes between the lagoons systems and the nearshore zone (or adjacent lagoons) to measure transport in and out of the lagoons (Fig. 2).

We will also deploy newly patented time lapse cameras (Ramirez et al., 2015) and meteorological stations on 3-meter towers adjacent to each lagoon system to capture freeze-up, break-up and ice-out. Such systems have proven valuable in determining the processes controlling coastal processes (Jones et al. 2009b). At each site, four of these low-cost, low-power cameras will be configured to capture a 220° field of view and include sensors for the acquisition of red, green, blue, infrared, and thermal imagery. Imagery will be acquired hourly as still photographs and video for the determination of wave period, height, and direction as well as ice cover and landscape phenology. Custom software for time series analysis of imagery in RGB, HSV, and L*a*b* color space will be used for automated image analysis. The meteorological stations will measure air temperature, atmospheric moisture, wind speed and direction, soil temperature and moisture, photosynthetically active radiation, and atmospheric pressure.

1.5.6 Hydrographic parameters: YSI water quality sondes will be used to measure depth profiles of temperature, salinity, pH, dissolved oxygen, and chlorophyll during each field campaign visit. Likewise, custom-built pCO₂ sensors will be used to measure CO₂ profiles in the water column. These sensors consist of an NDIR CO₂ sensor (Vaisala GMM 222) enclosed in a PTFE membrane (*sensu* Johnson et al. 2010) and have been successfully deployed in Elson Lagoon (see Theme 3, Ecosystem Metabolism). Water for alkalinity, inorganic nitrogen, and organic matter analyses will be sampled from 1-2 depths (above and below the pycnocline when present), using a peristaltic pump. Water will be filtered as soon as possible after collection. Alkalinity titrations and optical scans of filtered water to quantify chromophoric dissolved organic matter (CDOM) will be conducted in Barrow/Kaktovik. Water (frozen) and filters (dried) for all other analyses will be shipped to the UT Marine Science Institute (UTMSI) for remaining analyses.

1.5.7 Nekton, Benthic Biota: Benthic and water column biota will be collected using small grabs, plankton nets (20 and 335 μ m) and 1-m beam trawls following Dunton et al. (2012). Planktonic microbes will be collected at two depths with a peristaltic pump, and benthic microbes will be collected with a 20 cm³ syringe barrel (1.8-cm diameter) and split into surface (0-1 cm) and subsurface (1-3 cm) fractions. Samples will be used to assess changes in diversity, biomass, and abundance of infaunal and epibenthic organisms in the lagoons and provide material for stable isotope and fatty acid analyses. Samples will be rinsed and sorted coarsely in the field and then fine sorted to the lowest taxonomic level (species if possible), while the material is fresh for both quantitative and stable isotope and fatty acid analyses. To assess annual patterns in populations of larger fish species, LTER scientists and local agencies on the North Slope will collaborate to fish two gillnets in the western sampling region and two in the eastern sampling region. They will be set perpendicular to shore for 24 h, twice a week, during the same three-week period in August each year. We will also participate with local Iñupiat communities to collect material from fish harvested for subsistence (see **Section 2**). All fish captured will be identified to species and appropriate biological data and material will be collected for aging, demographics, and stable isotope analyses (to assess trophic status).

Table 1. General methods for data collection, temporal coverage for each method, and specific parameters identified as core measurements. PAR = photosynthetically active radiation, DOC = dissolved organic carbon, DON = dissolved organic nitrogen, POC = particulate organic carbon, PON = particulate organic nitrogen, CDOM = chromophoric dissolved organic matter, HPLC = high performance liquid chromatography, NEP = net ecosystem production, GPP = gross primary production, R = respiration.

Method	Temporal coverage	Parameters
WV2 Digitization	Annual	Coastline and barrier island position
MODIS	Seasonal	Landscape phenology
SAR	Seasonal	Sea ice cover and thickness
<i>In-situ</i> sensors (cameras)	Continuous	Landscape phenology, sea ice cover, sea state (wave period, height, direction)
<i>In-situ</i> sensors (climate)	Continuous	Air/soil temperature and moisture, wind speed/direction, precipitation
<i>In-situ</i> sensors (moorings)	Continuous	pH, temperature, salinity, water level (wave height and sea level), velocity
<i>In-situ</i> sensors (discreet)	Seasonal	pCO ₂ , temperature, salinity, O ₂ , pH, PAR, Chlorophyll (chl), NEP/GPP/R, velocity
Water biota	Seasonal	Diversity, abundance, biomass, stable isotope and fatty acid analysis of select species
Water biogeochemistry	Seasonal	Alkalinity, NO ₃ , NH ₄ , DOC, DON, CDOM, POC, PON, stable isotopes, fatty acids, Chl. (HPLC)
Benthic biota	Seasonal	Diversity, abundance, biomass, stable isotope and fatty acid analysis of select species
Benthic biogeochemistry	Seasonal	Chlorophyll (HPLC), pore water nutrients, %C, %N, stable isotopes, fatty acids
Subsistence fish sampling	Annual	Stable isotopes, fatty acids, freq. of occurrence

1.5.8 Benthic Biogeochemistry: Sediment samples for pigment, stable isotope, fatty acid, total organic carbon, and total nitrogen analyses will be collected using a 20 cm³ syringe barrel (1.8-cm diameter, 2-cm depth) at all stations from surface sediments retrieved by grabs. These samples will be frozen (-20°C) until analysis. Pigments targeted for analysis in the sediments are Chl *a*, the phaeopigments phaeophytin *a*, phaeophorbide *a*, pyropheophorbide *a*, and the accessory pigments Chl *b*, Chl *c*, fucoxanthin, peridinin, prasinoxanthin, and 19-hex-fucoxanthin. Chl *a* is a proxy for fresh algal organic matter in sediments

while the phaeopigments are used to assess the standing stock of degraded chlorophyll products from different pathways (see McTigue et al., 2015).

1.6 ECOSYSTEM MODELING (PI Lead: Spitz)

Coupled circulation/biogeochemical models will integrate data from several components of this research to test our hypotheses (articulated in the thematic sections below) and to circumvent the spatial and temporal limitations of the observations. Coupled models have been developed recently for the Bering Sea (Gibson and Spitz, 2011; Hermann et al., 2013; Banas et al., 2016) and Arctic Ocean (Zhang et al., 2010, 2014; Popova, 2012; Deal et al., 2014; Watanabe et al. 2014; Jin et al. 2016), but these models at best include highly simplified representations of riverine inputs as freshwater fluxes or as crude climatologies of nutrient fluxes. Moreover, these models use coarse spatial resolutions that are not suitable for application to lagoon ecosystems. The complexity of these biogeochemical models varies from one nutrient (N), one phytoplankton (P), one zooplankton (Z) and one detrital pool (D) to multiple NPZD, but none of them, except Gibson and Spitz (2011) and Hermann et al. (2013), includes a benthic component nor an explicit microbial loop. These two additional model components are extremely important, especially in shallow water systems where detrital food webs can dominate, and transformation from organic to inorganic material directly impacts the water column ecosystem and ultimately primary and secondary producers. We propose to expand and adapt the biogeochemical model from Llebot et al. (2016) to the planktonic species present in the various lagoons by adjusting the model parameter set and further develop the benthic component to include heterotrophic bacteria, DOM, microphytobenthos and benthic metazoans (Fig. 4). We also will add dissolve inorganic carbon (DIC), alkalinity and CO₂ using the same approach as Anderson and Pondaven (2003), which will make use of the new observations and allow testing of the proposed hypotheses. The Llebot et al. (2016) model was adapted from the Spitz et al. (2001) model and includes a benthos component, freshwater and marine phytoplankton, nano/micro- and meso-zooplankton, nitrate, ammonium, detritus, DOM, heterotrophic bacteria and dissolved oxygen.

The progression of the modeling effort will be incremental. First we will parameterize and run the model in a 1D mode (time and vertical dimension) in which stratification will be imposed from observations, lateral fluxes from measurements and hydrology models (see Theme 1 below), and surface forcing (light, ice melting and release of nutrient, particulate and dissolve organic matter) from new and past observations. Data assimilation (similar as in Spitz et al., 2001; Lancelot et al. 2005; Weir et al., 2013) will be applied using water column biochemical concentrations and transformation rates and benthic flux measurements to constrain model parameters. A three-dimensional circulation/ice model (finite element model, such as FVCOM, <http://fvcom.smast.umassd.edu>) will be developed for each study lagoon. The proposed ecosystem model then coupled to the circulation/ice model will be run in a 3D mode and calibrated with the available observations (see **Section 1.5**) to address our hypotheses. We have experience in using finite element circulation and ice models (i.e., SELFE and FVCOM) and ecological models, and all the necessary tools are available. The step-wise approach (1D to 3D mode) is necessary

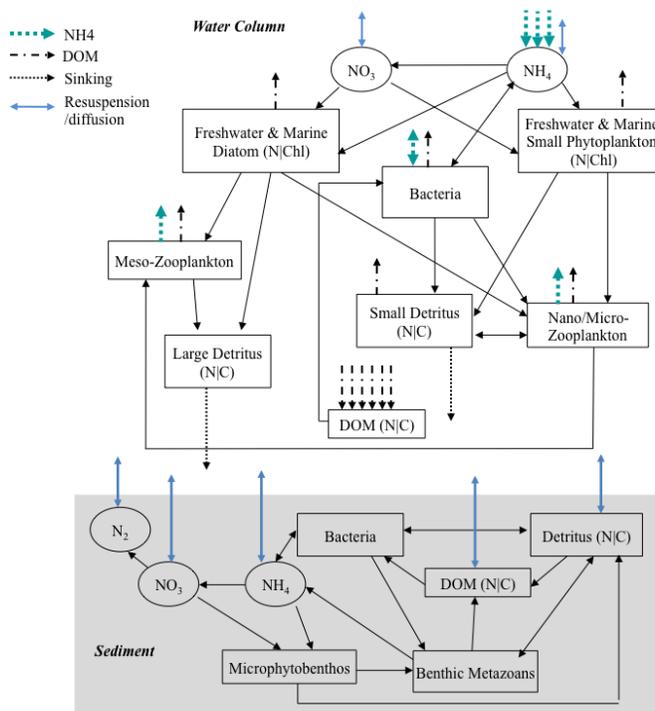


Figure 4. Schematic of ecosystem model components, including explicit treatment of C and N cycling through microbial and metazoan pools in the sediments and water column (after Spitz et al., 2001).

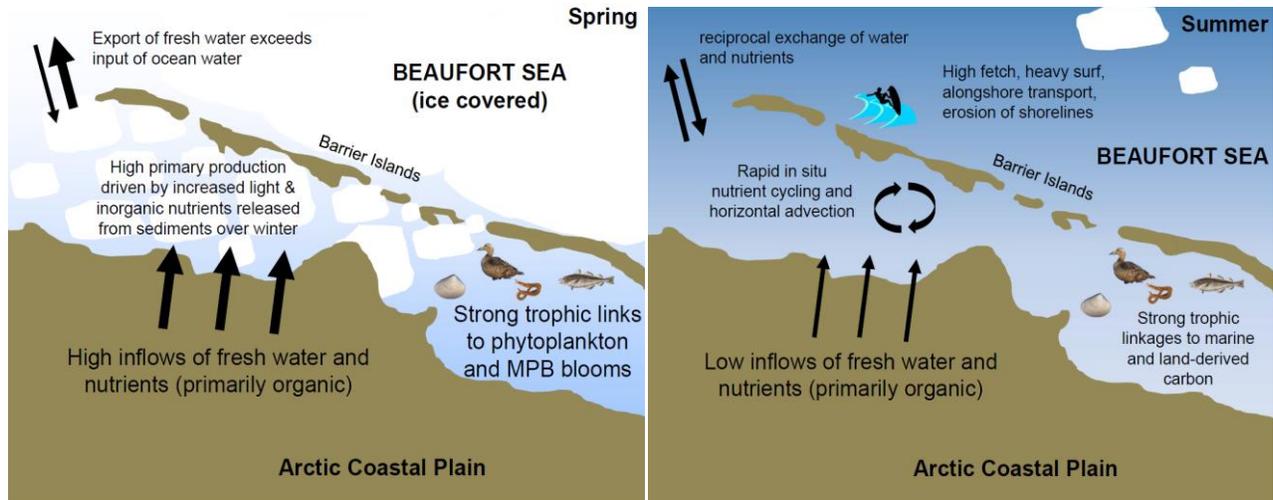


Figure 5. Conceptual model of major lagoon inputs, exchanges, processes and trophic linkages.

due to the complexity of the biogeochemistry, from a microbial controlled ecosystem when ice is present to plankton/benthos controlled when sufficient light is available and the lagoon is ice-free.

1.7 THEMATIC STUDIES

Our overarching question, as articulated in the introduction, will be addressed by testing the following hypotheses related to themes 1-4 that focus on key features of lagoon dynamics (Fig. 5). Links with the “five core areas of long-term data collection” as defined in the LTER program solicitation are identified in parentheses after each hypothesis.

