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TITLE OF PROPOSED PROJECT **LTER: Resilience in the Environmental Mosaic of the Northern Gulf of Alaska (NGA) Shelf Ecosystem**

| REQUESTED AMOUNT | PROPOSED DURATION (1-60 MONTHS) | REQUESTED STARTING DATE | SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE |
|---|---|---|---|
| $ 6,761,974 | 72 months | 10/01/17 | 1632529 |

THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

- ☐ BEGINNING INVESTIGATOR (GPG I.G.2)
- ☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C.1.e)
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# PROJECT SUMMARY


## Overview:

We describe the creation of a new LTER site in the Northern Gulf of Alaska (NGA), a subarctic marine biome characterized by enhanced productivity and high environmental variability. Two decades of research by the Seward Line long-term multi-disciplinary program demonstrate the important role intense variability has on species- and community-level dynamics. This past research has provided preliminary information essential to assessing ecosystem resilience by highlighting emergent properties of the NGA:

- A pronounced spring bloom and regions of sustained high summer production
- A stable base of energy-rich zooplankton grazers
- Substantial sinking flux of organic matter
- Efficient transfer of primary production to higher trophic levels

The LTER site will continue and expand the Seward Line program to cover observations from spring to fall, and examine features and processes that drive productivity in the NGA to understand how short- and long-term climate variability propagates through the environment to influence lower trophic level organisms. On the NGA shelf it is these assemblages that, directly or indirectly, support the species of fish, benthos, seabirds and marine mammals that are iconic for Alaska.

## Intellectual Merit :

The research focus of the NGA LTER site will be on mechanistic understanding of processes that underlie environmental variability promoting high productivity and resilience. Building on prior knowledge, we propose to test three hypotheses centered on ecosystem emergent properties:

1. Changes in the hydrologic cycle affect spring bloom production through changes in cloud cover, the stratification/mixing balance, macro- and micronutrient supplies, and transport pathways.
2. Hot spots of high summer primary and secondary production result from interactions between the fresher ACC and more saline offshore waters as promoted by shelf geomorphology and regional winds; hot spot timing and magnitude will be influenced by changes in the hydrologic cycle.
3. Nutritional and life history patterns of NGA consumers minimize trophic mismatch, buffering spatial and temporal variability in lower trophic level production and leading to resilience in the face of long-term climate change in the NGA.

We will address these hypotheses with a cohesive research program that includes: a) seasonal time series studies that addresses short- and long-term environmental and ecosystem variability through a spring-to-fall field observational program that will build upon, and enhance the Seward-Line times series, a leveraged mooring component that will enhance frequency of temporal measurements, and collaboration to obtain higher trophic level data; b) process studies that initially focus on hypothesized mechanisms leading to variability in NGA production in time and space; c) modeling studies that incorporate physical and biogeochemical observations and provide a framework for testing hypotheses, and for predicting ecosystem response to projected environmental changes; d) a data management component that provides a repository and a platform for data visualization to facilitate synthesis.

Advantages to the NGA as an LTER site: a highly productive biome not represented by the LTER network; a strong climate context provided by two decades of Seward Line observations; pronounced variability that allows ’space for time’ investigation; a rich history of coupled bio-physical modeling of the region to advance prediction of ecosystem response to perturbation.

## Broader Impacts :

Data and metadata will be available online to LTER colleagues, educators & students, and resource managers. Our Education & Outreach component includes development of a series of videos featuring understanding gained from this research, and scientist in ocean-related STEM careers. These will be shown through various venues, including the Alaska SeaLife Center, will be incorporated into virtual field trips for K-12 students, and will be available to the LTER schoolyard network. We will train graduate and undergraduate students across disciplines and in field techniques. Our synthesis work will aid in effective ecosystem-based management of commercially important fisheries in Alaska.

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For font size and page formatting specifications, see GPG section II.B.2.



Appendix Items:

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

## Resilience in the Environmental Mosaic of the Northern Gulf of Alaska Shelf Ecosystem

The **subarctic marine biome** comprises highly productive shelf seas that support rich and diverse ecosystems; the NGA in particular (Fig. 1) sustains one of the world's largest commercial fisheries (e.g., Sumailia et al. 2011), as well as iconic species of seabirds and marine mammals. The central feature of the subarctic marine biome is strong seasonality of environmental drivers (heat, winds, freshwater input, and light; Fig. 2). While seasonality lends a quasi-predictable nature to the subarctic production cycle, a hallmark of this environment is marked variability in the timing and frequency of production events, as well as in the spatial expression of these events. Environmental variability over longer time scales also characterizes the subarctic biome, from multi-decadal fluctuations and trends to latitudinal excursions of the subarctic biome in conjunction with glacial retreats and advances. Our central premise is that the NGA ecosystem is adapted to this variability, in that species and communities possess a range of behavioral, functional and compositional attributes that allow ecosystem emergent properties to be regained following disturbance. We propose to apply this resilience framework to the study of the NGA ecosystem and to cross-system comparisons, to the further our understanding of this important ecological property. Thus the overarching theme of the NGA LTER is:

**Intense environmental variability leads to high resilience in the northern coastal Gulf of Alaska**

We define resilience as the recovery of ecosystem emergent properties after disturbance or perturbation (Holling 1973, Levin & Lubchenco 2008). Emergent properties arise from the concatenation of ecosystem elements, and comprise the underpinnings of high NGA productivity across trophic levels (see below). How and why resilience arises – or does not – is a topic of intense interest and study, as humankind seeks to understand how anthropogenic activities affect marine and terrestrial systems, and to employ ecological understanding in the service of management and conservation imperatives (e.g. Folke 2004, Selkoe 2015).

We argue that the Seward Line is the ideal foundation for a program intended to advance ecological understanding of resilience in high latitude systems. Begun as part of the US GLOBEC program, Seward Line multidisciplinary observations have now occurred at least twice yearly for 20 years (Weingartner et al. 2002, Sousa et al. 2016), with earlier observations at the coastal GAK1 station going back to 1970 (Royer & Grosch 2006). The program, now embedded in a network of nearshore observations extending from Prince William Sound (PWS) to Cook Inlet, is under the support of the Gulf Watch Alaska (GWA) program, a legacy of the 1989 Exxon Valdez oil spill. This extensive observational base has also contributed to a rich modeling legacy for the region (e.g., Coyle et al. 2012, Fiechter et al. 2009, 2011). Yet, ecological research in the NGA is still in an early phase relative to most U.S. coastal regions, and there is much that remains uncertaintylear about the properties that support the region's high productivity and abundant fisheries. The knowledge gained from this and other programs has revealed the importance of the hydrologic cycle to the regional physical environment (Fig. 3D), including salinity-dominated control of water column stratification (Fig. 3D), variable and often heavy cloud cover, frequent storms, and variable timing and magnitude of freshwater discharge (Janout et al. 2010). The NGA is in the midst of long-term changes to regional hydrology (Fig. 4C; O'Neel et al. 2015), leading to potentially complex ecosystem responses including the potential for surpassing resilience capacities and altering the system state. Building on prior knowledge, we conceive three hypotheses centered on the interplay between the hydrologic cycle and ecosystem emergent properties:

1. *Changes in the hydrologic cycle affect spring bloom production through changes in cloud cover, the stratification/mixing balance, macro- and micronutrient supplies, and transport pathways.*
2. *Hot spots of high summer primary and secondary production result from interactions between the fresher ACC and more saline offshore waters as promoted by shelf geomorphology and regional winds; hot spot timing and magnitude will be influenced by changes in the hydrologic cycle.*
3. *Nutritional and life history patterns of NGA consumers minimize trophic mismatch, buffering spatial and temporal variability in lower trophic level production and leading to resilience in the face of long-term climate change in the NGA.*

To investigate ecosystem response to perturbations, and address these hypotheses, our approach to the NGA LTER (Fig. 1B) will consist of:

i) Observing the NGA over long times scales so as to understand the ecosystem responses to major low-frequency climate perturbations and trends;
ii) Conducting process studies in times and places of steepest environmental gradients, to understand short-term ecosystem response to forcing variations, and to experimentally probe the mechanisms by which strong variability promotes high productivity and resilience.
iii) Modeling the effects of perturbation to elucidate the physical and ecological mechanisms that give rise to high productivity, resilience and emergent properties.
iv) Comparing/contrasting NGA resilience responses to those in other marine and terrestrial LTER sites.
v) Disseminating findings through education and outreach

## The NGA environment and ecosystem

**Physical setting** – The deep (200-300 m) continental shelf of the NGA is bounded by coastal mountains inshore and a trench offshore, cross-cut by deep canyons, and linked to numerous complexes of fjords and sounds. Wind stress curl associated with Aleutian Low cyclones drives the Gulf of Alaska subarctic gyre circulation (Wilson & Overland 1986) (Fig. 1D), which consists of the Alaska Current in the eastern Gulf, the Alaskan Stream in the northwestern and western Gulf and the North Pacific Current along its southern edge (Reed & Schumacher 1986, Musgrave et al. 1992, Lagerloef 1995). The North Pacific Current separates the subarctic seas from the subtropical seas, and across this boundary the very nature of water column stratification changes from a thermally controlled system in the south to a freshwater controlled system to the north (Fig. 3D; Carmack 2007). The transition, which occurs near the 10ºC surface isotherm (Reid 1965, Roden 1970, Talley 1993), separates the subtropical (e.g., CCE) and subarctic (NGA) biomes and defines many emergent properties associated with each. In the case of the haline-stratified subarctic system, these include iron-limited high-nutrient offshore waters, the depth of the winter mixed layer, the timing of the onset of spring stratification and the spring bloom, and the presence of the low-salinity Alaska Coastal Current (ACC) (Carmack 2007). Such contrasts make the proposed NGA LTER ideally complementary to the CCE program.

Aleutian Low cyclones promote a strongly downwelling system, wind-induced mixing down to depths of ~100 m during winter, and the delivery of copious amounts of precipitation (2-6 m $yr^{-1}$) to the coastal mountains (Weingartner et al. 2005). Together, downwelling and runoff drive the ACC (Fig. 1D), a wind- and buoyancy-driven flow that represents an important nearshore habitat and an advective corridor carrying fresh water, heat and plankton around NGA towards the Bering Sea (Royer 1982; Luick et al., 1988; Weingartner et al. 2005). In summer the Aleutian Low is displaced by the North Pacific High pressure system, favoring weak upwelling in the mean although energetic storms can occur throughout the year. The runoff of freshwater stems from a limited number of discrete point-source rivers (e.g., the Copper, Kenai, and Susitna rivers), and an extensive network of small flows that contribute about half of the total terrestrial discharge (Royer 1982). Together, they represent one of the largest freshwater inputs to the world's ocean (700-1000 $km^3$ $yr^{-1}$; Royer et al. 1982, Wang et al. 2004, Hill et al. 2015). The runoff includes new precipitation, snow melt, and net glacial ablation (Fig. 3E), which has contributed as much as an additional 60 $km^3$ $yr^{-1}$ in recent years (Ardent et al. 2002, Neal et al. 2010, Beamer et al. 2016), contributing to the long-term freshening of the upper NGA water column (Fig. 4C). Despite the importance of the freshwater cycle in controlling stratification, the coastal flow regime, and the delivery of limiting micronutrients and particulate matter to the Gulf , many fundamental aspects of the freshwater system remain unknown, including freshwater dispersal locations and rates.

Oceanic circulation in the NGA is further impacted seasonally by mesoscale eddies that propagate southwestward along the shelf break (Okkonen et al., 2003; Crawford et al., 2007). These dominantly anticyclonic eddies typically form during winter either on the broad shelf south of Yakutat or further to the southeast on the narrower shelf off Sitka. Years of increased eddy activity in the NGA have been associated with intensified downwelling-favorable wind conditions (Henson & Thomas, 2008; Okkonen et al., 2001). Communication between these eddies and the ambient shelf waters represent an unknown but potentially important conduit for moving nitrate-rich basin waters onto the outer shelf, and for the dispersal of low-salinity, iron-rich coastal waters to the basin (Ladd et al. 2005, Janout et al., 2009).

**Nutrient dynamics** – *Macronutrients:* Winter recharge of nutrients to surface waters of the NGA shelf results from a combination of downwelling, which transports nutrient-rich offshore waters onto the shelf, and deep mixing of nutrient-rich water (Childers et al. 2005). Low frequency climate variability (Fig. 4A) impacts freshwater discharge and sea surface temperature (SST), and as such affects the maximum winter nutrient concentrations. For example, contrasting anomalous SST and freshwater discharge during the 1998 El Nino and 1999 La Nina years (Weingartner et al. 2005) resulted in lower/higher spring nutrients, respectively, along the Seward Line (Childers et al. 2005). Interannual variability in winter nutrient recharge is most pronounced on the inner shelf (Trahavnosky et al. in prep) (Fig. 3B) where the influence of freshwater is greatest. Continued intensification of the hydrological cycle and warming of surface water is expected to influence winter nutrient recharge in the Gulf of Alaska.

The intense spring bloom leads to complete drawdown of nitrate in the inner shelf by summer (Childers et al. 2005, Trahavnosky et al. in prep); nitrate limitation in the mid-shelf is also observed (Fig. 3B, 5D; Strom et al. 2006). The onset and duration of inner shelf low-nutrient conditions is also earlier and longer than in the rest of the shelf. Spatial and interannual variability in nutrient drawdown reflects floristic assemblages along the shelf (Fig. 5D; Strom et al. 2006).

Spatially variable nutrient input in summer results from shelf geomorphology. Canyons in the vicinity of Kodiak Island receive flow of nutrient-rich slope water, which in combination with tidal mixing provides a mechanism for continued nutrient input and sustained high production (Mordy et al. in press). To the east, a semi- permanent eddy feature is observed offshore of Kayak Island (Stabeno et al. in press) that promotes exchange between iron-rich ACC waters and offshore high-nitrate, low-chlorophyll (HNLC) waters. Summer nutrient replenishment to the shelf is promoted by mesoscale eddy-associated exchanges, and by mean weak upwelling.

*Micronutrients:* Although HNLC conditions in the offshore Gulf of Alaska have been shown to result from Fe-limitation (Martin et al. 1989, Boyd et al. 2004), full-blown Fe limitation on the NGA shelf is not expected given the constant (although variable) supply of freshwater. Seasonal and interannual variability in the supply and availability of Fe have been poorly studied in the NGA domain, but some patterns have emerged. Large cross-shelf gradients in reactive iron (i.e. Fe likely available for biological uptake in the timeframe of a season), observed especially in late summer (Fig. 3C) but also in spring, stem largely from rapid removal of labile suspended particulate Fe within the ACC (Wu et al. 2009, Lippiatt et al. 2010, Aguilar-Islas et al. 2016) and the removal of the colloidal fraction of dissolved Fe (Wu et al. 2009). Also observed were gradients in nutrient ratios, with N:Fe ratios being higher in spring and in offshore waters (Aguilar-Islas et al. 2016). Winter mixing enhances the concentration of macronutrients at the surface (Fig. 3B), but due to scavenging of dissolved Fe, insufficient dissolved Fe is supplied in relation to available nitrate, and phytoplankton communities can potentially experience iron stress in the absence of additional Fe sources (Aguilar-Islas et al. 2016). Our observations suggest that offshore of the ACC, the NGA shelf community might experience varying degrees of Fe-stress. Thus variability in Fe dynamics is likely an important influence on rates and composition of NGA planktonic communities.