1.7.1 Theme 1. How and in what form do nutrients and water arrive in Beaufort Coast lagoon systems? (PI Leads: Rawlins, Tweedie, McClelland)

Hypotheses:

- 1a. Terrestrial runoff in spring is the primary source of new nutrients (predominantly organic) to lagoons, with direct inputs from coastal erosion and groundwater seepage becoming important secondary sources in late summer. (Core areas 1, 3, 4)*
- 1b. Nutrient fluxes from land will increase in the future, and proportional contributions from coastal erosion and groundwater seepage will become greater. (Core areas 3, 4, 5)*

Rationale: Lagoon biogeochemical cycling and food web characteristics are undoubtedly influenced by inputs from terrestrial ecosystems. Under Theme 1, we examine three transport mechanisms that provide inputs to Arctic lagoons from terrestrial systems: river discharge, which dominate inputs early in the hydrologic year (spring freshet); groundwater seepage, which has been poorly studied to date, but may be important late in the ice/snow free period; and coastal erosion, which prevails throughout the ice- and snow-free period. Work under Theme 1 will strengthen our understanding of how contributions from surface runoff, groundwater, and coastal erosion vary seasonally, and address how the relative importance of these sources may be shifting with climate change.

Studies across a wide range of spatial scales, including river systems on the North Slope of Alaska (McClelland et al., 2007; McClelland et al., 2014) as well as larger systems within the pan-Arctic drainage area (Raymond et al., 2007; McClelland et al., 2012; Holmes et al. 2012; Kicklighter et al., 2013; McClelland et al., 2016), have demonstrated the prominent role that the spring freshet plays in the export of water and water-borne constituents from land to sea in the Arctic. Groundwater inputs, on the other hand, have been given less attention in Arctic regions because permafrost presents a barrier that limits surface-groundwater transfers. Shallow groundwater does, however, flow through seasonally thawed soils, and may be a significant source of nutrients to coastal waters in late summer, when soil thaw depth is at a maximum and river flow is typically at a minimum. Preliminary sampling of

groundwater seepage into Kaktovik Lagoon (during August) showed that DOM concentrations are 10-100 times higher than in river waters during the same period. Groundwater DOM is also anticipated to be more labile than river DOM because it has not been subject to the intense photo-mineralization that river waters experience during transport in the summer (Cory et al., 2014).

While present contributions of groundwater are probably under-appreciated as sources of nutrients supporting coastal ecosystems in the Arctic, changes in hydrology associated with warming are likely to increase the relative importance of future groundwater contributions. As the Arctic warms, enhanced precipitation and evaporation rates are leading to an overall intensification of the hydrologic cycle (Rawlins et al., 2010). At the same time, the active layer is deepening (Romanovsky and Osterkamp, 1997; Streletskiy et al., 2014) and the proportion of groundwater to surface water flow is

expected to increase (Frey and McClelland, 2009). In general, we expect watershed export of organic matter to vary as a function of water discharge because organic matter concentrations are positively correlated with river discharge rates in the Arctic (Holmes et al., 2012; McClelland et al., 2014; McClelland et al., 2016). However, changes in water flow paths accompanying permafrost thaw make it more challenging to anticipate how fluxes of water-borne constituents to the coastal ocean will change in the future (Frey and McClelland, 2009). Where proportional flow through mineral soils is enhanced, organic matter export could actually decrease while fluxes of dissolved inorganic nutrients increase. Where organic-rich soils extend deep into the permafrost, on the other hand, thawing will enhance organic matter export. Given that many of the lagoons along the Alaskan Beaufort Sea coast are coupled to small watersheds that drain primarily low lying terrain in the coastal plain, we expect an overall increase in organic matter fluxes over time.

Shoreline erosion has been recognized as a potentially important source of nutrients in some locations around the Arctic, but this LTER will break new ground by considering surface water, groundwater, and erosional inputs to Arctic coastal waters in concert. Erosional coastlines dominate the Beaufort Sea Coast, which is comprised of 42% sheltered mainland-lagoon shorelines and 58% open-ocean exposed coastlines that are eroding at -0.9 and -1.8 m yr^{-1} respectively (Gibbs and Richmond, 2015). With arctic warming and the combined effect of decreased summer sea ice extent, longer fetch for wave propagation, and warmer sea surface and ground temperature, the propensity for arctic coastal erosion rates and land-ocean sediment inputs to increase has been recognized for some time (Forbes et al.; 2011; Lantuit et al., 2009, ACIA 2004). In some areas of the exposed Beaufort Sea Coast where erosion

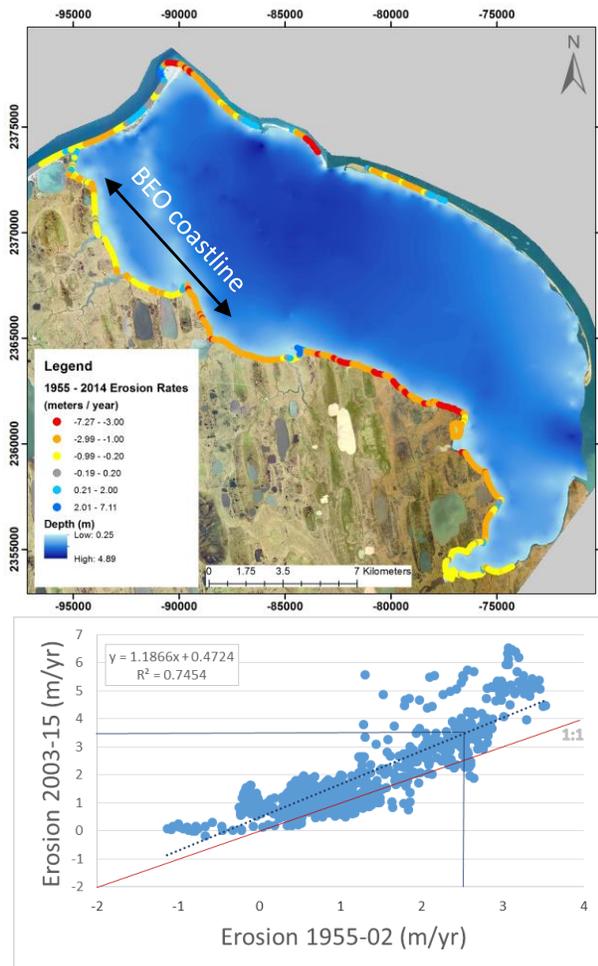


Figure 6. Normalized annual coastal erosion between 1955 and 2014 for Elson Lagoon, WorldView2 image mosaic, and bathymetry derived from >150km of bathymetric surveys (top panel). Erosion rates are greatest on coastlines with an aspect perpendicular to dominant northeast winds where relative deep water offshore prevails. Bottom panel shows a 25-35% increase in modern erosion rates for the Barrow Environmental Observatory (BEO) coastline. From Tweedie et al.(2016).

rates are among the highest in the world ($\sim 18 \text{ m y}^{-1}$), recent erosion rates appear to have increased and in some areas doubled over the past half century (Jones et al., 2008; Jones et al., 2009a,b), although high rates of inter-annual variability prevailed (Arp et al., 2010). Until recently, comparable increased erosion rates have not been documented for Beaufort Sea Coast lagoon environments. Interestingly, 2003-2005 rates of coastal erosion in Elson Lagoon were 25-30% higher than rates documented between 1955-2002 (Fig. 6), where the magnitude of increase was greatest for sections of coast where historical rates of erosion rates were highest (Tweedie et al., 2016). Such shifts have the capacity to result in the addition of $0.2\text{-}1 \text{ m}^3$ of soil loss per meter of coastline per year to Elson Lagoon, which equates to a loss of 16-66 kg of carbon per meter of coastline per year and/or $6,100\text{-}30,500 \text{ m}^3$ of soil and 560-2013 tons of carbon per year for our Elson Lagoon study site alone. Although the prevalence of such trends in other Beaufort Sea lagoons has yet to be examined, such increases are likely to have profound impacts on lagoon morphology, physico-chemical properties, circulation, biogeochemical cycling, and food web structure.

Approach: Freshwater inflows and nutrient contributions to the lagoons associated with surface water, groundwater, and coastal erosion will be quantified using a combination of hydrologic modeling, field measurement, and remote sensing techniques.

Hydrologic Modeling - River discharge gauges are maintained by the US Geological Survey near the mouth of the Kuparuk River (gauge 15896000) and at more inland locations on the Sagavanirktok (gauge 15908000) and Colville (gauge 15875000) rivers. Daily data for these rivers are available in near-real time in a publically-accessible online database (<http://waterdata.usgs.gov/ak/nwis/rt>). For the most part, however, river, stream, and groundwater flows into our proposed study sites are not monitored. Thus, hydrologic modeling is necessary to provide comprehensive estimates of freshwater inflows to the lagoons. We will estimate daily water fluxes from Alaska's North Slope to the Beaufort Sea using intermediate (5-km) and high resolution (sub-km) approaches. The intermediate resolution approach will be applied to the entire coastline between Barrow and the Jago River delta, whereas the high resolution approach will be applied to the specific lagoons that have been identified for intensive studies. Recent advances in saturated-unsaturated, variable-density ground-water flow applications to frozen geologic media that have opened the door for high-performance computing to examine the impacts of climate change and permafrost degradation on surface and subsurface hydrologic flows. The Pan-Arctic Water Balance Model (PWBM; Rawlins et al., 2003; 2013) will be used for the intermediate resolution work. This model includes snow and ground temperature dynamics (with phase change) that are key in controlling seasonal active-layer development in permafrost areas (Fig. 7). The model is partitioned

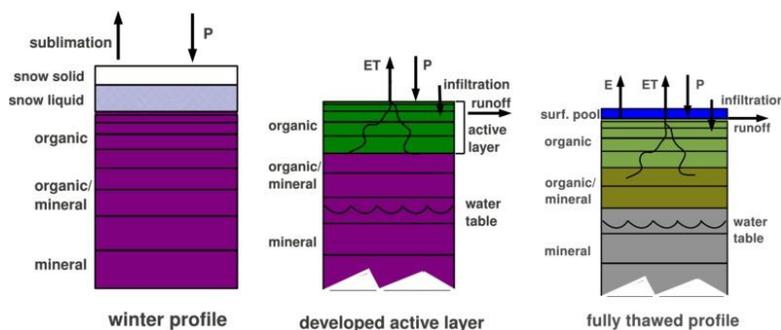


Figure 7. Schematic of PWBM soil profiles for winter (left), spring (center), and summer (right). Profile for transition back to frozen condition during autumn not shown. Water pools on the surface if infiltration capacity is exceeded. Drainage between layers follows Darcy's Law as solved through the Richard's equation. The model incorporates sub-grid scale open water extents. P = precipitation, E = evaporation, and ET = evapotranspiration.

vertically into 23 soil layers. Carbon density data (Hugelius et al., 2013) is used to parameterize upper organic-rich soil layers and associated thermal and hydrological properties (Lawrence and Slater, 2008).

We will model hydrological fluxes at the sub-kilometer scale by coupling PWBM to the SUTRA model (McKenzie and Voss, 2013). Modeled permafrost temperatures from the 5-km PWBM simulations will be used to specify initial permafrost distribution in SUTRA, providing a consistent parameterization of permeability and other hydraulic properties. Over the entire study region, lakes, ponds, and wetlands will be delineated using a

Table 2. Existing atmospheric and river discharge data sets that will support hydrology modeling.

Data Set	Variable	Period of Record
NASA NEX-GDDP	Meteorology	1950-2100
Climate Research Unit (CRU)	Meteorology	1950-present
NASA MERRA	Meteorology	1979-present
NCEP CFSR	Meteorology	1979-present
USGS Hydrology	River discharge	1970-present

new 30 m product of open water derived from Landsat data (Carroll et al., 2016). Land-surface topography (90 m NED) and locations of surface water features will be fixed as the upper surface boundary. Transient infiltration/exfiltration and heat fluxes predicted from the PWBM model will provide the upper boundary conditions to the SUTRA model. An important distinction here compared to all previous 3-dimensional model efforts is that we will simulate transient hydrologic conditions that capture freeze-thaw dynamics. In this way we will estimate the timing and amount of surface and subsurface water entering the lagoons. Routing of water to the lagoons will be estimated based on gradient flow, defined on a simulated topological network (STN; Vörösmarty et al., 2000).

Model parameterizations for soil and vegetation type will take advantage a data recovery and archiving effort (http://above.nasa.gov/cgi-bin/above/inv_pgp.pl?pgid=716) funded as part NASA's Arctic Boreal Vulnerability Experiment (ABOVE). Data on surface water extent will also be acquired from ABOVE. Atmospheric forcing (e.g., air temperature, precipitation, and wind) will come from observations and from gridded datasets and/or reanalysis products (Table 2). We will use discharge data from existing USGS gauges as well as targeted surface water and groundwater flux measurements (discussed in detail below) at our study sites to validate simulated discharge. Comparison of simulated discharge from PWBM (applied at a 25 km resolution) to measured discharge data from the Kuparuk River show that the model captures the marked seasonality in runoff that is typical of this region, and successfully predicts the timing of peak runoff within a few days (Fig. 8). Application of this model to smaller drainage areas will introduce greater uncertainty, but running the PWBM at 5 km resolution and coupling with SUTRA for the sub-km scale will greatly improve our ability to estimate hydrologic inputs at a variety of scales across the study domain.