**Primary and secondary production** – The seasonal cycle constitutes the largest source of variability in NGA primary producer biomass (Fig. 6A; Waite & Mueter 2013, Brickley & Thomas 2004). Seasonal variability is also evident in rates of primary production (Strom et al. 2010, 2016), in phytoplankton community composition, and likely in the ecosystem fate of photosynthetically fixed carbon. The spring bloom is heavily dominated by large chain diatoms, primarily members of the genera *Thalassiosira* and *Chaetoceros* (Strom et al. 2016). As the water column stratifies and nutrients are drawn down in surface waters, diatoms are largely replaced by much smaller photosynthetic flagellates and picocyanobacteria (Fig. 5D). The fall bloom, to the extent that it occurs, comprises mainly small forms as well; we will obtain more detailed taxonomic information on these flagellates from our proposed pigment analyses. Both primary producers (Strom et al. 2006) and secondary consumers (see below) show pronounced cross-shelf gradients (Fig. 5) from more typically coastal to more oceanic species and physiological conditions, reflecting the gradients in dissolved nutrients that characterize this shelf. Superimposed on these seemingly orderly seasonal and spatial patterns are both interannual variability in bloom timing, duration and intensity (Fig. 6A; Henson 2007, Waite & Mueter 2013), and a spatial mosaic of resource regulation and phytoplankton biomass levels (Fig. 3A, 5D). Owing to this spatial and temporal heterogeneity, primary production in the NGA – even during the spring season alone - can be variously limited by light, nitrogen, iron, and grazing (Strom et al. 2006, 2007, 2016). Resource limitation may act synergistically, as well: for example, low light conditions as seen during early spring typically increase phytoplankton Fe demand (Sunda & Huntsman 1997, Maldonado et al. 1999) during a time of year when Fe supplies from freshwater runoff are near their annual low (Fig. 3E).

NGA microzooplankton reflect temporal and spatial gradients in primary producers, with a spring biomass maximum and strong cross-shelf gradients in biomass and body size (Fig. 5E, Strom et al. 2007, submitted). Microzooplankton are key consumers in the NGA ecosystem: studies during the GLOBEC program indicated that they consume approximately half of diatom production, and nearly all of small phytoplankton production (Strom et al. 2007). Little is known, however, about how these proportions are influenced by interannual variability or by mesoscale features in the NGA – our program will investigate this further. Recent data from the Continuous Plankton Recorder program has suggested a long-term decrease in the importance of dinoflagellates in the NGA (S. Batten pers. comm.), and during our most recent field program we found that ciliates usually dominated the microzooplankton community (Strom et al. submitted). Samples from spring 2016 have demonstrated that many of the ciliates on this shelf retain photosynthetically active chloroplasts from their phytoplankton prey (Fig. 6C), likely an adaptation to the episodes of prey scarcity that are a product of the mosaic nature of this shelf ecosystem.

The NGA metazooplankton is dominated by a suite of about 2 dozen species of grazers and a dozen predators, within which we see a full spectrum of strategies for coping with environmental variability. Spring communities are dominated by three co-occurring "oceanic" *Neocalanus* species, while summer communities are dominated by three *Pseudocalanus* species. Initial studies along the Seward Line have already established the grazing rates (Liu et al. 2005, 2008), growth rates (Napp et al. 2005, Hopcroft et al. 2005, Liu & Hopcroft 2006 a,b, 2007, 2008, Pinchuk & Hopcroft 2006, 2007) and production potential (Coyle et al. 2013) of the dominant metazoan zooplankton. Seward Line data over the past 2 decades have fundamentally revised our understanding of zooplankton in the NGA ecosystem, including their degree of cross shelf zonation (Fig. 5B), along with their interannual variability in response to environmental variables (Fig. 7C; Coyle & Pinchuk 2003, 2005, Pinchuk *et al.* 2008, Doubleday & Hopcroft 2015, Sousa et al. 2016). NGA metazooplankton are important prey for foraging species, including even the mucus-net feeding pteropods and larvaceans (Armstrong et al. 2005, Cross et al. 2005). Our LTER program will focus on the dynamics and resiliency of NGA keystone metazooplankton species, as well as patterns of change in the overall zooplankton community in relation to environmental forcing.

**Particulate matter cycling** – The cycling of particulate matter (PM) represents a major vector for carbon, nutrients, sediment, and organisms in the NGA. PM dynamics are controlled by a myriad of physical, biological, biogeochemical processes occurring in the NGA and at its margins. Satellite imagery and recent surveys with in situ optical instruments reveal a dynamic mixture of terrigenous and biogenic particulate matter due primarily to the combined influences of offshore biological production, riverine inputs from land, and the resuspension of bottom sediments (Feely et al. 1979; Turner et al., *submitted*). Concentrations of particles generally increase from offshore to onshore (Fig. 5C), a reflection of the riverine inputs. Vigorous currents, tides, and waves coupled with high PM concentrations make lateral transport of PM important in this region (e.g. Lam et al. 2006), and vertical transports result from biogenic material that is not retained and recycled in the food web of the euphotic zone. This sinking supply of organic matter is responsible for fueling the benthic ecosystems and productive fisheries of the NGA. Although relatively little is known about the biological carbon pump in this region, the magnitude and composition of sinking organic matter fluxes as measured during our LTER will serve as integrative measures of the function and status of the NGA ecosystem.

**Higher trophic levels** – Fish communities in the NGA are dominated by piscivorous demersal species (Conti and Scardi 2010), notably arrowtooth flounder, walleye pollock, Pacific cod, Pacific Ocean perch, and Pacific halibut, whose distribution and abundance reflect major environmental gradients (Fig. 4D; Mueter & Norcross 2002, Gaichas et al. 2011). A range of other flatfish, rockfish, and shellfish (shrimp, crab) contribute to harvested communities, while lipid-rich forage fish (e.g., Pacific herring, capelin, sandlance, eulachon) are important tropic intermediaries for piscivorous fishes and seabirds (Anthony et al. 2000). NGA fishes show a wide range of life history strategies (Doyle and Mier 2012), from late, high productivity spawners that favor shallow spawning habitats to early, deep spawners with low fecundity and a long larval duration. Indeed, on the basis of this range of life history strategies, Doyle & Mier (2012) suggested that Cushing's (1975, 1995) match-mismatch hypothesis might not apply in the NGA. However, these early life history strategies do strongly relate to the response of NGA fish species to environmental forcing and variability (Doyle et al. 2009; Doyle & Mier 2016).

As highly visible apex predators, seabirds, with their different diets and foraging behaviors, link ocean hydrography, chemistry, primary productivity, lower trophic levels, and fisheries (Piatt et al. 2008, Gonzales-Solis & Shaffer 2009). Nearly 50 species use the NGA year-round or seasonally with 8 predominating; thus, our long-standing seabird observations are providing a rich data set showing bird distribution reflects to some extent that of their prey. For example, the piscivorous common murre (*Uria aalge*) is more common inshore, while the planktivorous fork-tailed storm petrel (*Oceanodroma furcata*) prefers more offshore waters. Some of these species appear to be sensitive to interannual variability and long-term change, as reflected in Seward Line and extensive long-term observations within PWS and at Middleton Island (e.g. Hatch 2013, Cushing 2014). Likewise, the NGA is home to iconic populations of marine mammals (especially sea-otters, pinnipeds and whales) that capitalize on the region's productivity, and are closely monitored by a variety of agencies. Many of these populations also show change over time, linked to a variety of natural and anthropogenic factors (e.g., Monson & Bowen 2015, Matkin et al. 2014, Hui et al. 2015).

## Ecological Framework

The conceptual framework for the NGA LTER is:
***Intense environmental variability leads to high resilience in the northern Gulf of Alaska***

**Theory** – The concept of ecological resilience dates formally from the seminal work of Holling (1973), and has great contemporary relevance for understanding how ecosystems respond to disturbance (ranging from stochastic short-term perturbations to long-term climate change), as well as how ecosystem utilization by humans might be managed in such a way as to retain key ecosystem services (e.g. Hughes et al. 2005, Selkoe et al. 2015). We define resilience sensu Levin & Lubchenco (2008) as "the amount of change or disruption that is required to transform a system from being maintained by one set of mutually reinforcing processes and structures to a different set of processes and structures". Further, we distinguish resilience (the propensity to return to a set of key functions and properties after disturbance and change) from stability (the propensity to resist change) (Holling 1973, Gunderson 2000). The long-term, comparative nature of the LTER network is an ideal setting for investigation of resilience (e.g., Peters et al. 2011); we argue that inclusion of NGA in the network will add exciting opportunities for advancement of resilience theory as well as its application to endeavors such as modeling future climate change scenarios and developing ecosystem-based management tools.

Like all complex adaptive systems, the NGA includes elements predicted to increase resilience, and others that are widely believed to decrease this capacity. Among the latter are the NGA's relatively low biodiversity (Fautin et al. 2010), episodically short food chains (Ruzicka et al. 2013), and instances of strong top-down control within the food web (Liu et al. 2005, Mueter & Norcross 2000, Shimoto et al. 1997). However, past ecosystem responses to strong perturbations (see below) support the hypothesis that the NGA is a particularly resilient ecosystem. We suggest that this property ultimately arises as consequence of the region's latitude and unique geomorphology, which promote intense environmental variability and lead to a spatial and temporal mosaic of conditions, resources, and ecosystem properties.

Environmental variability in the NGA arises at both predictable (e.g., strong seasonality) and stochastic (e.g., dramatic weather events, climate regime shifts) frequencies (Fig. 2). As well, the complex physical setting leads to a high degree of spatial heterogeneity (Fig. 3A). This temporal and spatial mosaic, we believe, has promoted adaptations leading to high resilience (see below). This follows closely the reasoning of Holling (1973, 1996), who argued that it is instability itself (large fluctuations in space and time) that leads to the evolution of highly resilient systems, through various mechanisms that increase flexibility and promote a return to a given stability domain (Fig. 1C; Gunderson 2000). We believe a broadly comparative approach, such as that afforded by the LTER network, is essential to deepening understanding of resilience in ecological systems, while the long-term framework allows investigation of specific attributes contributing towards resilience.

**Defining resilience: emergent properties** – Essential to determining the ecosystem response to disturbance, and to assessing resilience, is defining the "set of mutually reinforcing processes and structures" (Levin & Lubchenco 2008) that constitute the critical elements of the NGA ecosystem in its present form (Table 1). The past decade and a half of study has given us the ability to create such a definition:

**Table 1**. Emergent properties of the NGA, their significance and means of assessment

| Emergent property | Significance | Assessment |
|---|---|---|
| Pronounced spring bloom | Largest annual phytoplankton biomass & production signal | Satellite ocean color; *in situ* chlorophyll; primary production |
| Regions of sustained high summer production | Predictable 'islands' of biomass during low production season | Satellite ocean color; in situ chlorophyll; primary production |
| Stable base of energy-rich zooplankton grazers | Buffer and stabilize interannual variability in primary production | Abundance and taxonomic data; production, lipid content |
| Substantial sinking flux of organic matter | Fuels benthic communities | Sediment traps; LISST-DEEP & UVP5 optical particle sensors |
| Efficient transfer of primary production to higher trophic levels | Supports high production of fish, birds, mammals | Biomass ratios among trophic levels; feeding experiments |

These emergent properties arise from particular species assemblages and their interactions: large (mainly chain-forming) diatoms in spring, chloroplast-retaining ciliates; large lipid-rich zooplankton with characteristic life histories; an assemblage of forage fish species. Our LTER project is designed to assess the contributions of these critical ecosystem elements to the overall community in the face of spatial and temporal heterogeneity on a variety of scales. Identifying the conditions that promote NGA emergent properties and associated communities, as well as those that lead to other stability domains, will increase our ability to understand resilience and to predict the consequences of environmental change in this and other coastal marine ecosystems.

**Achieving resilience: adaptations** – *Species level: Life history variability and nutritional plasticity:* Present-day plasticity in zooplankton feeding and life history responses suggests a genetic repertoire capable of adjusting to variable environmental conditions in the NGA. Life history plasticity has been best studied in the large copepod genus *Neocalanus*, whose life cycle (Fig. 7B) exemplifies a "bet hedging" strategy: reproduction occurs at depth during winter (fueled by lipid stores from the prior year) and spawning occurs over a 4-6 week interval, such that first-feeding stages can stagger arrival times and persist in surface waters in anticipation of the variably-timed spring bloom (Miller & Clemons 1988). For *N. plumchrus*, life cycle timing (the period of peak abundance in surface waters) can vary by up to two months in a manner linearly related to upper ocean heat content (Fig. 7A); additionally, there is evidence that exceptionally warm years may result in a second seasonal cohort, a reproductive strategy more akin to that of the North Atlantic dominant, *Calanus finmarchicus* (Mackas et al. 2007). A similar bet-hedging strategy (long-lived larvae, winter spawn) appears to characterize a number of NGA fish species, including Pacific sand lance and capelin (both important forage species). In general, though, NGA fish species show a range of life cycle strategies, and tend to group, in their temporal fluctuations, according to endpoint strategies as identified by PCA ordination (e.g., timing, ubiquity, fecundity; Doyle & Mier 2012). The relationship between these various strategies and resilience is an on-going research area to which our program will contribute.

Nutritional plasticity – the ability to feed omnivorously on a wide range of particle types – has been seen for major copepod taxa *Neocalanus* (Liu et al. 2005, 2008), *Calanus marshallae*, *Metridia pacific* (Padmavati et al. 2004) and *Pseudocalanus* spp. (Cleary et al. in press). *Pseudocalanus* and *Metridia* in particular may employ omnivory to avoid food limitation and sustain active spawning over the entire NGA production season (Napp et al. 2005, Hopcroft et al. 2005). Summer dominant zooplankton *Pseudocalanus*, *C. marshallae*, and *Metridia* are important prey for a range of fish species including juvenile pink salmon, age-0 pollock, and other forage fish (Kendall et al. 1987, Wilson et al. 2006, Armstrong et al. 2008). However, little is known about how diet in these copepod species responds to low production, small particle-dominated summer prey communities. One key may be large ciliates, which can be important contributors to microzooplankton biomass during low productivity periods. This mixotrophic strategy (Fig. 6C), in which chloroplasts from ingested phytoplankton prey are retained for days to weeks while photosynthetically fixed carbon is transferred to the ciliate 'host', is an adaptation allowing particle-feeding ciliates to bridge periods of low prey availability (Stoecker et al. 2009), as well as effectively transforming small photosynthetic prey into larger photosynthetic cells..