Coastal Erosion - Coastal erosion/accretion rates will be measured as both aerial and volumetric loss/gains. To quantify coastal aerial change on an annual basis for each lagoon, shorelines digitized from high spatial resolution imagery (**Section 1.5.4**) will be input to the USGS Digital Shoreline Analysis System (DSAS), and an analytical protocol will be followed to ensure direct inter-comparison with Gibbs and Richmond (2015) and the national standards for the analysis and reporting of coastal erosion rates. The Gibbs and Richmond (2015) study also provides both legacy datasets for the Beaufort Sea coast to the late 1940's and a fundamental baseline for referencing and comparing future erosional activity. Legacy erosion monitoring transects established by Jerry Brown (near Barrow) and Torre Jorgenson (near Barrow and Kaktovik) that include monitoring of active layer depth and are among the oldest monitoring

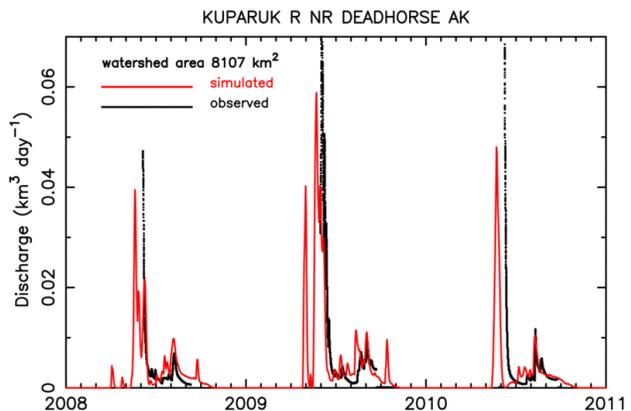


Figure 8. Observed (black) and model-simulated (red) daily river discharge flow for the Kuparuk River for years 2008, 2009, and 2010 (Rawlins, unpublished data). In the PWBM simulated discharge is the catchment's runoff, totaled from surface and groundwater contributions, routed along a simulated topological network (STN).

sites of their kind in the Arctic will be maintained and also used for field-based validation of remotely sensed products. To quantify volumetric loss, the 2010-2012 USGS aerial LIDAR survey of the Beaufort Sea Coastline associated with Gibbs and Richmond (2015) will be fused with DSAS analysis and used to calculate sediment input to the lagoons assuming a block-fail model as described below. Coastal morphological classification and the length of coastline between DSAS-defined transects will be used for scaling of seepage estimates to the entire lagoon level.

Nutrient Inputs - While the hydrologic modeling and remote sensing work discussed above will allow us

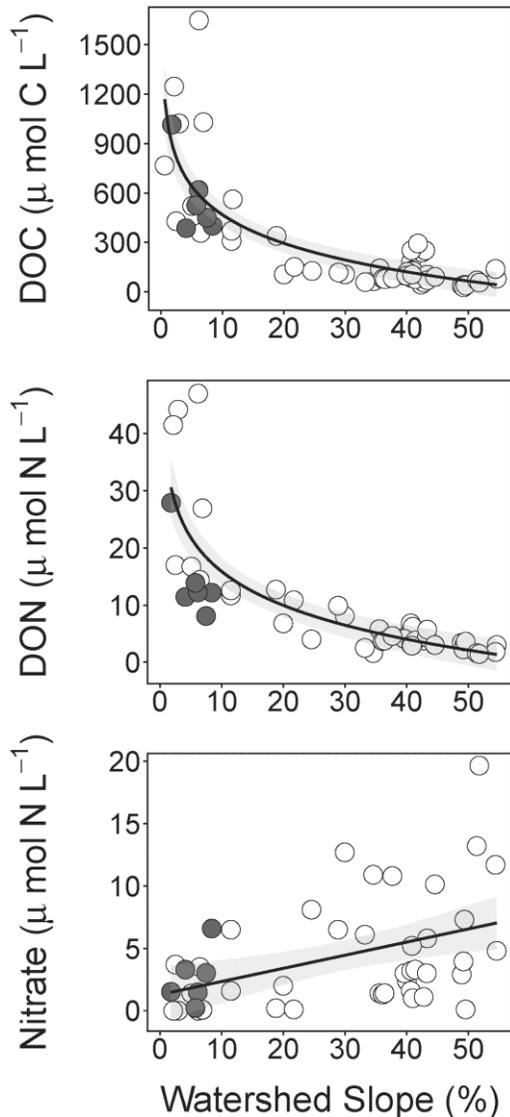


Figure 9. Relationships between mean slope values of watersheds and concentrations of DOC, DON, and nitrate in Arctic rivers (McClelland unpublished data). Open circles identify data from Alaska's North Slope. Data from larger rivers (black dots) around the pan-Arctic are also included. All data are from late June through early September.

to estimate freshwater and bulk erosional inputs from land to sea along the Alaskan Beaufort Sea coast (including specific inputs to the LTER focal lagoons), these estimates must be coupled with data on water and soil chemistry to address *hypotheses 1a and 1b*. Initially we will use existing data on the nutrient content (organic and inorganic) of river water, groundwater seepage, and coastal soils to translate estimates of water and soil fluxes into estimates of nutrient fluxes across the land-sea interface. We have river water data from a wide range of locations and scales across the North Slope of Alaska showing strong relationships between DOM concentrations and watershed slope (Fig. 9, top and middle panels) that provide an excellent basis for assigning concentrations to surface water flows under current conditions. Relationships between watershed slope and dissolved inorganic nitrogen concentrations are weaker, but still useful for deriving initial estimates (Fig. 9, bottom panel). Much of the concentration data shown in Figure 9 is from samples collected by volunteers at government agencies (USFWS and USGS), researchers visiting the North Slope for their own research, and adventurers traveling down rivers on the North Slope. We developed and distributed sampling protocols and kits that facilitated this sampling. The LTER will expand this sampling approach to engage residents in Kaktovik, Nuiqsut, and Barrow and thereby increase coverage proximate to our focal lagoons. By continuing this sampling over time, we will be able to constrain uncertainty in our surface water concentration estimates and quantify how relationships between watershed characteristics and nutrient concentrations vary between seasons and change over longer timeframes. Watershed slope is clearly a dominant variable, but other factors may emerge as important for specific nutrients as the dataset grows. We have far less data on groundwater at present, but samples collected from the Kaktovik region provide a starting point for assigning nutrient concentrations in groundwater seepage to the lagoons. These data will be augmented over time by sampling of groundwater along the shorelines of the LTER focal lagoons during August field trips (when the active layer is approaching maximum thaw depth). Groundwater sampling sites will be established at 10-15 points along the

landward shoreline of each lagoon, and seepage rates as well as nutrient concentrations will be measured. Conversion of volumetric erosion rates to nutrient fluxes will utilize published data for the Beaufort Sea Coast (Hugelius et al. 2013; Kanevskiy et al., 2013; Ping et al., 2011; Jorgenson and Brown, 2005) and be embellished with additional sampling employing the same sampling approach as that used by Ping et al. (2011) within defined landscape and coastal morphometric units.

In addition to the distributed, collaborative sampling approach described above for surface waters, we will establish and maintain fixed sampling sites on the lower reaches of the Jago River (Kaktovik region), Kuparuk River (Prudhoe Bay region), and Avak Creek (Barrow region) that will be visited during June and August. Nutrient concentrations will be measured at all three sites. In addition, water discharge will be measured at the Avak Creek and Jago River sites. As mentioned in the hydrologic modeling section above, the USGS maintains a discharge gauge on the lower Kuparuk. Work at the Jago, Kuparuk and Avak sites will allow us to directly track long-term changes in season-specific nutrient concentrations and fluxes at select nodes within the system. Furthermore, our new water discharge measurements will provide additional calibration/validation data (beyond those available from USGS gauges in the Colville, Sagavanirktok, and Kuparuk drainages) in support of our hydrologic modeling.

Although our ongoing measurements for the LTER will allow us to address *hypothesis 1b* over time, we will also use modeling to explore possible trajectories of future changes in freshwater and erosional inputs. More specifically, we will use downscaled and bias adjusted future climate data derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012) to explore how hydrologic fluxes may change. Here, we will leverage daily downscaled projections from models in the NASA NEX-GDDP for forcing data. We will follow the approach described by Walsh et al. (2008) to select 5 top models among the NASA NEX-GDDP, for two RCP scenarios (e.g., RCP4.5 and RCP8.5). This will provide ten depictions for the future climate to year 2100. At present coastal erosion models are poorly parameterized for Arctic coasts where continuous permafrost prevails. Although we are partnered to efforts nationally (DHS-Arctic Domain Awareness Center) and internationally (ACD) where our measurements are being used to improve model parameterization and validation, we will employ a mixed methods approach (e.g., structural equation modeling, random forest) until dynamic models mature to ascertain the key biophysical controls on erosion trends and use these to project future erosion rates with uncertainty extrapolated from DSAS analyses. Regression tree analysis of DSAS output for 537 transects across an Elson Lagoon coastline monitored since 2003 with DGPS suggests that >80% of the variability in aerial loss can be accounted for by a mixed model that includes nearshore bathymetry, aspect of the coast, elevation of the coastal bluff, and the land cover of the coastal margin being eroded.

Translating future projections of hydrologic and erosional fluxes into projections of nutrient fluxes depends on assumptions about how discharge-concentration relationships and erosion rates change with climate in the Arctic, but we will develop a range of nutrient flux scenarios that formalize our assumptions and can be tested against observation-based LTER flux estimates as the LTER matures. This work will investigate potential future changes in nutrient inputs as manifested by alterations in factors such as surface water flow and soil infiltration amount, groundwater discharge, active layer thickness, talik prevalence, flowpath length, catchment net primary productivity, and erosional loss.

1.7.2 Theme 2. How do changes in ice, freshwater discharges, and circulation influence the connectivity between lagoons and shelf waters of the Beaufort Sea? (PI Leads: Kasper, Mahoney, Tweedie)

Hypotheses:

- 2a. Water exchange between lagoons and open coastal waters is controlled by interactions between river discharge, sea ice, water level (e.g., waves and storm surge), and barrier island geomorphology over seasonal to multi-decadal timeframes. (Core areas 3, 4, 5)*
- 2b. Seasonal, inter-annual, and inter-decadal variability in water exchange between lagoons and open coastal waters will increase with climate change in the Arctic. (Core areas 4, 5)*

Rationale: Annual growth and melting of sea ice exerts a seasonal control on water exchange between lagoons and open ocean areas along the Alaskan Beaufort Sea coast (Harris et al., 2016). As ice thickens

during the fall and winter, passes between barrier islands that connect lagoons to the open ocean are increasingly restricted. The spring freshet and fall storm season also influence water exchange on a seasonal basis. However, to understand water exchange dynamics in a changing Arctic, these seasonal phenomena must be considered in combination with inter-annual to inter-decadal changes in coastline and barrier island geomorphology, topobathy, current, wave, and sea ice dynamics. Over the long term, we expect changes in ice cover (e.g., timing, thickness and extent) and river discharge characteristics (e.g., timing and magnitude of the spring freshet) to alter the frequency and intensity of water exchange between lagoons and the Beaufort Sea shelf in concert with barrier island position and morphology.

Approach: We will use a combination of year-round and seasonally-deployed automated sensors together with campaign measurements during April, June, and July/August (Fig. 10) to investigate lagoon water exchange dynamics. The backbone of this scheme is the network of year-round bottom-mounted platforms instrumented with MicroCATs, BPRs, and TCMs (see **Section 1.5.5**) that will be placed in lagoons and just offshore of passes between islands in each of the three focus areas (Fig.1) to measure variations in sea level and current. Along with the MicroCAT measurements of water level, the BPRs and will enable estimates of along- and cross-shore sea level slopes. Sea level slope is one of the dominant dynamic variables for the nearshore zone (e.g., Lentz and Fewings, 2012) and thus it is critical to estimate sea level slopes when attempting to understand exchange between lagoon systems and offshore.

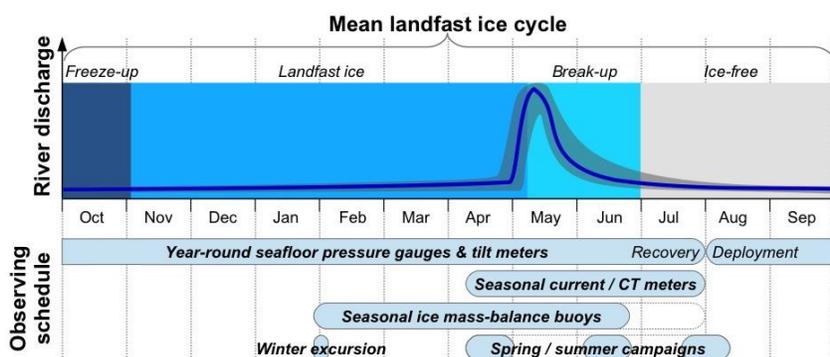


Figure 10. Representative annual cycles of landfast sea ice (Mahoney et al. 2007) and river discharge along the Alaskan Beaufort Sea coast together with the annual observing schedule for physical processes.

The TCMs will allow us to estimate another critical dynamic variable, transport (i.e., water velocity integrated over the water column), between the lagoons and offshore associated with the spring freshet, winds, storm surge, and waves. In addition to the lower frequency variations in sea level due to tides and meteorological forcing that both the MicroCATs and BPRs are capable of measuring, using burst sampling, the BPRs will measure surface gravity wave height and period as well. The combination of MicroCATs, BPRs and TCMs will allow us to quantify how different forcing mechanisms (e.g., surface gravity waves, storm surge, tides and sea level set-down/up due to upwelling/downwelling favorable winds) contribute to exchange between the lagoons and offshore and how the prevalence and strength of these different mechanisms vary for the full range of time scales captured in the LTER. The continuous time series of temperature and salinity measured by the MicroCATs will be used to identify the occurrence of melt and discharge events and, together with transport estimates, to estimate water residences time through simplified salt and temperature budget calculations.

The year-round measurements will be supplemented by seasonal current measurements in channels between barrier islands. Where water depth permits, we will use acoustic Doppler current profilers (ADCPs). Elsewhere, we will measure water velocity using tilt or point-type current meters. A total of 10 seasonal current meters will be deployed in this manner, co-located with the bottom-mounted year-round BPR and TCM platforms (Fig. 2). These ice mounted current meters will allow us to measure the thin, under-ice boundary layers where fresh, river influenced water is expected to be transported (e.g., Alkire and Trefry, 2006; Kasper and Weingartner, 2015). Note that a typical, bottom mounted, upward looking ADCP in water profiling mode (e.g., mode 1, Teledyne RDI, 2006), will not capture the thin under-ice boundary layer where fresh, river influenced water is transported (e.g., Weingartner et al. 2009).

Each of the seasonal, ice mounted current meters will be accompanied by a string of 2 low-cost HOBO type conductivity and temperature sensors in order to estimate salt and heat fluxes out of the lagoons during the periods immediately before and after the spring freshet.

A single “sentinel” mooring equipped with a Seabird SeacatV2+ CTD with a precise Digiquartz pressure sensor and ADCP equipped to measure wave height, direction and period as well as water column currents will be maintained in the nearshore zone (8-12 m water depth, offshore of the barrier islands) to supplement the array of inexpensive pressure, salinity, temperature recorders and MicroCAT CTDs. This instrumentation is already available and will be mounted to a frame equipped with an acoustic release for annual recovery and turn-around using small boats. Similar techniques have been used extensively in the Beaufort Sea for previous measurement campaigns (e.g., Sellman et al., 1992; Weingartner et al., 2009). This sentinel mooring will be rotated between the three different domains within the study region (Fig. 2) in 2 to 3-year occupations.

After freeze-up of the lagoons (which will be monitored using coastal cameras and SAR remote sensing), the winter growth and summer melt processes of lagoon ice will be observed using seasonal ice mass balance buoys (SIMBs), which measure ice thickness, snow depth and the near-surface temperature profile from the atmosphere to the ocean. Together, these observations will allow us to determine the timing and extent of melt and discharge events in spring and estimate the unfrozen extent of lagoons in winter. SIMBs will be deployed during a short winter field excursion and recovered during the spring observing campaign (Fig. 10). Iridium satellite telemetry provides real-time observations and ensures security of data in the event an SIMB is not recoverable. Spatial profiles of temperature and salinity will be obtained during SIMB deployment as well as during the core spring/summer campaigns. Water and ice samples will also be collected for stable isotope analysis (e.g., $\delta^{18}\text{O}$) to aid in identifying source water masses (Fig. 11). These approaches have demonstrated that seasonal runoff and lagoon exchange are likely important determinants of water residence times (Harris et al., 2016).

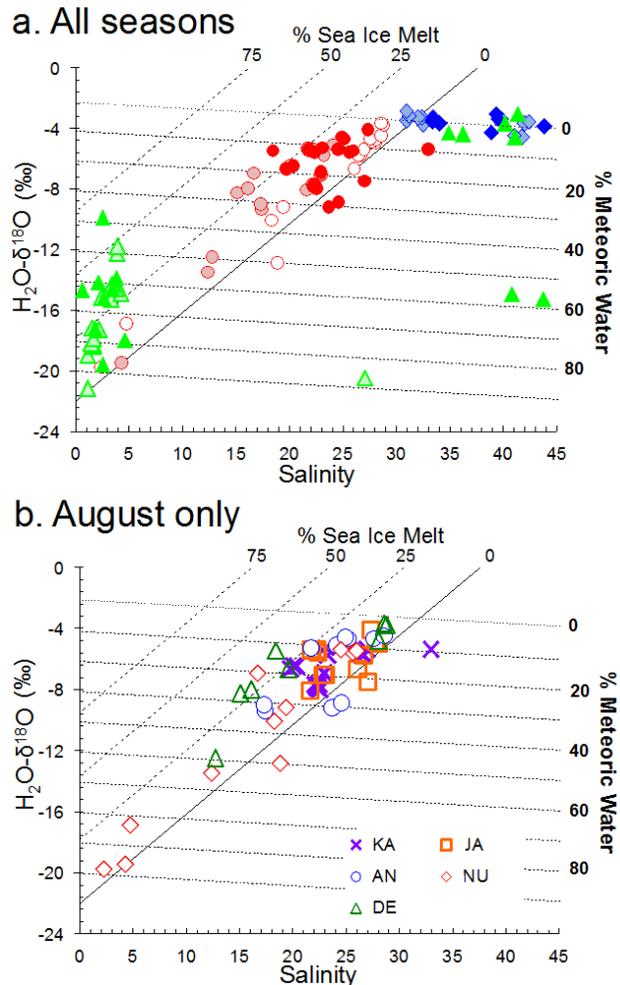


Figure 11. a) Relationship between $\text{H}_2\text{O}-\delta^{18}\text{O}$ and salinity for water samples from 1 m (open symbols), 2 m (shaded symbols), or ≥ 3 m (filled symbols) in different Beaufort Sea lagoons during three sampling months (April = blue diamonds, June = green triangles, August = red circles) from 2011-2014. The solid line shows the expected mixing line between the Polar Mixed Layer and meteoric water. Dashed lines show estimated fractions of low salinity water from sea ice melt (long dash) and meteoric water (small dash). b) Relationship between $\text{H}_2\text{O}-\delta^{18}\text{O}$ and salinity in August from all depths. Meteoric inputs (river inputs and direct precipitation) and sea ice melt dominate in June with polar marine waters becoming exclusively prevalent following break-up. From Harris et al. (2016).

Ecosystem Model components linked to Theme 2: Circulation models for the Arctic Ocean developed over the last two decades are becoming increasingly realistic. However, these models are too coarse to quantify the water exchange between lagoons and open coastal waters. This exchange is likely to be a critical structuring factor for the biology and chemistry of highly productive lagoon ecosystems. Thus it is necessary to couple high-resolution circulation models of the lagoons to the coarser resolution of an open ocean model. This will be performed during the course of the project using a finite element circulation/ice model, such as FVCOM. Model current velocity, sea level, temperature, and salinity will be calibrated against proposed observations. Initially, seasonal and inter-annual exchanges will be addressed using new observations to constrain water fluxes at the model boundaries (land/rivers/groundwater/open ocean), and using atmospheric forcing from observation (see Table 2). Then we will use output from a large-scale open ocean model (temperature, salinity, velocity fields, biogeochemical concentration; Zhang et al., 2010; 2014) to force the high-resolution model at the coastal boundary. This model will be used to quantify water exchange and biogeochemistry under varying regimes of river discharge, sea ice, water level, and barrier island geomorphology, and will forecast the impact of changes in water exchange on lagoon ecosystems.

1.7.3 Theme 3. How are biogeochemical processes within the lagoons linked to inputs of terrestrial organic matter, autochthonous production, and inorganic carbon and nitrogen cycling? (PI Leads: Lougheed, Hardison, McClelland)

Hypotheses:

- 3a. *Arctic lagoons are net heterotrophic systems that serve as hot spots for decomposition of land-derived organic matter and release of CO₂ and N₂ to the atmosphere, with peak CO₂ and N₂ production rates in spring and early summer, and slower but cumulatively significant production in winter. (Core areas 1, 3)*
- 3b. *Inorganic nutrients supporting primary production in the lagoons are chiefly supplied by decomposition of sediment organic matter, from which the proportional contribution of terrestrial versus locally produced material varies strongly among seasons and between years as a function of terrestrial input dynamics. (Core areas 1, 3, 4)*
- 3c. *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 CO₂ and N₂ to the atmosphere. (Core areas 1, 3, 4, 5)*

Rationale: Shallow coastal lagoons receive abundant nutrients and light that support active primary production, yet coastal lagoons are often net heterotrophic (i.e., primary production < respiration), as external inputs of organic matter discharged from adjacent terrestrial ecosystems fuel high rates of respiration (Borges and Abril, 2011). In Arctic lagoons, terrestrial inputs include larger amounts of organic matter from river discharge (McClelland et al., 2014) and coastal erosion (Brown et al., 2003). As discussed under Theme 1, groundwater may also be an important but understudied source of organic matter to the lagoons. In addition, it is likely that high rates of benthic production and decomposition contribute substantially to nutrient cycling in the shallow lagoons of the Beaufort Sea. However, the roles that autochthonous vs. allochthonous organic matter and nutrient sources play in biogeochemical cycling in benthic and pelagic zones of Arctic lagoons remain largely unknown and unstudied.

Standing stocks of organic and inorganic nutrients within lagoon and nearshore coastal waters of the Alaskan Beaufort Sea vary strongly among seasons. Organic carbon and nitrogen concentrations peak during spring and early summer, while inorganic nitrogen (Connelly et al., 2015) and CO₂ likely accumulate under the ice during winter (Kling et al., 1992). This is particularly striking in the lagoons, where ammonium concentrations exceeding 100 μM have been documented under the ice at some locations during late winter (Dunton, unpub. data). Inorganic nutrients in the water column are drawn down rapidly during and shortly after ice break-up. These decreases in inorganic nutrients are accompanied by blooms of phytoplankton (primarily diatoms, as determined by pigment and lipid analyses; Connelly et al., 2015). However, process studies that quantify nutrient transformations, ecosystem metabolism, decomposition, and exchanges across the sediment-water and water-atmosphere

interfaces are sorely needed to develop a complete understanding of biogeochemical cycling within the lagoons. While we expect our understanding of seasonal dynamics to increase quickly using a combination of process and stock measurements, the LTER study will allow us to address how longer-term variations in terrestrial inputs and ocean exchange characteristics (discussed under Themes 1 and 2) interact to influence biogeochemical cycling.

Approach: Using a combination of benthic incubations and water column measurements, we aim to determine how the relative roles of benthic and pelagic biogeochemical cycling vary over space and time in the lagoons. More specifically, to address *hypothesis 3a*, we will examine seasonal and spatial variability in ecosystem metabolism and benthic nutrient cycling, and test whether nutrient fluxes are enhanced due to springtime inputs of terrestrial organic matter, most notably in the nearshore. Stable isotope ratios, C:N ratios, and fatty acid analyses (discussed in detail as they relate to analyses of trophic relationships under Theme 4) will be used to help quantify organic matter sources contributing to sediments and suspended POM. Optical properties such as specific UV absorbance and spectral slopes of CDOM will be analyzed to help differentiate sources of DOM. In both cases, selective decomposition of organic matter (*hypothesis 3b*) will be tracked by quantifying changes in source indicators in lability bioassays. We will also address *hypothesis 3b* using spatial mapping approaches (Anderson et al., 2009; Semiletov et al., 2011), where spatial distribution of pCO₂, O₂ saturation, excess DIC and sediment δ¹³C in the coastal zones are used to infer relative inputs from highly eroding coasts or river plumes, based in part on signatures of marine production/decay versus terrestrial carbon. *Hypothesis 3c* will be explored in the near-term using our ecosystem model, and quantified over the longer-term through analyses of empirical results from repeated LTER measurements.

Ecosystem Metabolism - Only 3% of published studies on aquatic ecosystem metabolism have taken place in the Arctic (Staehr et al., 2012), and we are committed to providing estimates of Arctic lagoon gross primary production (GPP), respiration (R), and net ecosystem production (NEP) that can be compared across ecosystems and through time to assess responses to environmental change and contribute to regional and global level estimates of production. Recently, McGuire et al. (2010) modeled land-ocean-atmosphere carbon flux for the major watersheds of the Arctic basin and concluded that while some watersheds, such as those draining into the Beaufort and Chukchi Seas are carbon sinks, the Arctic Basin overall is a net source of greenhouse forcing (CO₂). However, flux of carbon within and through aquatic ecosystems represents a largely ignored, yet likely substantial component of regional carbon budgets (Walter et al., 2006; Repo et al., 2007; McGuire et al., 2010). Most studies on aquatic carbon transport to the Arctic Ocean have focused on the largest Arctic rivers (i.e., Yukon, Mackenzie, Lena), which are generally sources of CO₂ to the atmosphere (Anderson et al., 2009; Semiletov et al., 2011; Striegl et al., 2012). Dominant carbon sources to the Arctic Ocean included some combination of coastal erosion (Semiletov et al., 2011) and riverine fluxes (Rachold et al., 2000; Striegl et al., 2007; Tank et al., 2011; Abnizova et al., 2012). Clearly, these large rivers are important to Arctic carbon budgets and we aim to develop a similar understanding for smaller but more numerous lagoon ecosystems in the Arctic. To our knowledge, this will be the first study to address and improve this critical gap in knowledge for coastal waters of the Beaufort Sea.