*Community level: Functional redundancy*

Differences in the NGA's three *Neocalanus* life histories (Miller et al. 1984, Miller & Clemons 1988) raise the potential for resilience in this genus overall. In brief, the species differ in their stage of diapause, timing of arrival in surface waters, first feeding life-stage (Saito & Tsuda 2000), and habitat preference (surface mixed layer vs intra/subpycnocline - Coyle & Pinchuk 2005). This difference in depth results in both *N. plumchrus* and *N. flemingeri* being carried further across the shelf by the spring downwelling favorable winds, while *N. cristatus* remains most abundant in offshore waters. All three species grow rapidly (Liu & Hopcroft 2006), begin showing accumulation of storage lipids during the 3rd copepodite stage, and spend a protracted period accumulating substantive lipids stores during the 5th copepodite stage (Tsuda et al. 1999, 2001). Together these factors result in a sequence where *N. flemingeri* copepodites appear first and show a consistently more advanced life stage than their congeners, allowing them to descend first while *N. cristatus* remains in the upper water column feeding during July (Coyle & Pinchuk 2005). Environmental variability likely yields differential success of each *Neocalanus* species, with their functional redundancy resulting in a relatively stable biomass of large copepods during spring and early summer from year to year.

Year round, the NGA neritic habitat is numerically dominated by several *Pseudocalanus* species (Frost 1989), whose strategy appears to be slower growth but similar development times as found for the larger copepods (Liu and Hopcroft 2008b). Compared to larger species, these egg-carrying copepods seldom appear to be food-limited, with active and sustained spawning occurring over the entire productive period (Napp et al. 2005). Thus, like the *Neocalanus* species, *Pseudocalanus* may be somewhat uncoupled from concurrent resource availability, buffering variability in the ecosystem. Regional differences occur in the relative mixture of species both across the NGA shelf (Napp et al. 2005) and throughout the subarctic Pacific (e.g. Yamaguchi & Shiga 1997, Bailey et al. in press), reflecting differences in habitat/food preference (Cleary et al. in press) and thermal optima (Ershova et al. accepted). Contrary to expectation, we find that even in this genus, some late-stage copepodites accumulate lipids and descend to depth during fall, while others remain active in the surface layers (Hopcroft, unpublished), life history attributes that further contribute to resilience within the NGA.

Euphausiids appear to show similar redundancy, with two of the five *Thysanoessa* species co-dominant in the NGA. The 5 species show cross-shelf habitat preferences and different responses to climate trends and variability (Pinchuk et al. 2008). In warm years, the NGA can be flooded with the

California Current species *Euphausia pacifica* (Pinchuk et al. 2008), while in colder years the more arctic *Thysanoessa raschii* penetrates outward from its glacial refugia in the coastal fjords (Hopcroft, pers, obs.).

*Ecosystem level: Connectivity*
The position of the NGA with respect to global- and basin-scale ocean circulation pathways not only contributes to environmental variability, but also gives rise to a high degree of connectivity among marine biogeographic provinces. Inland fjords harbor glacial relict populations of species found mainly at higher latitudes (Questel et al. in press). Work with the copepod genus *Pseudocalanus* (Questel et al., in press) indicates connectivity between the Arctic (e.g., Beaufort and Chukchi Seas), the Bering Sea and the Gulf of Alaska. Both these pathways are supported by circulation studies describing mean northward but episodic southward transport from the Arctic into the Bering, and from the Bering into the GOA (Mordy et al. 2005, Ladd & Stabeno 2009). Transport of species into the NGA from further south occurs regularly (e.g., Wing 2006, Mackas et al. 2007), although physical transports are variable because of their links to climate state through wind and density gradients. Over the past 20 years, our observations show that a number of California Current species appear in the NGA in warmer years, with particularly strong signal arising as a result of the "blob" (Fig. 6D). Although this signal is small in relation to the overall zooplankton community, obvious questions arise about the frequency and magnitude of such events, and whether they will have an appreciable impact on the NGA ecosystem should warm events become more common. A high degree of connectivity among populations, communities and ecosystems can increase resilience by enhancing recruitment, by reducing the risk of local extinction, and by providing potential material, energy, and genetic subsidies (Bernhardt & Leslie 2013). However, highly connected ecosystems are at once more experienced with, and more susceptible to, invasions by exotic species. Trade-offs among these factors with respect to resilience are likely to depend on the magnitude and frequency of disturbance events (Bernhardt & Leslie 2013).

**Perturbation and system response in the NGA** – *Spring bloom failure of 2011:* Spring of 2011 in the NGA saw one of the lowest bloom intensities in recent decades, as estimated from shipboard chlorophyll measurements and remote sensing (Stabeno et al. 2016, Waite & Meuter 2013). Depressed phytoplankton photosynthetic parameters and growth rates (Strom et al 2016) indicated a physiological (bottom up) component to this bloom failure. Simultaneously, moderate macronutrient drawdown indicated removal of production from the system by top-down processes, perhaps including grazing by unusually abundant salps (Li et al. 2016). Although the ultimate environmental drivers of this failure remain unclear, we suspect a synergistic relationship between light and iron availability, the latter potentially related to late freshwater runoff (Aguilar-Islas et al. 2016, Strom et al. 2016). Spring bloom process cruises are designed to give us greater insights into the regulation by multiple factors of the crucial spring primary production peak. Meanwhile, however, the 2011 failure provides a window into ecosystem resilience. Spring abundances of microzooplantkon and small copepods were extremely low, while *Neocalanus* abundances were near normal. However, only a few lower trophic level effects propagated beyond spring – for example, unusually high proportions of ciliates in the microzooplankton (Strom et al. submitted) - while small copepod communities appeared to have completely recovered by fall (Hopcroft unpublished). In contrast, some striking effects of nutritional deficiency were seen at higher trophic levels, including low abundance of forage fish, early season seabird reproductive failures, and mushy halibut syndrome (Zador 2012). However, subsequent year-classes of dominant demersal fish species show little or no effect of this low production event (Stock Assessment Results Archive, AFSC, NOAA Fisheries). LTER hypotheses and research plans explicitly address the mechanisms by which the NGA ecosystem compensates for large variations in spring primary production.

*The blob:* An extreme warming event in North Pacific, termed "the blob" in both the popular and scientific press, was associated with an unusually stable atmospheric high pressure system (Bond et al, 2015) and tropical-extratropical teleconnections (Di Lorenzo & Mantua 2016) that enabled weaker-than-normal NE Pacific cooling over the course of the 2013-14 and 2014-15 winters. Warming associated with this large-scale feature and the extremely strong 2015-16 El Nino was observed along the Seward Line beginning in 2014 and lasting through at least early 2016. This warm event was associated with harmful algal blooms (e.g., the domoic acid producer *Pseudo-nitzschia*), most intensely off the California coast, but extending as far north as Kachemak Bay, Alaska (inshore of the NGA study region; Di Liberto 2015). As well, southern nekton species appeared in GOA waters, including the ocean sunfish, and blue and thresher sharks (Cavole 2016). Alaska also saw die-offs of common murres in unprecedented numbers, apparently due to starvation (USFWS Seabird die-off fact sheet 010716). However, GOA chlorophyll anomalies associated with the warming were minimal (Cavole 2016), and so far there have been few obvious effects on NGA mesozooplankton abundance. We anticipate following the ecosystem effects of this warm anomaly into the future as data on other food web components become available, and attempting to understand the stability and resilience responses that result.

*Low Frequency Climate Variability*: The 1976/77 Pacific Decadal Oscillation (PDO; Mantua et al. 1997) transition event (Fig. 4A) triggered an ecosystem "regime shift" in the Gulf of Alaska that resulted in a change from a shrimp and crab-dominated fishery to one dominated by pollock, salmon and halibut (Fig. 4B; Anderson & Piatt 1999, Beamish & Bouillon 1993). This transition to the warmer phase of the PDO and subsequent basin-scale biological restructuring illustrates the importance of abrupt change as driver of ecosystem variability in the NGA. The late-70s shift seems to have initiated long-term declines in some seabirds, with planktivorous and piscivorous species the most affected (Hatch 2013, Cushing 2012), likely due to limitations in prey availability (Jodice et al. 2006, Kitaysky et al. 2010). The ecological regime shift initiated in the 70's was aided by a subsequent period of stability of the "new" climate state (Litzow & Mueter 2014). In contrast, major ecosystem reorganizations have not followed more recent PDO shifts (e.g., 1988/89, 2007/008), although these appear to have been initiated by similarly large pulse disturbances (Litzow & Mueter 2014). The warming and freshening trends in surface waters of the North Pacific over recent years (Fig. 4C) might have contributed to the apparent resistance of the system to transitioning into an alternate ecological state following these later PDO transitions. Although ecosystem responses to low-frequency climate variability are clearly complex, we believe that questions regarding their impact will be more approachable given the LTER framework we propose to adopt. Two possible approaches, both of which will inform questions about resilience across trophic levels, are i) examining abundance time series of adjacent trophic levels for evidence of synchrony and/or functional complementarity, properties hypothesized to affect community-level resilience (e.g. Lindgren et al. 2016); and ii) scaling to generation time when examining the nature of responses to environmental forcing (e.g. Bestelmeyer et al. 2011), so that disturbance responses of long-lived species such as fish and some seabirds can be more realistically compared to responses at lower trophic levels.

## Approach of the NGA LTER

Past research in the NGA has led to a highly leveraged, cooperative network of observational platforms on which the NGA LTER will be built. As well, some of the first-ever lower trophic level process studies in the region were conducted in the early 2000s, providing glimpses into the mechanisms by which this ecosystem's stunning productivity is maintained. As a consequence of these efforts, we now recognize that intense variability across a range of scales is a hallmark of this system, and likely a major driver of species- and community-level adaptation. The resilience framework we propose for the NGA LTER will provide a common lens through which to view and interpret responses to environmental perturbation across a range of scales: from individuals through communities; from lower to higher trophic level, and from short to long time and space scales.

Building on prior knowledge, we identify three hypotheses centered on interplay between the hydrologic cycle and ecosystem emergent properties:

1. *Changes in the hydrologic cycle will affect spring bloom production through changes in cloud cover, the stratification/mixing balance, macro- and micronutrient supplies, and transport pathways.*
2. *Hot spots of high summer primary and secondary production result from interactions between the fresher ACC and more saline offshore waters as promoted by shelf geomorphology and regional winds; hot spot timing and magnitude will be influenced by changes in the hydrologic cycle.*

*3. Nutritional and life history patterns of NGA consumers minimize trophic mismatch, buffering spatial and temporal variability in lower trophic level production and leading to resilience in the face of long-term climate change in the NGA.*

These hypotheses are focused on areas that i) are poorly understood; ii) are likely to strongly influence production at multiple trophic levels; and iii) constitute strong environmental gradients in time and space, against which ecosystem response can be observed. H1 & H2 relate specifically to the hydrologic cycle, which is in the process of dramatic change in the NGA, while H3 postulates a specific strategy by which ecosystem resilience is achieved in the face of strong environmental variability. Our research program (described in detail below) has been designed specifically to test these hypotheses. Process work, modeling, and in-depth observation will be conducted in spring bloom and summer river plume environments, where productivity is likely high because environmental conditions bring together multiple resources from the mosaic that characterizes the NGA, and because environmental variability uncouples production and loss processes, allowing for biomass accumulation. Thus these high production events represent disturbances, quasi-predictable but with a strong element of stochasticity in their timing and intensity, against which species and community resilience can be tested. Long-term observation of the NGA affords us the opportunity to examine the response of longer-lived species and slower successional processes, and to relate annual and inter-annual variability to longer-term climate forcing, including secular trends (e.g., warming, freshening) and infrequent but major perturbations and shifts (e.g., ENSO, major climate shifts).

Our linked system of modeling, observation and experimentation will provide a robust test of system resilience, one that may be directly compared with findings from other long-term research sites, and that will develop our mechanistic understanding of the processes that underlie the high production levels of this unique ecosystem. Across all of the NGA study scales, our goal is to observe how emergent properties relate to disturbance, and to relate emergent properties to underlying organism capabilities and community behaviors; in this way we anticipate being able to relate adaptations across a range of scales to resilience responses in the NGA. While the ideal study would encompass trophic levels from bacteria to whales, our focus in this initial funding cycle will be on lower trophic levels. These are tractable to assessment by shipboard transect studies and remote sensing, respond on shorter time scales to environmental perturbation, and constitute the essential base of the food web in this relatively understudied region of the northern coastal oceans. Links to fish biology and ecology will be through our long-time NOAA colleagues (see LOI) and their wealth of relevant data and knowledge.

**NGA Connections to Other Programs** – The NGA's location on a productive continental shelf lends itself naturally to cross-site comparisons within LTER, in particular with the California Current (CCE) and Antarctic Peninsula (PAL) sites. While these share certain features with the NGA (deep shelf; narrow, intense coastal current; seasonally productive, large crustacean zooplankton as keystone species), they contrast strongly in other ways, including presence/absence of ice, freshwater flux, oxygen saturation, degree of seasonality, and regulation of primary production (e.g., by light, nitrogen and iron). This matrix of similarities and differences gives rise to tantalizing possibilities for hypothesis testing in terms of climate change effects on ecosystem structure and function. Indeed, these general locations (along with a 4th, Georges Bank), constituted the U.S. GLOBEC network of sites, chosen for their ability to inform comparative investigations of oceanographic effects on zooplankton population dynamics. Cross-site comparisons yielded insights into key common properties, such as the role of horizontal advection in delivering key resources and organisms (Di Lorenzo et al. 2013) and led to development of comparative end-to-end models (Ruzicka et al. 2013). The LTER framework will allow for a new, ecologically focused generation of cross-site comparison activities, from the role of specific climate perturbations (e.g., ENSO events) on ecosystem structure and function, to broader questions such as the ecosystem properties that give rise to thresholds and 'tipping points' in responses to disturbance and long-term climate change.