We expect considerable spatiotemporal variability in NEP and CO₂ flux due to both seasonality in autochthonous production (GPP), as well as the substantial and seasonally variable contributions of terrestrially derived carbon (i.e., DIC, DOC) towards metabolism. First, it is not unusual to observe build-up of CO₂ under ice in winter (Kling et al., 1992), which may then be released upon thaw or taken up due to photosynthesis under ice as conditions warm (Semiletov et al., 2004). Along the Beaufort Coast, we expect further seasonality in CO₂ flux, independent of any seasonality in GPP, largely based on seasonal patterns in DOC. We have observed a strong association between pCO₂ and DOC in Arctic waters (R²=0.75; Fig. 12), with highest DOC found in waters more closely linked to terrestrial landscapes (i.e., ponds, rivers; Fig. 12). Movement of this abundant DOC into the lagoons likely contributes to CO₂ efflux at certain times of the year. Notably, given seasonal variability in the lability of DOC transported from

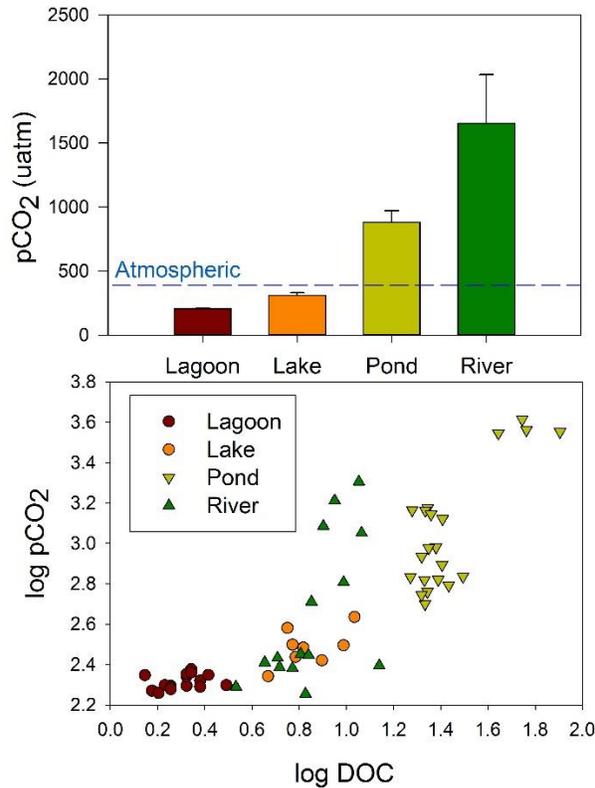


Figure 12. *pCO₂ concentrations in waterbodies near Barrow, AK (top), and the relationship between pCO₂ and DOC (bottom) in August 2015 (Lougheed, unpublished data).*

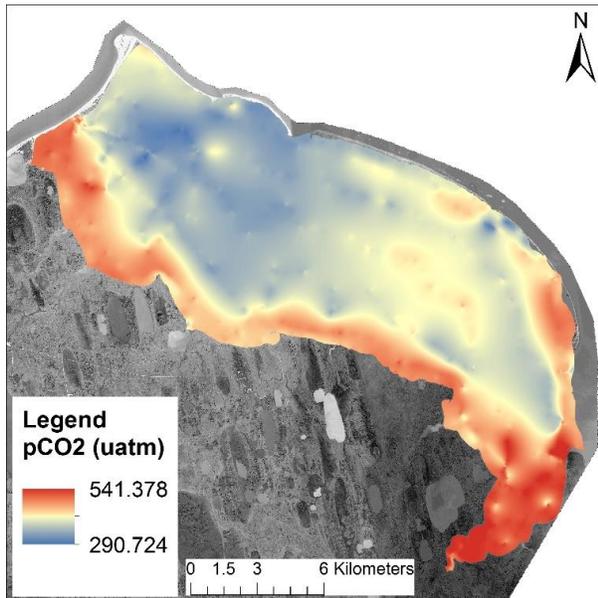


Figure 13. *Spatial variability in pCO₂ (measured at 50 cm depth) in Elson Lagoon during early August 2015 (Lougheed, unpublished data).*

Arctic terrestrial areas (Holmes et al., 2008), elevated DIC throughout the system may result when more labile compounds transported in spring are mineralized rapidly by microbes (Striegl et al., 2005).

Similarly, hydrologic inputs of DIC, produced in upstream terrestrial catchments, can also contribute to CO₂ oversaturation (Maberly et al., 2012; McDonald et al., 2013). We observed this effect in late summer 2015, where rivers flowing into Elson Lagoon had 8x and 5x higher pCO₂ and DOC, respectively, compared to the lagoon itself (Fig. 12), which resulted in elevated nearshore CO₂ (Fig. 13). This phenomenon can lead to the relatively rare co-occurrence of CO₂ supersaturation and positive NEP (McDonald et al., 2013), which we have observed in nearby Arctic tundra ponds (Lougheed et al., 2015a). Essentially, while photosynthesis is resulting in a net uptake of DIC (autotrophy), hydrologic inputs of DIC are provided far in excess of this need (apparent heterotrophy).

Many authors recommend a multi-platform sampling strategy to effectively sample the spatio-temporal variability we expect in the lagoons (Vernet and Smith, 2007). Thus aquatic NEP will be measured by multiple complimentary methods that will allow us to estimate, isolate and scale-up both GPP and R, as well as whole system metabolism and the relative roles of DOC and DIC in driving these. Sensor-based diel logging of dissolved oxygen will be used to determine GPP, R and NEP using a free-water metabolism (FWM) technique (Cole et al., 2000; Pace and Prairie, 2004; Staehr et al., 2010), which permits high temporal resolution (Vernet and Smith, 2007) and avoids artifacts associated with bottle incubations (Staehr et al., 2012). FWM is the method of choice for many ecological networks (e.g., GLEON, NEON, NERRS) and thus allows for cross-ecosystem comparisons and global syntheses of ecosystem metabolism (Hoellein et al., 2013). We have used FWM in tundra ponds since 2010 (Miller, 2013), where even during continuous summer daylight, PAR is sufficiently low between midnight and 2 am to allow for estimation of R. Our study will use a cutting-edge new technology, the HydroSphereTM (Planktos Instruments), which incorporates a multi-parameter probe into a



Figure 14. *HydroSphere™ (Planktos Instruments).*

submersible and GPS trackable unit (Fig. 14). This new platform meets our unique needs for a sensor that is deployable during ice cover, break-up, and open water periods because it can be programmed to float at a certain depth below the surface, without the need for a surface buoy. In brief, at each site, the HydroSphere™ will be deployed, attached to a 100-m tether, and allowed to collect data for 24 h. In addition to DO, it will log temperature, pH, light intensity, salinity, conductivity, and CO₂. The tether will be used to maintain position near the sample site, while allowing the unit to move with drift ice or currents and aid in retrieval. The HydroSphere™ will be calibrated prior to each deployment, with sensor-based DO measurements validated against lab analyses (Wetzel and Likens, 2000). Aquatic CO₂ flux will also be logged using the HydroSphere™, which will include an NDIR CO₂ probe by 2017 (S. Ensign, Plankton Instruments, pers. comm). Diel data collection will allow

precise estimates of diel variability in CO₂, expressed as pCO₂ (µatm) and flux (g C m⁻² day⁻¹) following corrections for diffusive exchange with the atmosphere. For sites where the HydroSphere™ is not deployed, CO₂ concentrations will be measured with a Vaisala NDIR CO₂ sensor enclosed in a PTFE membrane (*sensu* Hari et al., 2008; Johnson et al., 2010; Bass et al., 2012). This method has been successfully deployed by our group (Figs. 12 and 13), as well as others (Dinsmore and Billett, 2008; Crawford et al., 2013).

Optical properties of phytoplankton and DOC make them ideal candidates for remote sensing during the ice-free period (Vernet and Smith, 2007), with potential for linking these parameters to estimates of carbon flux (Tarin et al., 2016). Open water reflectance will be acquired with a dual channel Jaz spectrometer (Ocean Optics Inc.). Satellite imagery from WorldView-2 for dates matching the ground sampling dates will be corrected as required (see **Section 1.5.4**). Relationships between measured and logged variables and image reflectance will be examined (Menken and Brezonik, 2006; Patch Cannizzaro and Carder, 2006) to establish models for back-casting and predicting productivity estimates at these lagoon sites.

Benthic Nutrient Cycling - Despite receiving influxes of oceanic, riverine and groundwater inorganic nutrients, sediment nutrient release often satisfies a large proportion of the inorganic nitrogen and phosphorus needs of estuarine communities (Fig. 15; Giblin et al., 1997; Joye and Anderson, 2008; Nixon, 1981). This “internal” loading of nutrients, particularly nitrogen, may be important in fueling the spring bloom of the Beaufort Sea lagoons. Sediments also play an important role in nitrogen loss via denitrification and burial. Denitrification occurs in anoxic sediments and completely removes fixed nitrogen from a system via N₂ gas, which is largely

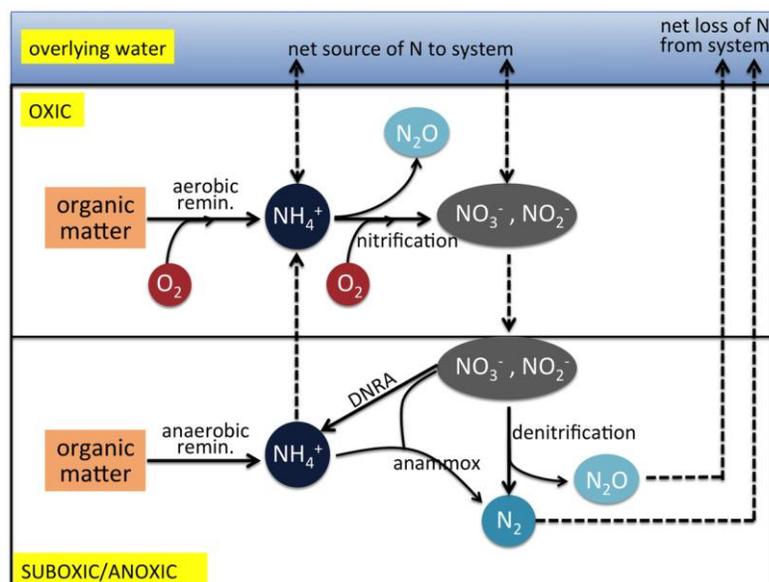


Figure 15. *Schematic of the nitrogen cycle in oxic and anoxic sediments. Release of regenerated NH₄⁺ to the overlying water results in sediments acting as a net source of bioavailable nitrogen to the overlying water. Conversely, denitrification produces and releases N₂, a biologically inert gas, which makes the sediments a net sink for nitrogen.*

unavailable to organisms. Denitrification is the major removal pathway of bioavailable nitrogen in the ocean (Nixon, 1981; Devol, 2015;). Understanding the role of sediments in the fate of organic matter is a critical aspect of ecosystem functioning in coastal systems. Specifically, the dominant nitrogen cycling pathway in sediments will determine whether sediments act as a net source or a sink for bioavailable nitrogen to the overlying water. Recent work in the nearby Chukchi Sea shows sediments to be important sites of NH_4^+ release, but high rates of denitrification make the sediments sites of net nitrogen removal from the system (Fig 16; Hardison et al., submitted). We predict changes in benthic metabolism and biogeochemical cycling over diurnal, seasonal, and longer time frames in the Beaufort Sea lagoons.

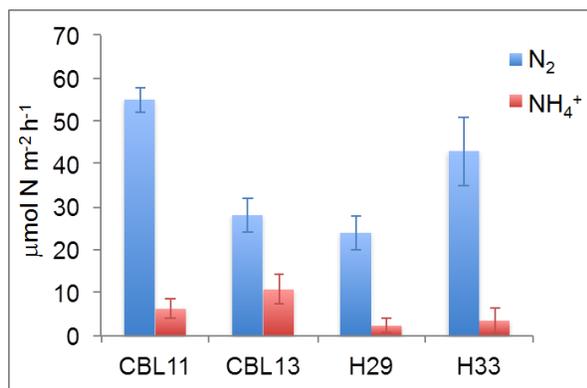


Figure 16. Net N_2 and NH_4^+ fluxes from sediments at four stations on the Chukchi Sea shelf (Hardison et al., submitted).

We will measure benthic gas and nutrient fluxes seasonally at all stations. Batch incubations of sediment cores will be used to measure light and dark fluxes of O_2 , N_2 , DIC, and inorganic nutrients (NH_4^+ , NO_x , PO_4^{3-}). Light/dark fluxes of O_2 and DIC will be used to quantify benthic metabolism parameters (GPP, R, NEP), allowing us to determine the trophic status of the sediments (i.e., net autotrophy vs. heterotrophy) for comparison with the net ecosystem metabolism measurements. Net N_2 fluxes will directly quantify net sediment denitrification rates, and nutrient fluxes will show whether sediments are a net sink or source for nutrients (Fig. 16). We expect these biogeochemical processes to show a light/dark effect because of the potentially important role of benthic microalgae in nutrient dynamics (McTigue et al.,

2015). 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 (e.g., McGlathery et al., 2007; Sundback et al., 2000; Valiela et al., 1997; Viaroli et al., 1996). Photosynthesis and respiration by benthic microalgae in the top few mm of the sediments cause large diel variations in O_2 concentrations and penetration depth, DIC concentrations, and pH (Risgaard-Petersen, 2004). In addition, benthic microalgae may take up porewater nutrients, thus serving as a cap on the sediment surface, reducing or eliminating nutrient flux to the overlying water (Hardison et al., 2011; McGlathery et al., 2001; Sundback et al., 2000). The changes in porewater O_2 and nutrient profiles have been shown to enhance denitrification in some systems (An and Joye, 2001), while reducing denitrification in others (Risgaard-Petersen, 2003; Sundback and Miles, 2002). We expect biogeochemical rates to vary seasonally due to accompanying changes in ice cover, light availability, freshwater inflow, and temperature, which will in turn influence production by phytoplankton and benthic microalgae and delivery of organic carbon to the sediments.

Batch incubations of duplicate intact cores (10 cm I.D. x 30 cm length) will be conducted first in the dark (6 h), then in ambient light (6 h) in temperature-controlled baths. Samples will be collected every 90 min, stored, and transported to UTMSI for analysis. Samples for dissolved gas concentrations (O_2 , N_2) will be collected in gas tight Exetainers, fixed with ZnCl_2 , and stored submerged at ambient temperature until analysis via membrane inlet mass spectrometry (MIMS; Kana et al. 1998). DIC will be collected in Exetainers, fixed with HgCl_2 , and refrigerated until analysis on a DIC analyzer (Apollo Sci Tech). Nutrient samples will be filtered through a 0.45 μm filter and frozen until analysis on a QuickChem nutrient analyzer (Lachat). Fluxes of dissolved constituents ($\mu\text{mol m}^{-2} \text{h}^{-1}$) will be calculated as the slope of the linear fit to the concentration changes over time, during light or dark incubations.