Exciting possibilities also exist for comparisons with the two terrestrial LTER sites in Alaska, Bonanza Creek (boreal forest) and the Arctic (tundra), particularly in the context of the resilience framework proposed here.. Both have as their focus the role of climate change in altering the ecosystem, through direct effects (e.g., warming) and increases in disturbance (e.g., hydrological changes, fires, pathogens). Our research encompasses many of the same concepts, and will likely experience similar regional forcing (Black 2009), but in a marine context. This terrestrial-marine contrast has the potential to generate novel insights into the fundamental mechanisms by which ecosystem resilience and/or reorganization results from climate change, and how those mechanisms are modulated by terrestrial versus marine organism and ecosystem properties.

**LTER Core Areas in the NGA**

*1. Patterns and controls of primary production*: Primary production rates will be measured directly on all project cruises, yielding estimates for spring, summer and fall. Primary production will also be estimated from satellite ocean color, and can be extrapolated from chlorophyll data in surface waters (e.g. Strom et al. 2016). Controls on primary production (light, micro- and macronutrients, grazing, sinking) will be assessed directly through resource/grazing manipulation experiments and particle dynamics measurements conducted mainly on process cruises; indirectly, by relating the above measures of primary production to data on grazer abundance and environmental condition; and through modeling studies that examine the influence of various freshwater input scenarios on the along- and cross-shelf distribution of limiting nutrients (nitrate and iron) and phytoplankton community structure and production.

2. *Spatial and temporal population dynamics and food web interactions*: Sampling is explicitly designed to capture the spatial and temporal dynamics of key populations in the NGA, including phytoplankton, zooplankton of various sizes and trophic levels, and fishes at life stages from larval through adult. Bird observations are part of all cruises. Food web interactions will be assessed indirectly through comparison of species abundance variations, and directly through experiments on process cruises. These will provide insight into top-down control of phytoplankton biomass (through measured micro- and metazooplankton grazing rates) and influence of the prey community on secondary production (through measures of zooplankton condition and egg production rates). Time-series sediment trap measurements on the GOA shelf will provide an integrative metric of food web status and export production from the NGA ecosystem. Ensemble calculations with the ecosystem model will be used to characterize the spatial and temporal scales at which small differences in environmental and diet preferences among sibling species (e.g., *Neocalanus*) affect the planktonic community structure under various oceanographic conditions.

3. *Patterns and controls of organic matter accumulation and decomposition*: Concentrations of DOC and suspended POC will be routinely measured on all cruises. The accumulation and export flux of particulate organic matter throughout the year will be assessed by combining time series sediment trap measurements with direct collection and in situ optical measurements of PM. Particulate organic matter observations will be assessed as a function of particle size. Taken together, observations of suspended and sinking organic matter will allow us to examine seasonal cycles of organic matter accumulation and removal from the upper water column, and to relate these to seasonal cycles of primary and secondary production and their environmental drivers. A long-term (~20 years) integration of the ecosystem model will provide a baseline solution for identifying the dominant physical and biological processes that control vertical and lateral export of organic matter on seasonal to interannual time scales.

4. *Patterns of inorganic inputs and movements of nutrients*: Dissolved inorganic macronutrient concentrations will be routinely measured on all cruises. Deep concentrations as measured on spring cruises will provide estimates of nutrients supplied to the ecosystem through late winter deep mixing, the most important source of macronutrients fueling the spring bloom. Spatial variability in nutrient concentrations during summer and fall cruises will elucidate mechanisms for post-bloom nutrient pumping onto the shelf. Iron size classes, chemical speciation and particle reactivity will be routinely measured in surface waters during survey cruises. Process cruises will provide the opportunity to measure

these iron species throughout the water column, and in perturbation experiments. In situ optical measurements and the investigation of PM on the LTER process cruises will enable us to assess the inputs, spatial patterns, and influence of lithogenic PM and its associated nutrients supplied by rivers and resuspension. As changing climate conditions are expected to significantly alter river discharge, the modeling component will focus on producing numerical solutions that reliably reproduce the physical (i.e., buoyancy gradients) and biogeochemical (e.g., iron delivery) processes associated with freshwater input at the coast. These simulations will in turn be used to characterize past, present and future variability of the along-shelf and cross-shelf distribution of limiting nutrients.

5. *Patterns and frequency of disturbances*: We will use a variety of observational and hindcast modeling methods to characterize disturbance in the NGA across a range of scales. Meteorological observations from NODC buoys and land-based stations (Fig. 1A) will provide data on cloud cover and wind speeds, which will allow us to identify and characterize surface irradiance levels and individual mixing events, respectively. The mid-shelf mooring will provide a high-frequency and multi-disciplinary view of the marine ecosystem from a single location, while PAR and ocean color data from remote sensing will provide a basin-scale view of irradiance and phytoplankton variability. Up- and downwelling events and the wind-driven flow field can be assessed using the Bakun upwelling index and atmospheric reanalysis products. Runoff timing and intensity will be assessed from individual USGS gauging stations on larger rivers (e.g., Copper River), while amalgamated estimates will be obtained from the D. Hill terrestrial discharge modeling effort proposed here. Size, location, intensity and frequency of mesoscale eddies and Alaska Current flow field variations will all be obtained from satellite altimetry products. Unusual warm and cold events will be evident from our shipboard and mooring observational program (Fig. 1A) in conjunction with Gulf Watch and other partner agency-collected observations. Larger-scale disturbances such as El Niño/La Niña events and potential ecosystem regime shifts will be tracked through the use of readily available climate and atmospheric structure indices including the PDO, NPGO, ENSO, PNA and NPI. The ecosystem model will be used to systematically explore how changes in the timing and magnitude of peak river discharge impact spatiotemporal gradients of limiting nutrients and planktonic community structure under various oceanographic conditions (e.g., weak, normal, and strong mesoscale eddy activity).

## Research Plan

**Long-term observations: Core program** – *Existing shipboard studies:* The Seward Line Program consists of 15 primary and 9 secondary stations along the Seward Line, and 12 stations PWS sampled in May and early September from the USFWS research vessel *Tiglax* (Table 2). The sampling program is designed to capture the major gradients in lower trophic level production, over the long time frame appropriate for investigation of low-frequency climate effects. This design, with added LTER elements (see below) will allow us to investigate the mechanisms by which variations in physical and chemical conditions translate into changes in the composition and abundance of organisms in the planktonic food web, and through collaborations, how fish (Duffy-Anderson & Shotwell, NOAA) and seabirds (Kuletz, USFWS) integrate and reflect these changes. The first-order driver of production variability is the intense seasonality of the system (Brickley & Thomas, 2004; Waite & Meuter, 2013). Seward Line cruises over the past 20 years capture the major spring-late summer gradient in this seasonality, while retaining a focus on important periods for the life cycles of various key zooplankton species. The early May period captures the peak productivity associated with the spring bloom. The consistent timing of the May cruise has allowed us to look at variation in nutrient delivery (Trahanovsky et al. in prep), as well as phenological shifts (i.e., Mackas et al. 2012) in the large *Neocalanus* copepods that dominate the spring (Fig. 2; Hopcroft & Coyle, in prep). September cruises capture the end of the low-productivity oceanographic summer, when nitrate is depleted and smaller phyto- and zooplankton dominate prior to the stormy fall overturn. Changes in the microzooplankton community and lower trophic level food web efficiencies appear to accompany this seasonal gradient (Strom et al. accepted), while changes in iron speciation (Aguilar-Islas et al. 2016) indicate seasonal differences in iron sources to the NGA.

**Table 2.** Proposed cruise schedule and cruise focus for NGA LTER, by season and year:

| | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|
| **Spring** (Apr/May) | Survey | Process: *spring bloom* | Survey | Survey | Process: *spring bloom* | Survey |
| **Summer** (June) | Process: *river plume* | Survey | Mooring | Process: *river plume* | Survey | Mooring |
| **Fall** (Sept) | Survey | Survey | Survey | Survey | Survey | Survey |

Oceanographic sampling methodology has remained stable since sampling began in the fall of 1997 (Weingartner et al. 2002), although the logistics of vessel availability (*R/V Tiglax*) has pushed summer sampling from mid-August to early/mid-September. All hydrographic and bottle-based work is conducted during the day (911 CTD, DIC, macronutrients, chlorophyll a, phyto-and microzooplankton composition/biomass), as well as collection of the smaller zooplankton species (150µm Calvet net) that do not migrate vertically and do not avoid collection. Since 2014, optical measurements of the particle size distribution (2.5 µm – 2.5 cm) have been conducted in conjunction with CTD rosette casts using an integrated Underwater Vision Profiler 5 (UVP5) and Laser In Situ Scattering and Transmissometer (LISST). Seabird and mammal observations are made during station transits. At night, sampling is conducted for the larger and more mobile zooplankton (500 µm Multinet), many of which can only be sampled efficiently during their daily migration toward the surface under the cover of darkness. Although this protocol results in some backtracking along the transect line, it ensures that all stations can be employed in analysis without biases arising from diel cycles.

*New LTER sampling:* We propose addition of new cross-shelf lines to the survey work that will inform on cross-shelf as well as alongshore gradients and influential features. The new eastern-most "upstream" lines are designed to capture offshore steering of fresh, iron-rich ACC waters across the shelf break, as well as the Copper River plume, a key source of freshwater, sediment and iron to the NGA. A new "downstream" line to the west of the Seward Line crosses shallow banks representing production hot spots in the northern Gulf (Coyle et al. 2012, 2013). We propose additional data collections that include micronutrient sampling (Aguilar-Islas et al. 2016), primary production using stable isotopes (Hama et al., 1983), dissolved organic carbon (DOC), and optically-derived particle size-spectra/flux using a LISST and UVP5 (Guidi et al. 2008, Picheral et al. 2010). These new efforts will add ca. 8 days to each of the existing Gulf Watch *Tiglax* cruises. During early summers with no process cruises, new observational cruises will be undertaken (Table 2), so that we gain a long-term view of this period when freshwater input ramps up, *Neocalanus* copepods leave the surface waters, and smolt salmon begin to enter the NGA from freshwaters.

**Moorings - Core program** – A mooring measuring T and S hourly at six depths has been deployed at Seward Line station GAK1 since 2000 (Janout et al. 2010). We propose to deploy an additional but more highly instrumented mooring on the mid/outer shelf (Fig. 1A). This mooring is one of a trio of similarly instrumented moorings planned for each of Alaska's three large marine ecosystems (Arctic, Bering & NGA) as part of AOOS's ecosystem monitoring capacity build-out plan (McCammon 2013). Assistance with mooring equipment purchases is anticipated from AOOS. Similar to the Chukchi Sea mooring (http://mather.sfos.uaf.edu/~seth/CEO/), we will obtain the following measurements: water velocity, directional wave spectra, particle size spectra and concentrations, pressure, temperature, conductivity/salinity, photosynthetically available radiation, colored dissolved organic matter, optical backscatter, nitrate, pH, $pCO_2$, chlorophyll *a* fluorescence, passive acoustic recordings, active acoustic volume backscatter at 38, 125, 200 and 255 KHz. In addition, the mooring will have a 24-bottle sediment trap (see above Particulate Matter section).

**Process Studies** – We propose process-oriented research activities on UNOLS vessel cruises during two spring and two summer periods (Table 2). We plan to target two key mesoscale features that represent potentially important drivers of production, while remaining poorly understood in the NGA: *the spring bloom and river plume dynamics*. Experimental and in-depth observational studies across these features will constitute an important aspect of our investigation of ecosystem resilience, as we focus on the response of emergent properties to natural and experimentally generated gradients and perturbations. Also, these features in the present-day ecosystem represent a space-for-time substitution and can provide insight into probable ecosystems structure and function in response to projected climate variability. We anticipate shifting our focus to other significant features (e.g., production 'hot spots' associated with shallow banks or mesoscale eddies) during future funding cycles. Process studies will consist of 3-week oceanographic cruises, on the UAF-operated *R/V Sikuliaq*. This vessel's capabilities will allow for increased personnel, including students, more sophisticated instrument deployments, and *in situ* and deckboard experimental studies.

1) ***Dynamics of the spring phytoplankton bloom***. This single largest yearly accumulation of primary production extends throughout the NGA domain. We will target the Seward Line region, where the breadth of the shelf facilitates the study of cross-shelf gradients in phytoplankton community structure, and will extend investigation into the slope region, where episodically eddies and associated filaments impact the boundary with HNLC waters and influence water column dynamics, as well as the nutrient supply and species composition of the outer shelf.

The April/May timing targets oceanographic conditions at the initiation and development of the spring phytoplankton bloom. Previous studies have yielded initial insights into processes governing this key annual event (Henson 2007, Strom et al. 2006, 2007, 2016) but fundamental aspects remain poorly understood. These include the magnitude and variability of organic matter fluxes to the benthos (assessed using a combination of particle observations during LTER); regulation of primary production jointly by light and iron (assessed using manipulation experiments during LTER); and variation in the transfer of primary production to higher trophic levels (assessed with grazing experiments during LTER). In addition, the fundamental 'critical depth' model by which bloom initiation is commonly understood (i.e., the establishment of water column stratification and consequent increase in light availability; Sverdrup 1953) has recently been re-examined (Behrenfeld et al. 2013), including in the western subarctic Pacific (Shiozaki 2014). Coupling our intensive process cruise observations with modeling will allow us to test different conceptual models of bloom initiation in the NGA (e.g., critical depth, critical turbulence, dilution-recoupling; Fischer et al. 2014), and to relate these to changes in the hydrologic cycle. The mosaic of physical and biological conditions we will encounter (Fig. 2, 3A), including variation in the nature of resource limitation of primary production and in the composition of the primary producer community, will provide a testbed for the study of resilience on shorter time and space scales. Proposed experimental work (described below) will specifically target individual, population and community behaviors that we hypothesize will contribute to resilience in the NGA, including nutritional and life cycle plasticity. We will assess nutritional plasticity through properties that vary in response to environmental gradients: i) abundance of mixotrophic microzooplankton; ii) microzooplankton community grazing rates on different components of the phytoplankton; iii) egg production rates and lipid accumulation in mesozooplankton; iv) mesozooplankton diets. Life cycle plasticity will be assessed by monitoring the timing and development of *Neocalanus* with respect to bloom timing. Throughout, our measurement of emergent properties will guide our assessment of the degree to which the ecosystem remains stable or exhibits resilience in the face of environmental perturbations.

2) ***River plume dynamics***. The large input of freshwater into the Gulf is largely constrained to the ACC, and affects production by contributing to variability in the supply of iron, silicate, sediment and buoyancy. Our summer process cruises will target the Copper River plume, the largest point source of fresh water to the NGA, and the topographic steering of the ACC by Kayak Island, which is thought to promote enhanced exchange between the low salinity ACC and offshore waters (e.g., Stabeno et al. 2016). These are likely crucial feature to the maintenance of summer production through a variety of physical and chemical effects on the ecosystem, and are anticipated to be highly sensitive to changes in

timing and magnitude of freshwater inputs. The Copper River plume also provides some of the strongest environmental gradients in the summer ocean (Fig. 2), against which we can test community resilience and response. As well, these cruises will encompass the spring-summer transition during which we anticipate seeing shifts in the nature of the the phytoplankton resource limitation in different domains, in the composition and activity of the micro- and mesozooplankton community, in the particle flux regime, and in the relative importance of wind and buoyancy to alongshore flow with consequences for nutrient input. June is also a pivotal time to assess the status and life cycle timing of *Neocalanus* as they complete their annual accumulation of lipids and begin to enter to deep-water diapause. Assessments of nutritional plasticity, life history variability, and ecosystem emergent properties will parallel those described for spring bloom cruises.

*In-depth observational work:* Process cruises will deploy an Acrobat undulating towed vehicle equipped with a FastCat CTD and Wetlabs ECO-Triplett sensors with Fluorescence, OBS and CDOM, and a SUNA nitrate sensor. The Acrobat can be towed at ca. 6-8 knots and sample down to ca. 80 m depth, with the *R/V Sikuliaq* providing underway hydrography, meteorological, sea-chest and ADCP current data. The Acrobat will allow us to capture truly synoptic section transects with very high resolution and allow us to adaptively adjust our process cruise station locations to optimally target the plume, front or other features under investigation. Satellite-tracked drifters will be deployed to track features (e.g. low salinity plume waters; low- or high-chlorophyll patches in the spring bloom mosaic) in the strongly advective environment of the NGA, allowing a Lagrangian approach to process measurements. In situ pump deployments will be conducted at select process study stations to obtain size fractionated particle composition information. This information will be extended spatially with the in situ optical data (UVP5 and LISST DEEP), and estimates of sinking particle flux will be computed in order to assess the relationships among particle composition, size distribution, flux, and functional types and the physical and biological processes that control them. In addition to the suite of core measurements (see above), process station work will examine iron speciation (important to its bioavailability) by investigating the size partitioning (particulate, and dissolved fractions), particle reactivity (acid leachable), and organic complexation of dissolved iron.

*Experimental studies:* Two main types of experiments are proposed for phytoplankton process studies, in addition to routine assessments of primary productivity and photophysiology (see 'core methods'). 1) Relative roles of macronutrient limitation and microzooplankton grazing in regulating phytoplankton intrinsic growth rates, community composition, and biomass accumulation will be measured using a modified dilution technique (Strom et al. 2007, Strom & Fredrickson 2008). 2) The role of iron in shaping phytoplankton communities and regulating production will be addressed with environment-specific experiments. For the low-light environment of the early spring bloom, the key questions are: does Fe limitation play a role in regulating spring production? Do light and Fe act synergistically to co-limit production? The former is suggested by the spring 2011 relationship between maximum photosynthetic rate and salinity observed in the eastern NGA (Fig. 6B). The latter has been shown for the open (HNLC) Gulf of Alaska (Maldonado et al. 1999) as well as for subsurface chlorophyll maximum communities in the CCE (Hopkinson & Barbeau 2008). To address these questions we will conduct deckboard microcosm experiments, adding light, Fe, and light+Fe to low light spring bloom communities, following Hopkinson & Barbeau (2008) and Johnson et al. (2010). For the river plume environment, the key question is: what is the role of river-born Fe species in regulating summer phytoplankton communities? Fe source manipulation experiments will build on the modified dilution experiment design by diluting ambient summer 'out of plume' communities with i) particle-free (filtered) water from the core of the river plume; ii) particle-free offshore deep water; iii) particle free water from the original community (control).

Mesozooplankton investigations during process cruises will include measurements of size at stage, as well as lipid-sac volume, for the three NGA *Neocalanus* species to examine how each has responded to the conditions experienced across years and in relationship to specific features. Shipboard incubations as well as ambient collection time-series will allow us to further document rates of lipid accumulation. For other copepods and euphausiids, the response to environmental variability will be assessed with egg production studies (Napp et al. 2005, Hopcroft et al. 2005; Pinchuk & Hopcroft, 2006). Nutritional plasticity will be assessed with feeding experiments using the most abundant copepod genera (spring bloom: *Neocalanus* spp.; *Metridia pacifica*; river plume studies: *Pseudocalanus* spp.; *Metridia pacifica*). These will follow the method of Liu et al. (2005, 2008) except that analysis of preserved samples using the LISST will substitute for FlowCAM analysis. LISST analysis in benchtop mode (e.g., Sumerel & Finelli 2014) will give prey removal size spectra that can be related to field particle size spectra obtained with the same instrument, allowing us to assess the degree to which dominant zooplankton taxa adjust their feeding behavior with environmental changes in prey availability. Hopcroft is currently working with Lenz & Christie (UHawaii) on transcriptomes for *Neocalanus flemingeri* to examine diapause cycles; these approaches may also provide insight on their relative growth and lipid synthesis activity state. A follow-up transcriptomics proposal is anticipated outside of this LTER proposal.

**Methods** – *Hydrography:* High-resolution vertical profiling of temperature, salinity, chlorophyll fluorescence, PAR, $O_2$, and beam transmission to within 4 m of the bottom will be collected at stations. Underway data will be collected continuously from shipboard sensors (T & S only on *Tiglax*) including Doppler current profilers and a broad suite of atmospheric and sea-chest sensors. Discrete oxygen and salinity samples will be collected from rosette bottles for calibration of high-resolution sensors. The physical and chemical data will be used to quantify the seasonal and interannual distributions of water masses in cross- and along- shelf gradients. Inter-decadal time scales will be addressed through the use of ship-based observations, ARGO buoy data, the GWA-supported continuous measurements at GAK 1, and climate indices including the PDO and the NPGO and atmospheric reanalysis products (e.g., NASA-MERRA wind fields). Satellite sensor data will be used to place our shipboard data in broader spatial and temporal contexts. These data, combined with atmospheric and oceanographic model reanalysis hindcasts, help characterize additional aspects of the system that we do not directly measure.

*Macronutrients and Iron:* Ambient distribution of dissolved inorganic macronutrients (nitrate, nitrite, ammonium, phosphate and silicic acid) and the micronutrient iron, will be used in conjunction with water column physical data (e.g., light availability, salinity, water column stability) to determine resource variability to the phytoplankton community in space and time, and to identify the relative importance of various processes in supplying nutrients to surface waters.Vertical nutrient profiles will be obtained from the regular CTD rosette packages (macronutrients only), and from a dedicated trace metal clean CTD rosette package (Aguilar-Islas et al. 2013) (iron and macronutrients) (Process cruises only) deployed with Kevlar wire. Underway surface sampling will be done with a towed trace metal clean surface sampler (Aguilar-Islas et al. 2016) outfitted with an EXO1 sonde (YSI) to obtain real-time, in-situ beam transmission, T and S data. Trace metal clean techniques will be utilized in the sampling, processing and analysis of all Fe samples. All sample processing will be done inside an ISO-5 laminar flow clean bench. Surface filtered (0.4 µm) and unfiltered samples will be collected at and in between stations with greater resolution inshore and/or in the vicinity of strong salinity gradients. Vertical profiles of filtered and unfiltered samples during process cruises will be collected at selected stations. Seawater from pressurized (UHP N2 gas) Niskin-X bottles will be transferred to acid-clean bottles using acid-clean Teflon tubing. Dissolvable iron will be obtained from an unfiltered subsamples, dissolved iron, and Fe-binding ligands will be obtained by vacuum filtering seawater through polycarbonate (PC) membranes (0.4 µm) mounted on Teflon holders. Suspended particles collected on PC filters (20 and 0.4 µm) will be frozen on board for further processing to obtain leachable and refractory suspended particulate iron (e.g., Aguilar-Islas et al. 2013). Samples for Fe fractions associated with process cruise experimental studies (see below) will be obtained in similar manner.

Determination of all iron fractions will take place at UAF by inductively coupled plasma mass spectrometry (ICP-MS) (Aguilar-islas et al. 2013). Analysis of organic iron binding ligands will be done by competitive ligand exchange, cathodic stripping voltammetry (CLE-CSV) also at UAF (Aguilar-Islas et al. 2016). Frozen macronutrient samples will be analyzed at the Oceanographic Data Facility (ODF) in San Diego, CA for analysis. ODF has participated in and provided high quality nutrient data for programs such as WOCE, JGOFS, CLIVAR and GEOTRACES.

*Particulate Matter:* The spatial and temporal dynamics of PM will be assessed through a combination of time-series sediment trap collections, *in-situ* optical measurements, and *in-situ* large volume pumps. Year-round time series of sinking particle fluxes will be assessed with a moored 24-bottle sediment trap (Technicap PPS 3/3-24S with 24 sample bottles). Features of this model trap help minimize collection biases associated with horizontal currents. The trap location (100 m below the surface) places it below the base of the euphotic zone and above the observed depths of the benthic nepheloid layer. Trap cups will be poisoned with a formalin brine and collection will be programed at higher temporal resolution during expected higher flux (May & Oct.). Samples will be analyzed for particulate mass, total carbon, inorganic carbon, nitrogen, phosphorous, silicon, and aluminum. This time series data will be expanded spatially during the survey and process cruises using optical data from the CTD-rosette mounted UVP5, LISST-DEEP, transmissometer and fluorometer. The LISST DEEP targets small (2.5 µm- 500 µm) particles. The UVP5 detects larger particles and plankton between 100 µm – 2.5 cm and allows for in situ particle imaging and real time analysis. The optically-derived particle distributions will be used to estimate patterns of lateral and vertical fluxes across the study region. Lateral fluxes will be computed from the product of the current velocities (assessed from moored and shipboard ADCP) and suspended particulate concentrations. Optically- derived size distribution data will be combined with size-specific settling velocities and carbon contents to map the high-resolution spatial and vertical distributions of sinking particle fluxes using the relationships of Guidi et al. (2008), McDonnell and Buesseler (2012), and new regional ones determined as part of this study. During process cruises, PM will also be assessed at select stations with large volume in situ pumps (in-situ high volume pumps (McLane), outfitted with 142 mm filter holders in three size stages. Each size class will be analyzed for total carbon, inorganic carbon, macronutrients and aluminum.

*Chlorophyll and primary production:* Chlorophyll *a* depth profiles will be measured at all stations as an estimate of phytoplankton biomass and to calibrate *in vivo* fluorescence sensors on CTD packages. Samples will be filtered at low pressure onto GF/F filters, extracted, and analyzed fluorimetrically on board (Parsons et al. 1984). At selected stations chlorophyll will be size-fractionated through 20 µm pore-size PC filters to estimate biomass partitioning into ≥20 and <20 µm size classes. These two size classes respond to different sets of environmental conditions and have different fates in the NGA food web (Strom et al. 2007, 2010). Remote sensing estimates of chlorophyll (NASA's MODIS Aqua) will be used to provide broader scale estimates of phytoplankton biomass (Waite & Mueter 2013). Depth-integrated primary production will be measured during 24-h deckboard incubations using uptake of 13C-bicarbonate (Hama et al. 1983, Imai 2002), as we did successfully during the recent GOA-IERP program. Stable isotope enrichment and associated POC determinations will be done at the UC Davis stable isotope facility. Phytoplankton photosynthetic efficiency Fv/Fm will be measured after 30 min dark acclimation on all water samples collected for primary production experiments, using a Walz Water PAM fluorometer. Low values of Fv/Fm are a sensitive indicator of iron limitation (Suggett et al. 2009). The 'light curve' capability of the Water PAM will also be used to assess photosynthesis - irradiance response parameters including photosynthetic efficiency and maximum photosynthesis rate (Jakob et al. 2005), particularly in association with process cruise experimental studies (see below).

*Phytoplankton and Microzooplankton abundance, biomass and community composition:* To assess phytoplankton community composition, two types of microscopy samples will be collected: formalin-fixed samples for inverted light microscopy (diatom and dinoflagellate identification); and glutaraldehyde-fixed samples for epifluorescence microscopy (nano- and picophytoplankton identification and enumeration; Strom 2016). Epifluorescence samples will also yield the abundance, biomass, and composition of the <20 µm heterotrophic flagellate community (Sherr & Sherr 1993). For microzooplankton, acid Lugol's fixation and inverted light microscopy will be used to identify, count and size all microzooplankton ≥15 µm using a semi-automated digitizing system (Strom 2007; submitted) to yield abundance, biomass and composition of this crucial size class of microzooplankton directly consumed by mesozooplankton. We will also collect periodic samples for fixation in HMTA-buffered formalin, for identification of chloroplast-retaining ciliates using methods adapted from Stoecker et al.

(1987). Community composition samples will be collected at a subset of grid stations (e.g., ca. 20 stations per cruise for phytoplankton, focused on significant environmental gradients such as cross-shelf transects, and ~ 60 samples per cruise for microzooplankton). Highest priority for sampling will be surface mixed layer samples; we will collect occasional vertical profiles from stations showing vertical structure in hydrography and chlorophyll (fluorescence) distribution.

Phytoplankton community composition will also be evaluated using HPLC analysis of biomarker pigments (Mackey et al. 1996, Swan et al. 2016). Pigment analysis should be especially valuable for assessing composition of the morphologically cryptic but phylogenetically diverse communities of small flagellates that dominate the stratified portions of the NGA production season. Samples will be analysed by R. Goericke (see LOI), the pigment analyst for the CCE LTER, allowing direct comparison of taxonomic responses to environmental variability in the two systems (Taylor et al. 2012).

*Meso/Macrozooplankton:* Metazoan zooplankton, the key linkage between the production by single-celled organisms and larger organisms, encompass a wide array and vast size range of species. We use three different types of plankton nets. During daytime, zooplankton samples will be collected with a Quad net (25 cm diameter nets of 1.6 m length equipped with GO flowmeters). A pair of these, constructed of 0.15 mm mesh, will sample small, primarily early copepodid stages of calanoids (e.g., Coyle & Pinchuk 2003, 2005), while nauplii and the smallest copepodid stages of neritic species will be sampled with the pair constructed of 0.05 mm mesh. Along the Seward line station work during night-time will use a 0.25-$m^2$ Hydrobios Multinet system with 0.5 mm mesh nets will be fished to assess large zooplankton and micronekton, such as euphausiids (important components in the diet of many fish, sea-birds and marine mammals). The Multinet is equipped with one drogue net plus five nets that can open and close at specific depths, typically in 20m intervals. Depth, flow meter counts, and volume filtered are recorded every second. We propose to fish our deepest net to 200m and use a single net for 100-60m to make our collections more comparable to those intervals sampled by the CCE LTER. For expediency, the new transect lines will be sampled with the same 60 cm diameter 0.5 mm mesh Bongo nets used by both NOAA and the CCE LTER fishing to a maximum depth of 200 m. Zooplankton samples will be preserved (10% formalin), stained (Rose Bengal),and analyzed by LTOP methods to the lowest taxonomic category possible. Taxonomic processing will follow established methods (Coyle & Pinchuk 2005) to obtain estimates of wet weight biomass. Our analysis suggest multinet collections are consistent with those obtained using a MOCNESS during the GLOBEC years, consistent with recent work suggesting mesh size is more important than design for mesozooplankton species (Skjoldal et al. 2013).