Lability bioassays (e.g., Holmes et al., 2008) will be run on water column and sediment samples to complement the process measurements discussed above. Specifically, we will quantify how composition indicators (molar ratios, stable isotope values, fatty acid profiles, CDOM) change during 7 and 14 day dark bottle incubations conducted at 4 and 25°C. Although it is notoriously difficult to translate these data into field-relevant processing rates, these bioassays will provide information on the

relative lability of different organic matter sources fueling decomposition in the water column and sediments.

Ecosystem Model components linked to Theme 3: Our biogeochemical model, while of intermediate complexity, includes a detailed microbial food web (nitrogen and carbon), primary and secondary producers for the water column and the sediment. It will allow us to quantify net ecosystem metabolism (production minus respiration) and to identify switches between states of net heterotrophy and autotrophy in relation to terrestrial input dynamics. We will first use the model in a 1D mode to constrain the model parameters to realistic ranges based on the observations of rates and fluxes collected during the project. With these 1D simulations, we will be able to describe seasonal variability in the various components of the lagoon ecosystems and their contributions to CO₂ production (removal) and outgassing (intake) to the atmosphere. Our subsequent 3D modeling effort will allow for detailed assessments of the advective effects on the gas exchange among the various locations of the lagoon as well as with the atmosphere. We will also explore potential gradients of heterotrophy and autotrophy in the lagoons on seasonal to interannual time scales. In order to address *hypothesis 3c*, perturbation experiments, such as Monte Carlo simulations, of the various sources of organic matter and nutrients (permafrost thaw, erosion, terrestrial input), will be performed and will explore the full range of possible magnitudes of these sources. We will assess which sources will have the largest impact on the whole ecosystem and its pathways.

1.7.4 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? (PI Leads: McMeans, Crump, Iken, Dunton)

Hypotheses:

- 4a. *Extreme seasonal variations in salinity, temperature, and organic matter supply (external sources and local production) control microbial and metazoan community structure (composition and diversity) and trophic linkages (carbon sources, trophic positions) within the lagoons.* (Core areas 1, 2, 3)
- 4b. *Microbial and metazoan communities with higher taxonomic diversity have higher stability (reduced variability) and resiliency (inter-annual reestablishment of function), which is driven by complementary resource use, the presence of functional redundancies, and consumer foraging behaviors that closely track resource fluctuations.* (Core areas 1, 2, 5).
- 4c. *Long-term changes in the magnitude and variability of terrestrial inputs and water exchanges between lagoons and the open ocean will influence microbial and metazoan community structure and trophic linkages and will alter ecosystem resiliency by reducing diversity, infaunal and epifaunal biomass, and the proportion of benthic perennial species.* (Core areas 1, 2, 4, 5).

Rationale: While salinity, temperature, and organic matter sources are all recognized as important variables that influence community composition and trophic linkages in estuarine systems, this LTER will address how these drivers interact over seasonal, inter-annual, and longer timeframes to shape communities and influence food web structure. We anticipate that variations in salinity and temperature act as primary drivers of community composition, but that trophic structure (including dominant pathways of energy transfer and number of trophic levels) will be controlled by variable organic matter supply from terrestrial sources and *in situ* marine production. In addition to phytoplankton blooms during the spring, benthic microalgae may be an important source of locally-produced organic matter in these systems. Over the long term, we anticipate that changes in the relative timing of terrestrial inputs and peaks in local production will drive changes in trophic linkages, stability, and resilience through effects on biodiversity and microbial processes.

Ecologists have long pondered what aspects of communities promote their stability (commonly measured as the variation in a population's dynamics; Donohue et al., 2013) and resilience (defined as the capacity of communities to reassemble and restore function following a perturbation *sensu* Westman, 1978; Odum, 1953; MacArthur, 1955; Elton, 1958; May, 1973). Species diversity is considered central to resiliency because more diverse communities can exploit a broader range of resources (niche complementarity) and have greater functional redundancy, meaning different taxa can step in following

disturbance to maintain ecosystem functions (Elmqvist et al., 2003; Shade et al., 2012). Recent ecological theory also suggests that certain food web structures, or patterns of trophic linkages, which arise from species and functional group diversity, increase stability compared to food webs lacking these features (Takimoto et al., 2002; McCann et al., 2005). For example, the presence of multiple resources that vary out of phase ensures that consumers have access to a constant food source. ‘Adaptive’ consumer foraging that tracks these resource fluctuations, via shifts in trophic position and carbon source use, stabilizes the food web by culling abundant resources and releasing rare resources from overconsumption. Thus, flexibility in species composition and trophic linkages that arise from taxonomic diversity, not simply species number *per se*, appear central to ecosystem stability and resiliency (Lunberg and Moberg, 2003). This idea is supported by recent studies that showed adaptive shifts in consumer foraging across lakes of different sizes (Tunney et al., 2012) and in microbial communities that sustained function in the face of perturbations without necessarily returning to their original composition (Song et al., 2015). However, food webs have overwhelmingly been treated as static, and the connections between community and food web structures, ecosystem functions, stability, and resiliency in the face of temporally changing conditions remain poorly categorized in nature (McMeans et al., 2015).

Approach: Our organizing principle is that season acts as a perturbation to which systems are well adapted and resilient, with high ‘ecological memory’, (i.e., the capacity to re-establish former functions via flexible structural rearrangements; Lundberg and Moberg, 2003). We will use the extreme seasonality of the Beaufort lagoons to explore if community composition and trophic linkages shift seasonally to

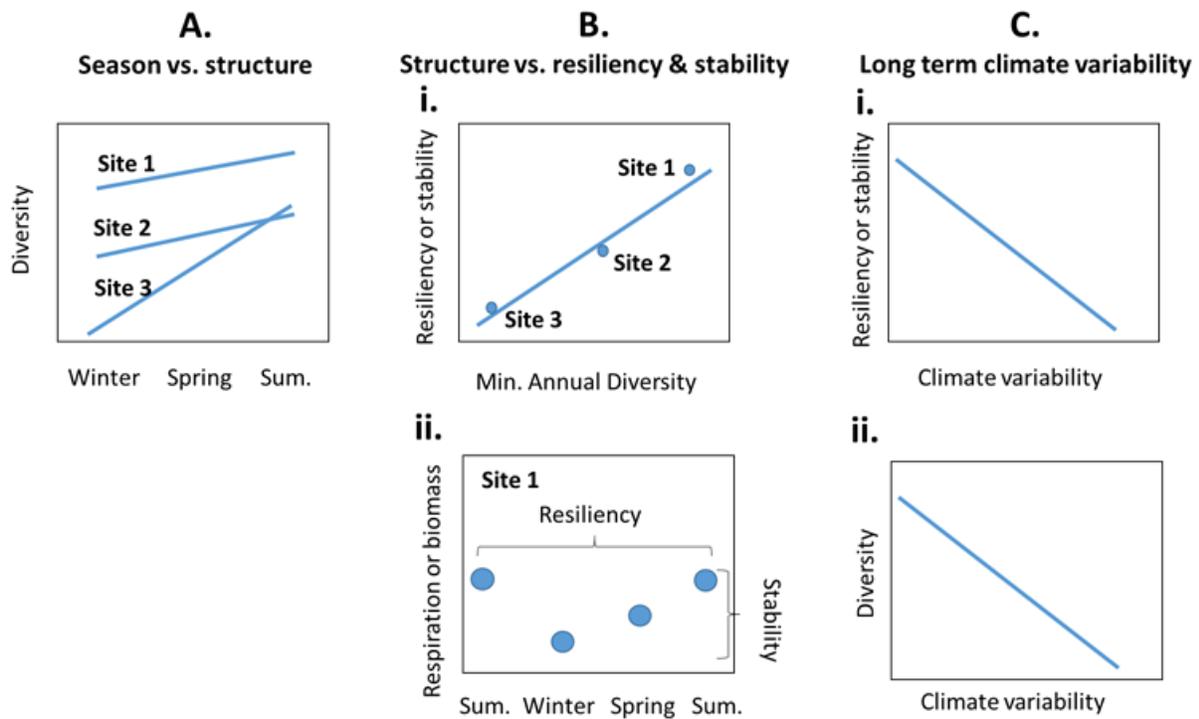


Figure 17. Physiochemical drivers are expected to affect microbial and metazoan community structure (e.g., diversity) and these structural responses are expected to differ across lagoon sites (A). Differences in seasonal structures across lagoon sites are expected to affect resiliency and stability. For example, sites with the lowest minimum annual taxonomic diversity may have the lowest stability and resiliency due to reduced niche complementarity and redundancy (Bi). Resiliency will be measured as the interannual reestablishment of function (e.g., respiration rate or biomass of key functional groups) and stability as the variability in function through time (Bii). C. Long term environmental changes, including increased variability of climate variables, are anticipated to affect resiliency and stability (i.) via their impact on key structures (e.g., diversity, ii)

sustain ecosystem functions, such as secondary production and microbial respiration, with low variability (indicative of stability) and with high inter-annual reestablishment of function from one productive period to the next (an indication of resiliency; Fig. 17). Sampling seasonally and interannually, across average conditions and deviations from average conditions (e.g., warm years and cold years), as well as across lagoons that differ in physiochemical characteristics, will provide new information about how ecosystems respond structurally to temporal variation in temperature, freshwater inflow, ocean exchange, and dominant sources of production (*hypothesis 4a*). Sampling across different sites is anticipated to uncover a variety of community and trophic structuring, from low to high taxonomic diversity, trophic positions, and degrees of resource coupling (i.e., foraging on multiple organic matter sources). We will explore how different community and food web structures relate to ecosystem stability and resiliency (*hypothesis 4b*) and use long-term data to test for altered stability and resiliency in the face of climate-driven shifts in the mean and variance of abiotic conditions (*hypothesis 4c*).

The Microbial Community - The base of food webs in Beaufort coastal lagoons is occupied by several interacting and species-rich microscopic communities that rely on allochthonous resources. Heterotrophic bacteria and Archaea recycle nutrients from terrestrial organic matter and make it available to primary producers. These organisms also produce biomass that feeds detrital food webs that are active year-round (Carlsson et al., 1993; Hamels et al., 2004; McCallister et al., 2004; van Oevelen et al., 2006b). In water, phytoplankton and bacteria-fed heterotrophic protists are the primary food sources for copepods, euphausiids, and other zooplankton that contribute to the diet of fish. In sediment, single-celled organisms (i.e., microbenthos) are the principle diet for the meiobenthos and macrobenthos that contribute to the diet of fish and birds (Gerlach, 1978; Tsuchiya and Kurihara, 1979; Andresen and Kristensen, 2002; van Oevelen et al., 2006a). Moreover, epibenthic biofilms created by benthic microalgae and

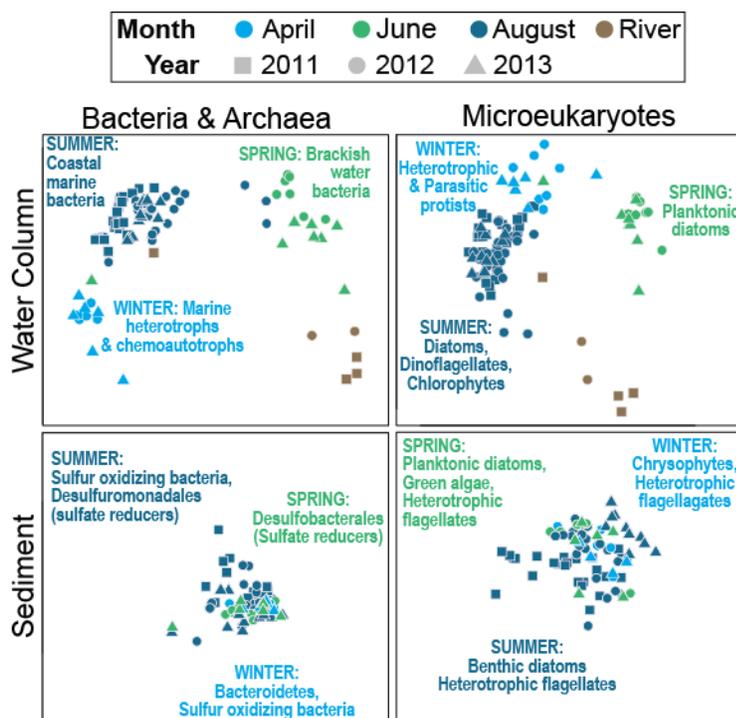


Figure 18. Multidimensional scaling diagrams of microbial community beta-diversity patterns for Bacteria & Archaea, and Microeukaryotes in water and sediment of Beaufort Sea Lagoons near Kaktovik (Kellogg et al., in prep.). Seasonally abundant organisms and functional groups are described in text.

bacteria are the primary food source for many important shorebird populations (Kuwaie et al., 2012; Jardine et al., 2015). Thus, microbial food webs in water and sediment are the mechanism by which terrestrial material subsidize lagoon production. Our preliminary research shows that the species composition of water column microbial communities responds strongly to seasonal variations in environmental conditions, whereas variations in sediment communities are relatively muted (Fig. 18). To address *hypothesis 4a*, and to better define the seasonal environmental drivers of microbial community structure, we will continue seasonal assessments of prokaryotic and microeukaryotic communities in water, sediment, and epibenthic biofilms, and will use coupled physical and chemical measurements to identify environmental controls on community composition.