Rates of secondary production of prey available to higher trophic level organisms will be calculated by applying growth and reproductive rates for copepods (Napp et al. 2005; Hopcroft et al. 2005; Liu et al. 2006a,b, 2007, 2008; Hopcroft unpublished) and euphausiids (Pinchuk & Hopcroft 2006, 2007) determined during the GOA GLOBEC program. Such relationships generally account for the influence of temperature, food availability and body size. Several such relationships are already incorporated into the coupled bio-physical models for the GOA. Estimates of biomass and production can then be used not only to quantify the prey fields for higher trophic levels, but to evaluate the performance of the biophysical models developed for the Gulf of Alaska.

*Fisheries:* While this proposal does not include a fisheries component, through collaborations we have access to a wide array of nearly concurrent fisheries data and we anticipate continued collaboration with both NOAA and state of Alaska fisheries scientists. NOAA Eco-FOCI fisheries surveys with associated oceanographic measurements are on-going from Kodiak westward to the Shumagin Islands since 1984. A similar program in south-eastern Alaska started in 2010 and is anticipated to continue. Eco-FOCI has biannual spring cruises (May/June) to assess larval fish distribution (Fig. 5A) that employ 505 μm Bongo nets with attached CTDs and CTD/bottle casts at a subset of stations for measurement chlorophyll and macronutrients. During summer and/or fall NOAA also conducts assessment surveys for both demersal and pelagic species either annually or biannually throughout the coastal Gulf, generally collecting Bongo nets and CTD information. Several biophysical mooring are maintained within our study area in support of those programs. Additional information on salmon returns and other upper trophic level populations is available annually via the Alaska Department of Fish and Game (ADF&G). We plan to make one side of Bongo net collection available to NOAA for larval fish analysis, collect neuston samples for them during spring surveys, and provided sorted material where appropriate. PIs Aguilar-Islas, Danielson, Hopcroft, and Strom have a history of collaboration with NOAA counterparts by sharing data and contributing to the new annual GOA Ecosystem's Assessment Report. (See letter of support).

*Seabirds & Mammals:*Seabird observations (20 year time series with gaps in the mid-2000s) are conducted by USFWS with additional support from NGOs. The Seward Line design (spring and fall seasons, cross-shelf) provides an opportunity to examine seabird responses to seasonal changes and the cross-shelf gradient of physical and biological parameters (Sousa 2011). Spring survey are prior to or at the beginning of the breeding period and fall surveys occurs when birds must prepare for harsh winter conditions or long migrations. The addition of an early summer cruises corresponds to the period when breeding birds are provisioning their young. Observations are made following accepted protocol (USFWS 2008) to estimate densities (birds/km$^2$) but additional observations (rare birds, mammals, large aggregations) are also recorded. Raw and processed data are submitted to the North Pacific Pelagic Database and to NPRB, and will be accessible via Seabirds.net. Marine mammal observations are semiquantitative because of difficulty in establishing survey "effort" and area.

**LTER Modeling** – This component will focus on the complex interplay between the strongly seasonal freshwater discharge at the coast and eddy activity offshore in controlling horizontal gradients of limiting nutrients (nitrate and iron) and, thus, phytoplankton and zooplankton community structure. While this topic has received previous attention from both observational and modeling studies (e.g., Coyle et al. 2012, Fiechter & Moore 2012, Ladd et al. 2005), greater emphasis will be placed on the effects of runoff associated with long-term trends and seasonal adjustments. Leveraging historical information, satellite observations, and recently-available projections for river discharge in the NGA region, we will use coupled physical-biogeochemical model simulations to characterize the expected cross- and along-shelf concentrations of limiting nutrients and phytoplankton/zooplankton species composition in response to changes in the seasonal climatology of freshwater input (e.g., timing and magnitude of peak discharge). The modeling component will also serve as a vehicle for testing hypotheses about ecosystem structure and resilience by exploring, for example, the importance of trophic level redundancy in the NGA planktonic community (e.g., sibling *Neocalanus* species) when subjected to "normal" and "extreme" changes in environmental conditions.

*Model Framework:* The ocean circulation model will be an implementation of the Regional Ocean Modeling System (ROMS), and the biogeochemical model coupled to it will be a derivative of the North Pacific Ecosystem Model for Understanding Regional Oceanography (NEMURO) model augmented with iron, carbon, and oxygen cycling. The choice of using ROMS is justified by the fact that a high-resolution configuration of the model (with tidal forcing and river discharge) already exists for the NGA domain and has been used to produce a 10-year hindcast for the period 1999-2008 (Danielson et al. 2016). Leveraging this existing ROMS configuration will substantially reduce time spent on model development during the initial phase of the project. While several alternate biogeochemical models exist for the NGA, NEMURO has already been successfully implemented in the region and provides a good compromise between lower trophic level complexity and computational efficiency (Fiechter & Moore 2009). Using ROMS and NEMURO will also benefit from a current NSF-funded project (PI: Fiechter) in the California Current region to advance coupled physical-biogeochemical data assimilation capabilities for these two models. The ability to perform data assimilation is attractive in the context of LTER, as it provides a way to seamlessly integrate available observations into model simulations to improve physical and biogeochemical state estimates, as well as to conduct systematic sensitivity analysis of the observing network (Fiechter et al. 2011). Because the NGA LTER site offers a perfect testbed for exploring novel physical-biogeochemical data assimilation techniques (owing to the availability of high resolution concurrent physical, biological, and chemical observations), we expect that the model framework that will be implemented during the first LTER funding cycle will serve as a platform for the development of future data assimilative models for NGA (either as add-on projects during the later stages of the initial LTER effort, or as a modeling priority for the next funding cycle). Specific details regarding the ROMS and NEMURO configurations are provided below.

*Regional Ocean Circulation Model.* ROMS is a hydrostatic, primitive equation model that employs terrain-following coordinates in the vertical, and orthogonal curvilinear coordinates in the horizontal. ROMS is specifically designed for regional applications and its advanced numerical algorithms and grid-structure make it well suited for modeling coastal regions characterized by complex bathymetry and coastlines (Shchepetkin & McWilliams 2005; Haidvogel et al. 2008). The proposed domain encompasses the entire coastal NGA north of 54°N with a horizontal resolution of 4.5 km and 50 vertical levels with stretching to increase resolution near the surface (Fig. 8A). The geographical extent to the south was specifically chosen to be sufficiently wide to resolve eddy activity along the shelfbreak and in the basin, yet sufficiently small to perform simulations at the relatively high-resolution needed to capture coastal dynamics associated with river discharge. Several atmospheric products are available to force ROMS at the sea surface depending on the period considered for the simulation (e.g., MERRA and CCMP/ERA for hindcasts and NAM for present-day simulation). High-resolution hindcast (Hill et al. 2015; Beamer et al. 2016) coastal discharge forcing fields for the Gulf of Alaska will provide linkages to the terrestrial domain. These hindcast and future climate scenario discharges are compiled by LTER collaborator D. Hill of OSU. Model initial and lateral boundary conditions for the hindcast simulations will be derived from several sources based on their temporal coverage (e.g., SODA or Mercator/GLORYS for long-term retrospective analysis and Global HYCOM for present-day runs). For the climate projection, we will initially use primitive variables (sea surface height, currents, temperature and salinity) and surface atmospheric fields (momentum, heat, freshwater and radiative fluxes) from the GFDL CMIP5 global climate model simulations (http://nomads.gfdl.noaa.gov:8080/DataPortal/cmip5.jsp).

*Biogeochemical Model.* The biogeochemical model will be based on the 11-component NEMURO model (Fig. 8B, Kishi et al. 2007). In its default configuration, NEMURO includes three limiting macro-nutrients (nitrate, ammonium and silicic acid), two phytoplankton size-classes (nanophytoplankton and diatoms), three zooplankton size-classes (micro-, meso-, and predatory zooplankton), and three detritus pools (dissolved and particulate organic nitrogen and particulate silica). NEMURO was specifically developed to represent lower trophic level ecosystem processes in the north Pacific and has been successfully implemented in the CCS (Chenillat et al. 2013, Fiechter et al. 2014), Gulf of Alaska (Fiechter & Moore 2011) and Kuroshio extension (Komatsu et al. 2007). A complete review of more than two dozen studies in which NEMURO or derivatives have been applied to various Pacific regions can be found in Kishi et al. (2011). For the purpose of this research, NEMURO has been augmented with a carbon sub-model based on the formulation of Hauri et al. (2013) by adding three compartments: dissolved inorganic carbon (DIC), alkalinity, and calcium carbonate ($CaCO_3$). An oxygen cycling component based on the formulation of Fennel et al. (2006) has also been added to NEMURO. Previous model studies by co-PI Fiechter have demonstrated that the availability of concurrent nutrient concentrations and rate measurements for phytoplankton growth and zooplankton grazing from the Seward Line significantly improved the ability to parameterize NEMURO for the NGA region (Fiechter & Moore 2009). New observations from the LTER effort will allow further calibration of key biological parameters (thus increasing model accuracy) and expand the spatial and temporal range of in situ variables available for model evaluation. For the hindcast simulations, initial and boundary conditions will combine information from available observations for the NGA (e.g., Seward Line) and climatological fields from the World Ocean Atlas. This approach is particularly important to impose realistic dissolved iron values for which no well-established climatological data exists at the spatial scales relevant to coastal ecosystem processes in the NGA. For the climate projection, we will initially use nutrient concentrations from the GFDL CMIP5 global climate model simulations (http://nomads.gfdl.noaa.gov:8080/DataPortal/cmip5.jsp).

*Modeling Tasks:* The overarching objective for the numerical experiments is to provide an understanding of how past, present, and future variability in freshwater input and offshore eddy activity impact along- and cross-shore distribution of limiting nutrients, and, therefore dictate planktonic community structure and resilience in the NGA. During its early stage (years 1 and 2), the modeling effort will also leverage a currently NSF-funded project (PI Hauri) focused on implementation of a high-resolution coupled physical-biogeochemical to study carbon dynamics and ocean acidification in the NGA.

*Phase I Tasks (Years 1-2)*

(1) Evaluate the ocean circulation model in the context of along- and cross-shelf transport associated with river discharge and mesoscale variability. This task will be accomplished using passive tracer and particle tracking experiments to identify how the distributions of limiting micro and macro nutrients respond to changes in the timing and magnitude of freshwater input and offshore eddy activity.

(2) Evaluate existing biogeochemical models for the NGA to identify an adequate level of complexity for the LTER objectives and the best approach for parameterizing key processes (iron limitation, zooplankton vertical migration, etc.).

(3) Produce a long-term (~20 years) historical simulation of the coupled physical-biogeochemical model and evaluate it against historical observations. This task will establish a baseline solution for the NGA physical and biogeochemical ocean states, and assess the ability of the model to reproduce along- and cross-shelf variability in nutrient concentrations and planktonic community structure.

*Phase II Tasks (Years 3-4)*

(1) Determine model sensitivity to observed variability in river discharge during period of weak, average, and strong mesoscale eddy activity. By imposing systematic variations in the timing and magnitude of freshwater inputs, we will be able to identify which particular phytoplankton and zooplankton functional groups respond most strongly (positively and negatively) to variations in the along- and cross-shelf distributions of limiting nutrients (i.e., the match-mismatch hypothesis).

(2) Generate ensemble calculation to explore sensitivity of planktonic community structure to uncertainty in biogeochemical model parameters. The main purpose of this task is to introduce "plasticity" in the biogeochemical model by exploring how variations in key biological parameters (e.g., phytoplankton growth rates and zooplankton grazing rates) affect seasonal ecosystem dynamics. By comparing each member to the ensemble mean and spread, we will be able to identify if certain parameter combinations lead to significant departures in the planktonic community structure. This approach was successfully used by Fiechter (2012) to identify the dominant biological processes controlling ecosystem response seasonally in the NGA.

(3) Perform a series of simulations for a subset of "normal" and "extreme" years (from the baseline solution) with increased functional group complexity in NEMURO to explore the potential relationships between trophic level redundancy and ecosystem resilience. The main focus of this task is to determine how small differences in environmental and diet preferences among sibling species (e.g., *Neocalanus*) affect the overall planktonic community structure under various oceanographic conditions.

*Phase III Tasks (Years 5-6)*

(1) Reevaluate the coupled physical-biological model configuration in light of the newly acquired observations, in particular with respect to the parameterization of biogeochemical processes.

(2) Produce a climate projection focused on determining resilience of planktonic community structure to expected future changes in timing and magnitude of river discharge. The main purpose of this task is to isolate the impact of freshwater input on ecosystem process in the NGA by running the coupled physical-biological model under "climatological" conditions except for the river discharge climate signal. "Climatological" conditions will be achieved by repeatedly forcing the model with atmospheric fields and open boundary conditions from the year in the baseline solution that produces spring bloom dynamics closest to the long-term mean.

(3) Explore various nesting strategies to produce a climate projection forced directly by global climate model solutions. This task will set the stage for assessing how future changes in the seasonality of river discharge and mesoscale eddy activity in the NGA will be beneficial (match) or detrimental (mismatch) to specific phytoplankton and zooplankton functional groups.

**Synthesis of proposed research activities** – The focus of all proposed NGA components is on the eocsystem response to *environmental variability*: the mechanisms by which variability gives rise to the largest production signals in the NGA, and the mechanisms by which species and communities exhibit resilience responses to disturbance across multiple scales. Hypotheses guiding long-term observations, process and modeling studies focus during this initial phase on hydrologic variability, which is undergoing profound long-term change in the NGA, and which interacts with resource delivery and organism distributions in time and space. As well, all NGA components will use the concept of emergent properties to evaluate responses to variability, and to initiate comparisons with resilience responses in other ecosystems. We anticipate on-going reciprocal interaction between all components of this LTER, as well as between the NGA and other LTER programs, as we explore resilience in this fascinating subarctic marine ecosystem.

## Education and Outreach Activities

**Resource management** – As one of the nation's most important fisheries regions (commercial fisheries landings at Kodiak Alaska rank second nationally for tonnage and third for value), understanding how the NGA ecosystem will respond to climate trends and perturbations is of economic as well as regulatory importance. As it did for the recent GOA-IERP program, our observational findings will contribute to NOAA's annual ecosystem report cards that generate simple environmental indices of use to resource managers. The NGA models can be used as the foundation for IBM models of the region's fisheries. Our ability to monitor and eventually predict oceanographic changes and lower trophic level responses in the NGA will be crucial for intelligent management of the region's abundant resources.