Preliminary research also demonstrated that seasonal prokaryotic and eukaryotic microbial communities reestablish annually (Fig. 18), suggesting that despite high sensitivity to seasonal

perturbations, these communities exhibit resilience in composition and probably also functional capabilities (Song et al. 2015). Interannual reestablishment of microbial communities has been seen in many different seasonally-impacted environments including soils (Bardgett et al., 1999), rivers (Crump et al., 2009), lakes (Crump et al., 2003), estuaries (Fortunato et al., 2013) and oceans (Fuhrman et al., 2015). Several recent studies suggest that seasonal communities develop from local seedbanks of rare (Gibbons et al. 2013) and possibly dormant taxa (Jones and Lennon, 2010; Lennon and Jones, 2011), or are dispersed into an environment from another location within the broader metacommunity (Crump et al., 2012; Declerck et al., 2013; Low-Decarie et al., 2015). This latter mechanism is likely important in the Beaufort lagoons, where extreme seasonal conditions in winter and thorough flushing during spring thaw may result in significant species reduction or loss. Links between these patterns in community composition and microbial ecosystem function are not always clear because of the extreme diversity of microbial communities and unknown degree of functional redundancy (Allison and Martiny, 2008), but we expect that microbial functions are resilient to seasonal perturbations due to high redundancy and flexibility in composition (Shade et al., 2012; Song et al., 2015). Because higher taxonomic diversity increases the likelihood of redundancies, we expect taxonomic diversity to be positively associated with resilience. However, functional resilience is also thought to vary with the species-specificity of the function and the degree of functional redundancy in a community. For example, the function of nutrient mineralization is common to a broad range of bacteria and may be more resilient than the capacity to metabolize oil-derived hydrocarbons, which is likely limited to a small number of taxa (Brakstad et al., 2008). To address *hypotheses 4b* and *4c* we will investigate how composition relates to functional resilience of seasonal microbial communities across the gradient of conditions inherent to the Beaufort lagoons and over time to determine if variation in winter conditions influences the interannual reestablishment of microbial communities and rates of function in sediment and water.

Prokaryotic and microeukaryotic community composition and functional capabilities will be determined in water and sediment samples from the core environmental sampling program (**Section 1.5.7**) for bacterial, archaeal, and microeukaryotic communities. Composition will be assessed with standard PCR amplicon sequencing protocols established by the Earth Microbiome project for 16S and 18S rRNA genes (Amaral-Zettler et al., 2009; Caporaso et al., 2012; Fortunato et al., 2013; Gilbert et al., 2014; Apprill et al., 2015). Function will be quantified with metagenomic DNA sequencing and with direct measurements of microbial respiration rates. The interannual reestablishment of microbial respiration rates will be used as an indicator of functional resiliency. Metagenomes to characterize the genomic capabilities of microbial communities by quantifying functional genes will be processed with internal control DNA (Satinsky et al., 2013; 2014) to correct for extraction efficiency and to calculate gene and organism abundance per ml water or per gram sediment. DNA sequencing will be done on Illumina MiSeq and HiSeq3000 platforms at OSU's Center for Genome Research and Biocomputing Facility. In each year we anticipate analyzing community composition with one Illumina MiSeq flow cell (~20,000 sequences per sample), and metagenomes with one HiSeq3000 lane (~5 gigabases per metagenome). Microbial respiration rates will be calculated from the change in dissolved O₂ during short-term incubation in gas-tight Exetainer vials at *in situ* temperature in the dark. O₂ will be measured as O₂:Ar with a Membrane Inlet Mass Spectrometer (Kana et al., 1994).

The Metazoan Community - We will use a suite of community composition indices and chemical biomarker to address how seasonal, interannual, and longer-term variations in physical conditions and organic matter sources influence metazoan community structure, resilience, and trophic linkages. Work will be conducted at shallow (< 2 m) and deeper (< 3 m) stations to account for very different physical dynamics in these two environments. Where water depths are < 2 m, the sediments are icebound and frozen for up to 9 months annually. Despite these conditions, however, shallow sediments are populated by a diverse invertebrate fauna by mid-summer, suggesting high resilience of these benthic assemblages and their functions (Churchwell et al., 2015). This rapid recruitment appears to be a product of a large brood stock available in coastal waters (Feder and Schamel, 1976) and the high fecundity of infaunal species (Dunton and Schonberg, 1980). We anticipate that the biomass of functionally important species

groups (e.g., grazers, deposit feeders, predators) are restored every summer by species that survive the local conditions or that immigrate from adjacent areas. The species composition and diversity of lagoon communities are also expected to vary spatially (e.g., as a function of sediment characteristics) and among years (e.g., depending on the harshness of winter conditions). We will explore how the severity of winter conditions influences community composition and resultant functions at multiple temporal scales by making coincident measurements of infaunal community structure at paired shallow and deep stations during both ice covered and open-water periods (**Section 1.5.7**).

Resilience within a single year will be quantified as the extent to which biomass values of key functional groups are restored from one summer to the next, following the winter perturbation (e.g., resiliency = $1 - |\text{biomass}_n - \text{biomass}_{n+1}|/\text{biomass}_n$ where biomass_n and biomass_{n+1} are consecutive summer values, see Fig. 17). Additionally, interannual indices of resilience will be calculated as the difference between any one summer's biomass value and the average summer biomass measured across multiple years. The variation in biomass values through time (measured as coefficient of variation) will be used to estimate ecosystem stability (Donohue et al., 2013). Experimental *in situ* manipulations will also be used to assess resilience and stability of benthic communities in response to coincident variations in the biophysical environment. These manipulations will include reciprocal transplants of infaunal organisms in benthic cores and measurement of condition indices (e.g., in bivalves), "recovery" experiments, and use of underwater time-lapse photography and ROV transects. We expect that systems with high resiliency will exhibit a high capacity to restore function every summer following harsh winter periods and that the biomass of key functional groups will exhibit low variability through time in systems with high stability.

Several biomarker techniques will be used to quantify trophic structure and variability in energy pathways in the lagoons. First, "bulk" stable isotope analysis of organic carbon and nitrogen in organism tissues, will be used to describe food web structure by trophic levels as in other Arctic systems (Iken et al., 2010; Divine et al., 2015). Bulk stable carbon isotopes will also be used to distinguish major carbon sources; for example, terrestrial/freshwater carbon is isotopically lighter than marine-derived carbon, which is reflected in the bulk carbon isotope signature of consumers (Dunton et al., 2012; Bell et al., 2016). To explore spatial and temporal variations in isotopic signatures, we will map ^{13}C and ^{15}N values in ArcMap (ESRI) using an appropriate spatial interpolation or regression routine depending on the nature of the data (e.g., inverse distance weighting, kriging, spatial regression). Second, we will employ a novel essential amino acid specific stable isotope approach that provides greater source specificity than bulk isotope analysis. Essential amino acids cannot be synthesized *de novo* by consumers, so they are conservatively taken up from a primary production source, creating a "stable isotope fingerprint" that makes it possible to determine the proportional consumption of marine, terrestrial and microbial production (Larsen et al., 2009; Larsen et al., 2013; Arthur et al., 2014). Third, we will use fatty acid biomarkers, a widely used technique (Dalsgaard et al., 2003) that takes advantage of the broad diversity of fatty acids in organisms, and tracks the transfer of organism-specific fatty acids through the food web. For example, the sum of n-3 and n-6 fatty acids in the tissues of a consumer provides information about terrestrial carbon use, and the sum of odd and branched chain fatty acids indicates the degree of reliance on bacterial biomass. Amino acid isotope and fatty acid biomarker analyses will focus on key pelagic and benthic organisms from multiple trophic levels to quantify their responses to seasonally changing carbon sources: copepods, euphausiids, amphipods (e.g., *Gammarus*, *Pontoporeia*), polychaetes (Terebellides, *Potamilla*), and fish (Arctic cod, sculpins). Bulk and compound-specific stable isotope measurements will be performed via elemental analysis isotope ratio mass spectrometry (EA-IRMS) and gas chromatography isotope ratio mass spectrometry (GC-IRMS) respectively (see **Facilities** documents). Bulk samples will be dried and ground into a homogenous powder before analysis. In addition, samples for bulk $\delta^{13}\text{C}$ analysis will be acidified to remove carbonates. Samples for amino acid analysis will be hydrolyzed, purified, and derivatized according to Larsen et al. (2013). Samples for fatty acid analyses will be extracted via a modified Folch approach and converted to fatty acid methyl esters. These samples will then be analyzed and quantified via gas chromatography.

Changes in species composition over seasonal, inter-annual, and longer timescales may affect the structure of food webs. More diverse consumer communities may better track resource fluctuations, thus

exhibiting more ‘adaptive’ food webs, because higher diversity increases the range of possible habitats and resources exploited under a wider range of environmental conditions (i.e., increased niche complementarity and redundancy, Lundberg and Moberg, 2003; Rooney and McCann, 2012;). Adaptive foraging is feasible in Beaufort lagoons because, during summer, different species within the benthic community differ in their carbon source usage, likely due to prey preference and selection (Dunton et al., 2012; Harris, 2015). Trophic interactions may also change on longer time scales because climate-driven changes in ocean exchange and freshwater inflow could affect the timing and relative availability of marine, estuarine and terrestrial resources. To test whether sites with lower diversity and less complex food webs have lower stability and resilience over seasonal and longer term time scales, respectively, we will compare community characteristics (composition, diversity indices; **Sections 1.5.7 & 1.5.8**) and food web structures ($\delta^{13}\text{C}$ and fatty acid based terrestrial carbon use, $\delta^{15}\text{N}$ based trophic positions) to stability and resilience metrics across lagoon sites (Fig. 17).

Ecosystem Model components linked to Theme 4: Our modeling effort will address Theme 4 hypotheses by characterizing seasonal and long term variations in trophic linkages and the relative importance of microbial food webs vs. phytoplankton and benthic microalgae-based food webs in water and sediments. The model will also be used to identify controls on trophic linkages including environmental controls (e.g., temperature, freshwater inflow, ocean exchange) on the dominant sources of production, and the role of microbial food webs in controlling primary and secondary production. We will use information from studies of microbial and metazoan community composition and biomarkers to steer development of this benthic-pelagic community model. Our biogeochemical model does not currently address questions about microbial and metazoan community structure because it only includes two phytoplankton (diatom and picoplankton), two zooplankton (micro and meso), one benthic animal, and one heterotrophic bacteria component. However, we will seek further funding to expand the biogeochemical model in a similar way as the Darwin model (Follows et al., 2007) and/or will use a trait-based model (Litchman et al., 2007) for the planktonic and benthic components. Trait-based models are useful for addressing the evolution of species assemblages by defining total biomass, mean trait, and variance of the trait. The main challenge with these models is that trait variance often to zero with time. Novel approaches have been proposed to circumvent this problem and they show promise (Merico et al., 2014). This trait-based modeling remains at the forefront of the ecological modeling for addressing the impact of changing environment conditions.

1.8 LINKAGES TO OTHER LTER PROGRAMS

Our proposed Beaufort Lagoon Ecosystems (BLE) LTER program has natural connections to two groups of ongoing LTER programs that will facilitate collaboration and synthesis efforts. The first group consists of the Bonanza Creek LTER (BNZ) and the Arctic LTER (ARC). These two inland LTER sites, located in the boreal forest of interior Alaska and the northern foothills of the Brooks Range respectively, include core research components focusing on land-water connections in permafrost environments. ARC has ongoing research addressing the biogeochemical openness of tundra ecosystems and is investigating short and long term impacts of climate change on freshwater transport of organic matter and nutrients across landscapes underlain by continuous permafrost on Alaska’s North Slope. BNZ is investigating impacts of permafrost thaw on biogeochemical cycles and stream chemistry in watershed with discontinuous permafrost. We will develop collaborations with these LTER programs to better understand controls and climate impacts on transport of water and water-borne nutrients from headwaters to the coast. The second group includes the LTERs focusing on shallow coastal ecosystems along the US east coast (Plum Island Ecosystems, Virginia Coastal Reserve, Georgia Coastal Ecosystems, and Florida Coastal Everglades). These systems represent a latitudinal gradient in seasonal conditions that will be extended by the BLE LTER, and they are also variable in estuarine geomorphology, freshwater flow, tidal amplitude, and watershed composition. These LTER programs are currently collaborating on several research topics including carbon cycling and salt marsh ecology, and they routinely send representatives to each others annual meetings. We will participate in this cross-fertilization effort at annual meetings, and will develop collaborations to investigate the impact of varying seasonality and terrestrial inputs on food web structure and carbon and nitrogen cycling. As noted in the introduction, the BLE LTER would contrast with the



Figure 19. *Our proposed Schoolyard and Citizen Scientist programs include experiential learning activities with PIs and graduate students as role models. Here, Ken Dunton collects samples with Kaktovik middle and high school students in April 2013 under a program that we started in 2007.*

PIE, VCE, GCE, and FCE LTERs not only because of the extreme seasonal variations in environmental variables that the Beaufort lagoons experience but also because these lagoons lack fringing salt marshes and seagrasses that are central to the function of shallow coastal ecosystems at lower latitudes.

SECTION 2: BROADER IMPACTS – Outreach and Education (PI Leads: Dunton and Lougheed)

Schoolyard: Many of the senior personnel have extensive experience partnering with K-12 schools in ways that bring hands-on science to teachers and students. PIs at both UTMSI and UTEP have extensive experience partnering with K-12 schools in ways that bring hands-on science to teachers and students. The PI (Dunton) has been committed to active involvement of scientists in K-12 activities in Kaktovik since 2007 (Fig. 19). He was PI for two consecutive NSF GK-12 awards, initiated the Scientist in Residence Program at the Port Aransas ISD, and directed Summer Science K-12 Programs in Kaktovik in 2007 and for the past six consecutive years. We plan to continue engaging students in Barrow and Kaktovik in this highly successful program as part of the proposed LTER effort. Funds are requested to bring K-12 science teachers from Texas to Kaktovik and Barrow each year to help us lead these K-12 Schoolyard programs. Our K-12 activities have support from the NSB, the USFWS Arctic Refuge, and the City of Kaktovik (see attached letters of collaboration).