**K-12 education** – An NGA LTER requires an innovative approach to outreach and K-12 education, to communicate ecological findings of importance to Alaskans and the nation, and challenges related to sustainable harvests of fish and marine mammals, in a way that contributes to the resilience of Alaska communities. Ecosystem dynamics take place at a variety of spatial and temporal scales in ways that are largely invisible to the public. Opportunities to involve educators, journalists, or members of NGA coastal communities directly in data collection is limited by the expense of berth space on sampling cruises. Accordingly, in combination with standard public and K-12 outreach methods, we propose to use video and animations as a primary means to increase understanding about the "state of the science" in terms of NGA dynamics, our scientific approach, and what we learn.

The development of our proposed outreach products will complement those already developed or underway related to long-term monitoring of the NGA ecosystem. Our products will be similar to those created by the Alaska SeaLife Center (e.g., a virtual field trip for the Gulf Watch Alaska (GWA) project). The videos will provides basic information about pelagic and benthic ecosystems in the NGA in the context of environmental drivers. They will focus on an overview of the LTER and its hypotheses in Year 2, and on what has been learned in Year 5.

Additional outreach through a variety of methods about the process and results of the annual cruises would be an important focal point for increasing public understanding about GAK-1 as a climate change "sentinel" for the Gulf of Alaska marine ecosystems. For Alaska communities, the most effective methods are direct "in-person" outreach in the community, public radio programs, local newspaper articles, and social media postings (proposed below). Annual outreach visits to a small number of Alaska coastal communities along the Seward line are already funded by NPRB and GWA.

**Year 1:** (1) Expand the existing Seward Line website (http://www.sfos.uaf.edu/sewardline) for outreach to K-12 and general public audiences. (2) Develop K-12 teaching activities and units focused on NGA ecosystem dynamics, marine technology, and critical thinking about the importance of NGA to people and the impact of human activities on the ecosystem.

**Year 2:** (1) Produce a project video and virtual field trip that includes animations of Northern Gulf of Alaska processes, to increase understanding about the importance of the NGA to people, and to increase understanding of the project's scientific approach and data-collection activities. (2) Disseminate the project video through the LTER Schoolyard Series, as well as at the Alaska Ocean and Islands Visitor

Center, Homer (annual visitation:75,000), the Alaska SeaLife Center, Seward, (annual visitation:150,000), the Coastal America Ecosystem Learning Network, and the Smithsonian Institution Sant Ocean Hall Ocean Today kiosk (potential audience: 20-30 million). (3) Disseminate K-12 teaching activities through the Alaska Sea Grant *Alaska Seas and Watersheds* website and in association with the virtual field trip on Alaska SeaLife Center website and on DVD. (4) Make datasets available for K-12 educators with guidance for student analysis and interpretation.

**Years 2-6:** (1) Update the project website with news and reports. (2) Disseminate the teaching activities and units and support their use through professional development trainings for teachers and informal marine educators in northern Gulf of Alaska communities as well as at state and national education conferences and listserves (i.e., Alaska Science & Math Teachers, Northwest Aquatic & Marine Education Association, National Marine Educators Association). Evaluate effectiveness of professional development in increasing teacher content knowledge and use and effectiveness of the teaching materials. (3) Provide public outreach through a variety of media: presentations in Northern Gulf of Alaska communities, conference presentations (e.g., Alaska Forum for the Environment), press releases, cruise blogs, scientist interviews by radio and television stations

**Year 5**: Produce a video, both for "stand-alone" use and for incorporation into the virtual field trip, to communicate our new understanding of the ecosystem as well as the value of long-term ecological research.

**Undergraduate education** –Each year, two REU students will be recruited nationally to participate in our summer research program. Applicants will be ranked by the LTER PIs, based on their interests they will be assigned or co-assigned to appropriate mentors. Mentors will work with the students to develop their own independent research project that leverages NGA LTER data and/or infrastructure. At present, there is no REU program operating in Alaska to provide an existing infrastructure, making a formalized "teaching" structure impractical. Upon arrival the PIs will provide the students with a series of overview seminars focused on the Gulf of Alaska. This will be followed by rotating the students through a week in the lab of each of the three major oceanographic disciplines represented by this proposal: physical, chemical and biological oceanography. Students will spend time regularly with each of PIs located in Fairbanks. The remainder of the time will be spent in their mentor's lab and on the June LTER cruise (along with other summer undergraduate hires, e.g. from WWU) to gain field experience in a multidisciplinary environment. Students will be integrated into the active graduate community at UAF. At the conclusion of the summer, students will present the results of their research at a departmental seminar. Depending upon project outcomes, students will be encouraged to present their results at a scientific meeting or to co-publish with their mentor. Feedback will be solicited from students mid-program, just prior to completion, and several months after completion so that we can adjust the REU program based upon their feedback. In addition, Strom will mentor WWU undergraduates, who will participate in fieldwork and project activities.

**Graduate Education** – We will mentor and train two M.Sc. and one Ph.D. students in multidisciplinary oceanographic studies. Additionally, the Seward Line has been providing ocean-going experience for graduate students since its inception. Cruises typically carry 3-5 graduate volunteers, plus a lesser number of students conducting their own research – we anticipate this pattern to continue. The additional berths available on the *R/V Sikuliaq* provide the opportunity for a larger number of students undertaking more structured course work during cruises (i.e., McDonnell's new observational oceanography course).

**General Public** – The PIs regularly give presentations in communities throughout Alaska regarding their research, including findings from the Seward Line program. The Alaska Marine Science symposium is regularly attended by the public as well as by agency and university members. The datasets generated under NGA will be accessible through intuitive visualizations on NGA and AOOS websites (see Data Management Plan).

## Result from Prior NSF Support

**Aguilar-Islas**: Project PI OCE-0928084: U.S. GEOTRACES Atlantic Section: The fractional solubility of aerosol iron in seawater, $115,305, 9/15/2009–08/31/2012. OCE-1137836: RAPID-Continuation of U.S. GEOTRACES Atlantic Section: The fractional solubility of aerosol-derived iron in seawater, $15,046, 7/01/2011–06/30/2012. *Intellectual Merit:* The solubility of aerosol-derived iron was investigated across the Atlantic Ocean during the two legs of the U.S. GEOTRACES Atlantic Section (fall of 2010 and 2011). Aerosol samples were collected with a high volume sampler interfaced to the GEOTRACES sector-controlled system, and filtered surface sea water was collected with the GEOTRACES towed sampler. *Broader Impacts:* Laboratory-based aerosol dissolution experiments contributed towards the training of a UAF master student (A. Mehalek). Results from the leaching protocol assessment performed during this project, informed best practices for leaching protocols during U.S. GEOTRACES Pacific (2013) and Arctic (2015) cruises. *Products:* Project results were presented at the 2012 Ocean Sciences Meeting, the 2012 Fall AGU Meeting (invited oral presentation), the GEOTRACES Data Synthesis Workshop (Norfolk, VA, 2013). Participation in the GEOTRACES aerosol inter-calibration exercise resulted in a co-authored publication: Morton et al. 2013.

Mueter, **Danielson** and **Hedstrom**: BEST SYNTHESIS: The variable transport of pollock eggs and larvae over the Bering shelf: A marriage of physics and biology. (ARC-1108440, $396,396.00, 2011-2013). *Intellectual Merit:* We examine the influence of advection on early life stages of pollock eggs and larvae over the Bering Sea Shelf and the role of atmospheric forcing in driving the Bering-Chukchi shelf circulation. The physics component of this study led to the formulation of a new conceptual model that describes linkages between longitudinal displacements of the Aleutian Low and the response of the Bering Sea and Gulf of Alaska subarctic gyres and the oceanic communications between the Pacific and the Arctic (Danielson et al., 2014). *Broader Impacts:* Model results contributed to S. Danielson's PhD thesis. Results were presented at Kawerak "Indigenous Knowledge and Use of Bering Strait Region Ocean Currents" workshop Nov 2013 in Nome, AK and described at the Pribilof Island Bering Sea Days week of science exploration at St. Paul Island. *Products:* Petrik et al. 2014; Danielson et al. 2014; Petrik et al. 2016; Danielson et al. 2016; model output archive: http://tds.marine.rutgers.edu:8080/thredds/met/catalog.html.

Milliff, **Fiechter**, Moore, Powell, Wikle, Hooten. OCE-0814749; 9/1/08-8/31/11. Collaborative Research: Estimating Ecosystem Model Uncertainties in Pan-Regional Syntheses and Climate Change Impacts of Coastal Domains of the North Pacific Ocean. $179,995 (UCSC portion). *Intellectual Merit:* Use modern statistical modeling methodologies to bear on state and parameter estimation for coupled physical-biological models focused on the role of iron limitation on lower trophic level ecosystem response in the coastal Gulf of Alaska. A novel extension of Bayesian hierarchical models (BHM) was implemented to synthesize disparate observations and deterministic model simulations for the CGOA. The BHM methodology provided a framework to combine the strengths of deterministic and probabilistic models to obtain uncertainty estimates for ecosystem state variables and parameters. *Broader Impacts:* As ecosystem managers and scientists learn to utilize state and parameter information in probability distributions, uncertain parts of the ecosystem model can be targeted for more intensive observations and more sophisticated parameterizations. *Products:* Hooten et al. 2011; Brown & Fiechter 2012; Fiechter 2012; Leeds et al. 2012a,b; Fiechter et al. 2013; Milliff et al. 2014.

**Hauri** OCE-1459834, 8/1/15-7/31/18, Unraveling the controls of inorganic carbon dynamics in the Gulf of Alaska with a regional three-dimensional biogeochemical model $502,465. *Intellectual Merit:* Identify the dominant controls and patterns of high $CO_2$ environments in the northern Gulf of Alaska. We are tailoring a 4.5 km horizontal resolution regional biogeochemical model to the Gulf of Alaska, with explicit forcing of coastal freshwater discharges and modeled iron limitation. Improved conceptual understanding of the controlling forces that mediate ocean acidification in the Gulf of Alaska. *Broader Impacts:* This project supports an outdoor science education program called "Girls in Icy Fjords" designed to help young women with fewer opportunities in life to build self-confidence and pursue a career in science or college education in general. *Products:* No publication as yet.

**Hill:** OIA-1137272, 08/2011 – 07/2013, US-Pakistani Developing Collaboration on the Current Estimation and Future Prediction of Micro-hydro Power Potential: Response to a Changing Environment. $49,980. *Intellectual Merit:* We developed a high-resolution dataset of historical and future monthly precipitation and mean temperature to drive runoff models. We also created a degree-index model code, which is designed to allow the development and of more physically representative process-based modules. *Broader Impact*: The developed products are valuable for many research fields, including agriculture, forestry, ecology, and hydrology. We have made them available through the PIs' website (globalclimatedata.org). We have been working directly with Pakistani universities (NUST) and industry (Chitral Engineering) to develop future proposals in this area. *Products*: Mosier et al. 2014; Mosier et al. 2016a, Mosier et al. 2016b. *Other Research Products*: 10 conference proceedings, freely available datasets, model codes, and user manuals (globalclimatedata.org).

**Hopcroft,** Lenz & Christie. [1] OCE-1459826. 2/1/2015-1/30/2019. *Collaborative proposal: Optimizing recruitment of Neocalanus copepods through strategic timing of reproduction and growth in the Gulf of Alaska*. $414,961 (UAF portion). *Intellectual Merit:* Transcriptomics are used to catalog the messages used by the cells to control the animal's life processes and specifically those signals related to dormancy in adults and nauplii. Laboratory and field approaches are used to determine physiological condition, duration and synchronization of reproduction in the emerging females, and the strategies for nauplius survival during low food conditions. Gene expression studies are used to develop molecular markers for female dormancy and reproductive readiness, and for naupliar growth and possible dormancy. *Broader Impacts:* A post-doctoral fellow is focused on this effort. Undergraduate and graduate students are involved in research projects crossing the boundaries of biological oceanography, physiology, molecular biology and bioinformatics. *Products:* Preliminary results have been presented at national/international meetings. No publications or data products as yet.

**McDonnell** – NSF OCE-1459835, 4/1/2015-3/31/2018, "Variability in particle size distributions, sinking velocities, and fluxes in the northern Gulf of Alaska." *Intellectual Merit:* Elucidate the magnitude and function of the ocean's biological carbon pump in the NGA through deployment of a moored sediment trap and underwater particle camera mooring on the continental shelf. A sediment trap was in September 2015, a new underwater time-series camera system was developed and built to image particles and plankton in conjunction with the time series sediment trap. The UVP5 and LISST instruments were deployed along the Seward Line and on surveys throughout the NGA. Insights into the patterns of lateral particle supply and vertical flux in relation to the chemical, biological, and physical features of the system has been gained. *Broader Impacts:* Support of a graduate student, and a new observational oceanography course involving a short training cruise. *Products:* Turner et al. (in review).

**Strom**, Palenik, Brahamsha: NSF 1021189, 9/1/10-8/31/13, $372,675 "Collaborative Research: Constitutive and inducible predation defenses in cyanobacteria". *Intellectual Merit*: This project investigated anti-predation defenses in marine *Synechococcus*, primarily through the use of mutant *Synechococcus* strains lacking specific cell surface proteins. We found that the paracrystalline S layer increased *Synechococcus* vulnerability to predation by ciliates and flagellates, the major predators of *Synechococcus* in both marine and freshwater ecosystems. *Broader Impacts*: a culture collection of planktonic alveolates that continues to be available and broadly shared with researchers in North America and Europe; organization of a special session on Phytoplankton Interactions at the 2013 Ocean Sciences meeting. Student participation: Six undergraduates, including four minority students; partial support of two graduate (M.S.) theses. A scientific communication course that produced an illustrated storyboard describing the ecology of Synechococcus; *Products:* Kolb (2012); Kolb & Strom (2013); Brown (2013); Gentekaki et al. (2014); Echevarria et al. (2014); Strom et al. (accepted); Janouškovec et al. (submitted).