We expect our Schoolyard efforts to complement and build on a recent NSF Polar IUSE funded to Lougheed and Tweedie, whereby students participate in authentic, collaborative research experiences, focused on quantitative skills development (through analysis of existing Arctic data sets), together with related field experiences in Barrow, AK. The future scientific workforce will undoubtedly need to integrate traditional scientific approaches with data intensive solutions to rapidly transform scientific knowledge and improve problem solving capacities. Thus, we will include a LTER data analysis component to our Schoolyard activities, where students and teachers will look at LTER data to help understand the ecology of lagoons near their communities, and how these are changing through time. Once datasets are introduced and analyzed, participants will collect and analyze similar samples, challenging them to “think like a scientist”. Through these activities, local students will gain an appreciation for the scientific research ongoing on their native owned and managed lands, while LTER scientists will gain valuable insight as to how traditional knowledge can complement our research efforts.

Citizen Scientists: In concert with K-12 Summer Science Programs, we propose to engage local high school seniors or recently graduated students as field research assistants to work directly alongside scientists in our field sampling efforts. Dunton and McClelland successfully employed high school students in Kaktovik in 2012 and 2013 as field scientists. We would like to formalize a long-term Citizen Science program through active mentorship in Barrow & Kaktovik, eventually incorporating all three Beaufort Sea Iñupiat villages, including Nuiqsut (at the head of the Colville River delta). Our experience has shown that involvement by high school or post graduate research assistants facilitates participation by village elders, which helps us disseminate our science to local communities.

Four Barrow and Kaktovik high school or post graduate research assistants (two from each village) will be selected and supervised by the PIs. They will provide field support for sampling on this project over the six-year period (different students may be selected on an annual basis). Their duties will include making basic hydrographic measurements (e.g., temperature, salinity, pH, etc.) using a YSI Sonde, biological sampling using nets, grabs, and trawls, assisting with the fisheries study, and working with local subsistence hunters to gather fish for biological analyses. In all cases, they will work with project scientists based in either Barrow (led by Tweedie or Loughheed) or Kaktovik (led by Dunton, Hardison, or McClelland). To further foster communication with the wider scientific and the public community, we will select Iñupiat research assistants to co-present results of our studies at regional scientific and public symposia (e.g., during the Arctic Section at the Alaska Marine Science Symposium (AMSS) meeting in Anchorage). They would be mentored and supervised during their two-day trip by the LTER scientists. Students will also be mentored in submitting abstracts and applying for travel grants to the Annual Meeting of SACNAS (The Society for the Advancement of Chicanos and Native Americans in Science), which is a unique venue that allows students to present their research in a nurturing environment, while also attending professional development workshops.

In recognition of the ecological and cultural values of the eastern Alaskan Beaufort Sea, the Refuge nearshore zone has recently been added to the National Marine Protected Areas network. Consequently, we will make every effort to include local residents in our research and present our findings in open-meetings in Barrow, Kaktovik, and Nuiqsut. Finally, science products, photographs, video clips and other sources of information will be posted on our dedicated project website.

Subsistence Fisheries Collaboration: The active subsistence fisheries in the Iñupiat communities of the North Slope, together with the observation of possible increased presence of Pacific salmon in the region presents a unique opportunity to involve the native villagers of the Beaufort Sea coast in our research activities. We propose additional activities for Citizen Scientists, ranging from high school students to the elders in the community, that include (1) the opportunistic collection of tissue samples from subsistence fish harvest, and (2) the implementation of a baseline sampling program that can be used to identify significant changes in relative abundance of Pacific salmon in the Beaufort Sea. First, through collaborations we have established with the local communities, subsistence hunters will be provided with containers to save tissue for analyses (Section 1.5.4). To facilitate this effort, each spring we will have community meetings at each village to answer questions about our research efforts and results, many of which will be of great interest and concern to local communities on the North Slope. Second, LTER researchers and Citizen Scientists will collaborate on gillnet sampling, optimized to capture salmon or larger species. Following sampling, carcasses of all captured fish will be offered to local residents for use. In addition to the scientific value of these efforts, we expect this collaboration to become a fruitful and rewarding example of the incorporation of traditional knowledge with more western scientific thought.

Graduate and Undergraduate Education: This project will offer valuable mentorship to students at all levels. We plan to use video classroom facilities to offer a dedicated weekly seminar course for the six or more Ph.D. level graduate students employed on this project to facilitate the exchanges of ideas and research results. Other students at all participating institutions will be invited to attend select seminars, where students and faculty will present their results, thus expanding the dissemination of our results. We have also budgeted funds to support up to two students annually (one at Barrow and one at Kaktovik) through the Research Experiences for Undergraduates (REU) program. We expect to recruit about one-

third of our undergraduate and graduate student participants from UTEP, a leading Hispanic training university. Finally, we plan to expand on the current REU program at UTMSI. This program is focused on Subtropical Marine Ecosystems (REUiSME), but current funding ends in 2018. If the Beaufort Lagoon LTER is funded, we plan to renew the program and expand the opportunities for REU students to include both polar and tropical systems. The current program has trained 72 students to date, including 15% first generation college students and at least 30% from traditionally underrepresented groups.

SECTION 3: RESULTS OF PRIOR NSF SUPPORT

Dunton, McClelland, and Crump ARC-1023582, \$1,000,025, 9/1/2010 – 8/31/2013, Collaborative Research: Terrestrial Linkages to Microbial and Metazoan Communities in Coastal Ecosystems of the Beaufort Sea. *Intellectual Merit:* This project has greatly improved our understanding of seasonal variations in salinity, biogeochemistry, and food-web relationships in lagoon ecosystems along the eastern Alaska Beaufort Sea coast. Results show that microbial community composition in the lagoons varies seasonally with terrestrial inputs, and that terrestrial organic matter is an important food source for biota in the lagoons. *Products:* This project has produced >20 presentations at national and international meetings and five publications to date (Nolan et al., 2011; Dunton et al., 2012; Connelly et al., 2015; Harris et al., 2016; Smith et al. 2016). An additional 3-4 papers are anticipated to emerge from this work over the next few years. *Broader Impacts:* The findings of this project provide a baseline for tracking climate change effects on nearshore estuarine ecosystems along the northern Alaska coastline. In addition, the project's impacts were broadened through 1) support and training of two graduate students and a postdoctoral scientist at UTA, and 2) a K-12 Summer Science education program conducted in Kaktovik by the project PIs and elementary school teachers from Texas during each project year.

Hardison and McClelland, EAR-1417433, \$514,792, 9/1/14 - 8/31/17, Where a river slows: investigating the oscillic freshwater zone. *Intellectual Merit:* This project is characterizing the physics of tidal freshwater zones (TFZs) in rivers, and addressing how TFZ physical dynamics affect nitrogen transport from watershed to estuaries. Modeling work conducted over the past year has informed intensive field work which began last summer. *Products:* One manuscript which formalizes how TFZs are defined and applies this framework to 12 rivers along the Texas gulf coast is currently in the final stages of preparation for submission. Hardison and McClelland's REU students have presented two posters related to the work at a national conference. *Broader Impacts:* To date, the project has supported three graduate students and four undergraduate REU students. We have also developed and participated in a Teachers on the Estuary (TOTE) program through the Mission Aransas National Estuarine Research Reserve (MA-NERR). The MA-NERR uses Fennessey Ranch, on the Mission River, for public outreach and education. Using recently purchased kayaks, we developed a field trip that takes advantage of the kayaks and highlights the TFZ that fortuitously occurs adjacent to the ranch.

Lougheed, ARC-0909502, \$389,800, 09/01/09- 08/31/13, Re-visiting "The Limnology of Tundra Ponds": Re-sampling historic sites to track global change in Arctic aquatic ecosystems. *Intellectual Merit:* Data indicate that the IBP ponds have significantly higher nutrient and algal concentrations than in the 1970s, are decreasing in size and have higher levels of primary production. Increased nutrients are likely being released from warming permafrost. *Products:* To date, this project has produced >25 conference presentations, 6 papers (Callaghan et al., 2011; Lougheed et al., 2011; 2015b; Andresen and Lougheed, 2015; Reyes and Lougheed, 2015; Andresen et al., In press), 3 Master's theses, and 1 PhD Dissertation. Data are archived at ACADIS. *Broader Impacts:* 4 graduate and 3 undergraduate students, primarily Hispanic, worked on and/or were supported by this project. Outreach to the community in Barrow occurred through Saturday Schoolyard talks, and incorporation of local students into our research.

Mahoney, ARC 0856867; \$1,388,000, 01/2010-12/2016 (including 1-year NCE), Collaborative Research on the State of the Arctic Sea Ice Cover: Sustaining the Integrated Seasonal Ice Zone Observing Network (SIZONET). *Intellectual merit:* SIZONet is a unique cross-disciplinary observing network that provides key data regarding the state of the seasonal ice cover in the Pacific Arctic, one of the most rapidly changing regions in the Arctic. Key findings from SIZONet include: i) the remarkable consistency in the onset of key stages of melt despite large interannual variability in forcing (Perovich and Polashenski,

2012); ii) the presence of systematic errors in modeled ice thicknesses in AOMIP models (Johnson et al., 2012); iii) the impact of decreased stability of landfast subsistence whaling practices (Druckenmiller et al., 2013); and iv) the relationship between ice concentration and walrus harvest success in St. Lawrence Island communities (Kapsch et al., 2010). *Products*: SIZONet data have been used in over 25 peer-reviewed publications spanning the physical, biological and social sciences as well as operational applications such as ice forecasting and satellite validation. *Broader impacts*: SIZONet data products have been utilized by a group of stakeholders that includes federal and local agencies, all levels of academia, private industry and residents of Arctic communities. Additionally, SIZONet has supported 3 PhD and 2 MS students as well as PI Mahoney when he was an early career researcher.

Tweedie, ARC-0732885, \$747,684. 09/01/2007-08/31/2011, IPY Back to the Future (BTF): Re-sampling old research sites to assess change in high latitude terrestrial ecosystem structure and function. *Intellectual merit*: This project rescued and resampled a range of historic research sites in northern Alaska and Canada. A high degree of variability was observed in the decadal change observed; where change was observed, it always corresponded with a wet land cover type; rates of colonization following deglaciation are increasing in the high arctic; lemmings were found to be essential for maintaining a peak season C sink in tundra near Barrow and the impact of their population outbreaks was greater than long term change trends documented for vegetation monitoring sites. *Products*: One special issue of AMBIO, 17 peer reviewed publications, 3 dissertations, and numerous presentations resulted from this project and two publications are in review. *Broader Impacts*: A postdoc, three doctoral students (2 Hispanic), and five undergraduates (all Hispanic) were trained on this project. Historic sites and data were rescued and archived with multiple archives (Arctic Vegetation Archive, AON-CADIS, Polar Data Catalogue)

Spitz, OCE-1357530, \$753,084, 03/01/2014-02/28/2017, Natural Iron Fertilization from the Patagonian and South Georgia Island Shelves to the Open Waters of the Southern Ocean. *Intellectual Merit*: Using a coupled ecosystem/iron/circulation model we examined quantitatively the processes of iron fertilization (e.g., tides, river and groundwater discharges, shelf/deep-ocean interactions, atmospheric dust deposition) leading to plankton blooms in ocean waters off of Patagonia and South Georgia Island. We found that the sediments and river discharge are important sources of iron for the spring bloom on the Patagonia shelf when the water column is well mixed. During summer when strong stratification is established, dust deposition plays an important role in maintaining the bloom. In addition, our simulations focused on the South Georgia Island and the Georgia Basin identified an active upwelling region of iron fertilization in the northwestern corner of South Georgia that had not been noted previously. *Broader Impacts*: These findings have been presented at Ocean Sciences 2016 meeting (2 talks and 1 poster). One undergraduate gained training and experience in modeling and data analysis and the necessary software to do so in Matlab and Python. This project contributed to the training of an Argentinean scientist, who spent the summer 2015 at OSU, and a post-doc in the development of a couple bio-physical model of the Patagonian shelf. *Products*: 3 publications and 1 in preparation resulted from this research.

Wooller, **Iken**, Horstmann-Dehn, and Gradinger, OPP-0902177, \$617,856 2009-2013. Tracking the seasonal contribution of algal fatty acids to the arctic marine system. *Intellectual Merit*: This project used a transformative approach of fatty acid specific stable isotope analysis to better track the complex seasonal interdependencies between arctic marine primary production and arctic marine food web components in the Bering Sea. The seasonal, proportional contributions of specific biomarkers derived from the two main primary producers, sea ice algae and open ocean phytoplankton, were tracked into higher trophic levels (sympagic, pelagic and benthic invertebrates and ice seals) in the Bering Sea. This project linked closely in concepts and through sample sharing with the Bering Ecosystem Study and Bering Sea Integrated Ecosystem Research Program - BEST/BSIERP, funded by the NSF and North Pacific Research Board (see NSF OPP-0732767). *Broader Impacts*: Two graduate students completed their PhD dissertations under this project and published their findings in peer-reviewed journals. Results from the project were presented at numerous scientific conferences and related to native communities through outreach activities.