**Fig. 1 The proposed NGA LTER: Domain, framework, organization**

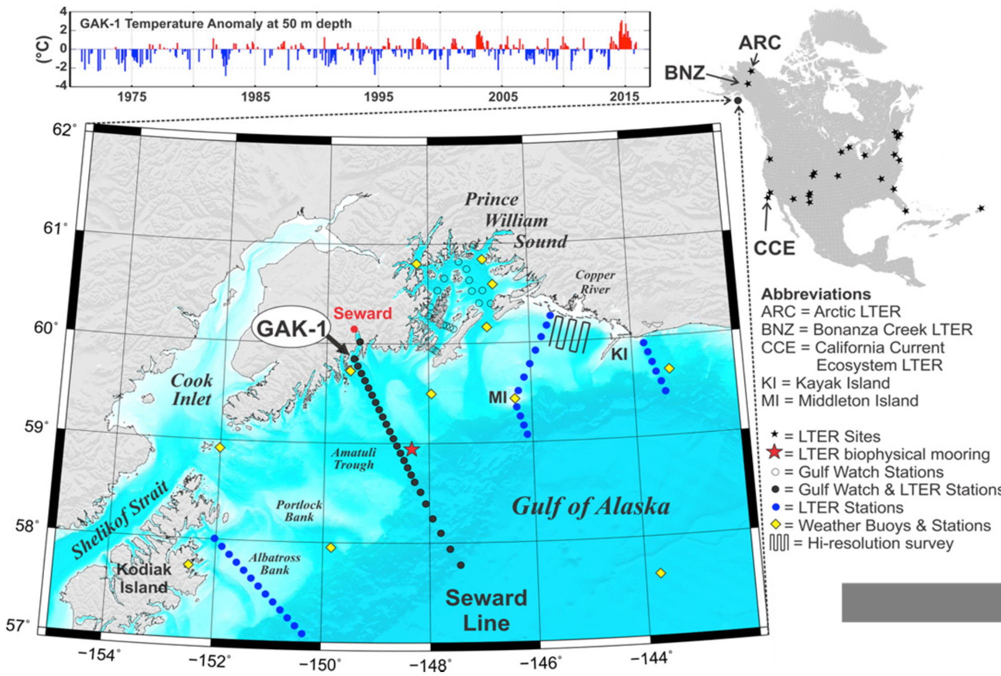



**Fig. 1A**. Proposed northern Gulf of Alaska LTER, showing proposed shelf sampling stations and other program assets. Top left inset shows upper water column temperature anomalies on the inner shelf (station GAK-1), including temporal variability and long-term increase; top right inset shows proposed NGA LTER in relation to other U.S. LTER sites.

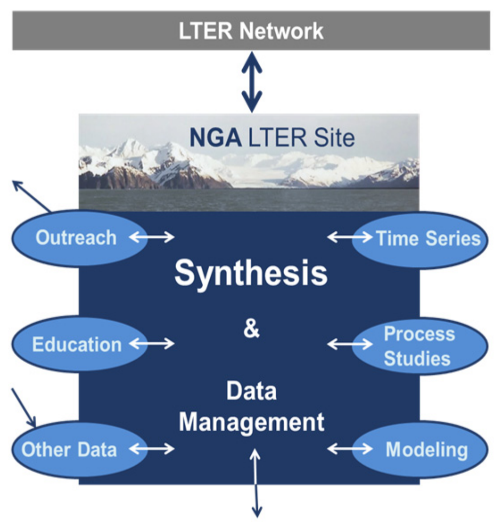
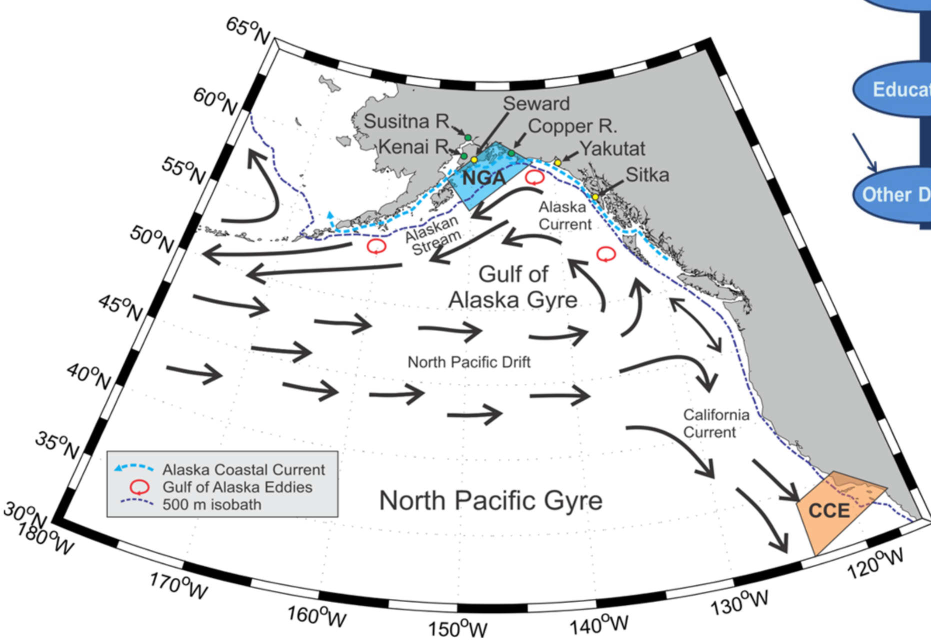



**Fig. 1B**. Structure of proposed NGA LTER



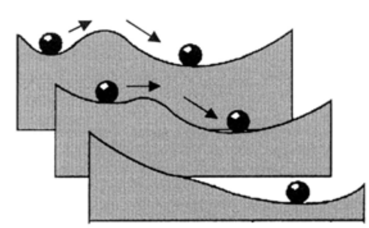
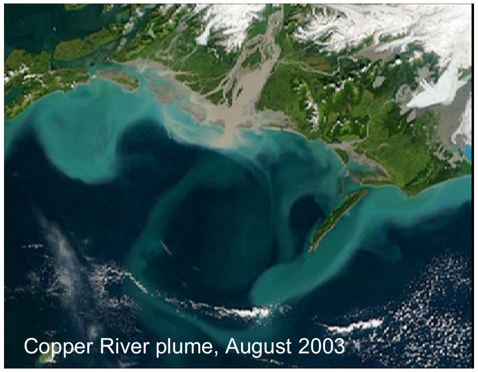
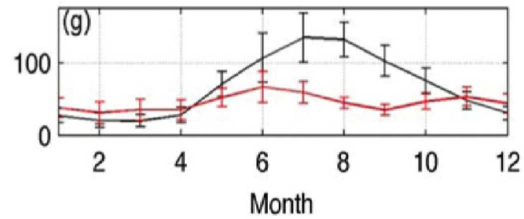
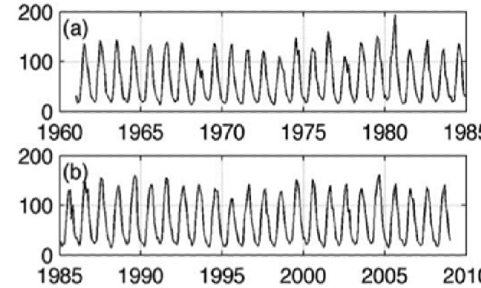
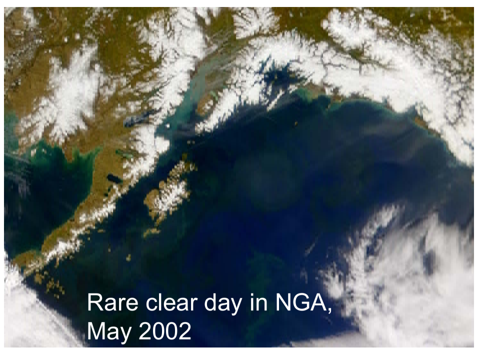
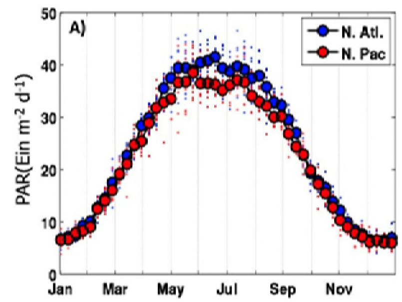
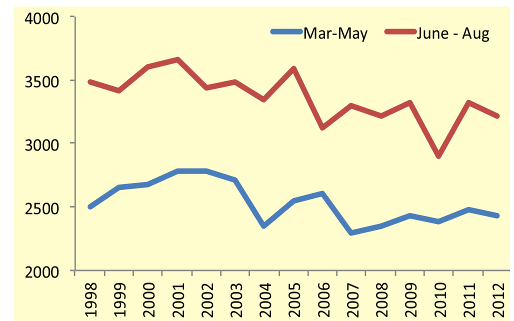
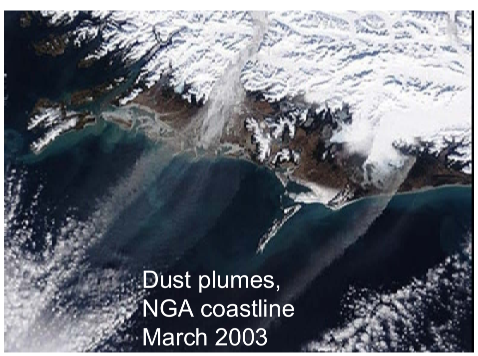
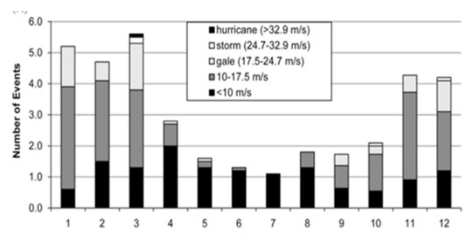
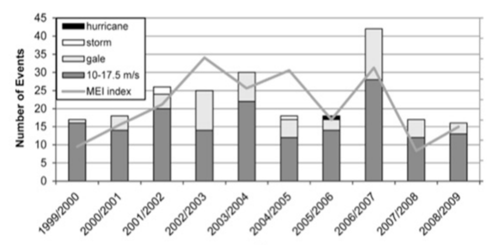



**Fig. 1C**. Ball-and-cup model of system stability. Valleys represent stability domains, balls represent the system components, and arrows represent disturbances. Ecological resilience is described as the width of the valleys in the stability landscapes (from Gunderson 2000)

**Fig. 1D**. Major circulation features of the eastern North Pacific. Blue and orange shaded regions show areas of CCE and proposed NGA LTER sites.

**Fig. 2. Variability in environmental drivers in NGA**

| | **Instantaneous** | **Seasonal** | **Interannual** |
|---|---|---|---|
| **Freshwater input** |   |   Average annual cycle of runoff (km$^3$) into Gulf of Alaska (black line). From model of Hill et al. (2015). |   Interannual variability in runoff (km$^3$) into Gulf of Alaska (Hill et al. 2015). |
| **Solar Irradiance** |   |   Average annual cycle of PAR in the North Pacific (red; centered on 47.5°N, 145°W) from Westberry et al. (2016) |   Interannual variability in seasonal PAR (moles photons m$^{-2}$) in eastern NGA |
| **Gap Winds** |   |   Annual cycle of gap wind events (offshore-directed, >10 m/s) in eastern coastal Gulf of Alaska (Ladd and Cheng 2016). |   Interannual variability in # of gap wind events in eastern coastal Gulf of Alaska (Ladd and Cheng 2016). |

## Fig. 3. Hydrography and nutrients in the proposed NGA LTER

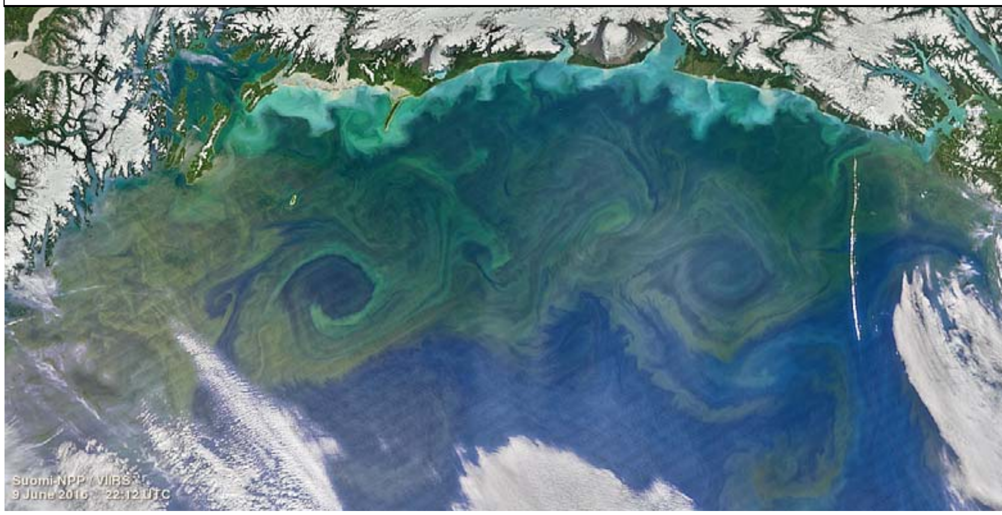
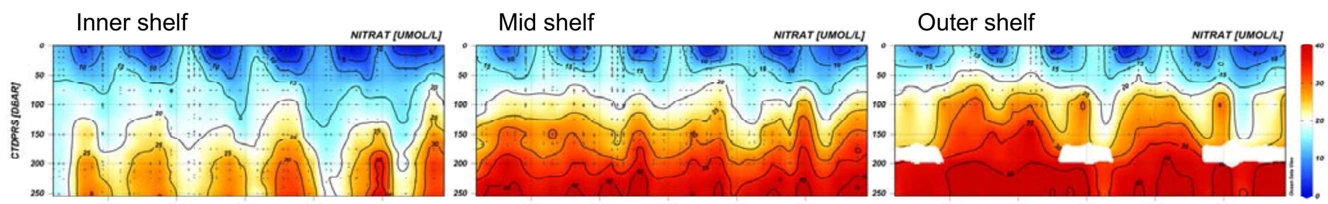



**Fig. 3A.** Ocean color image from June 9, 2016 showing runoff-derived suspended sediments in the coastal current (turquoise), and high chlorophyll in eddy structures (green).

**Fig. 3B.** Time series of nitrate depth profiles (μM) on the Seward Line, 1999-2004 (from Trahavnosky et al. in prep)



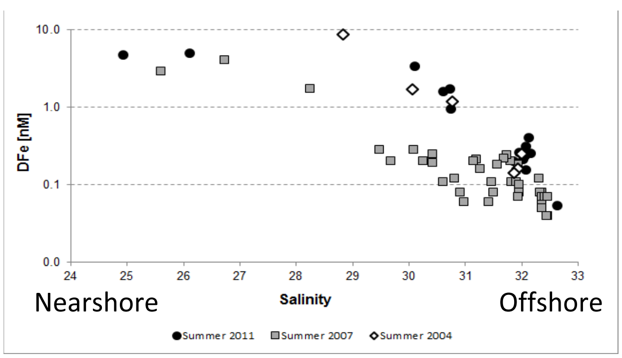




**Fig. 3C.** Dissolved Fe concentrations along the Seward Line in 3 different summers, as a function of salinity (from Aguilar-Islas et al., 2016)

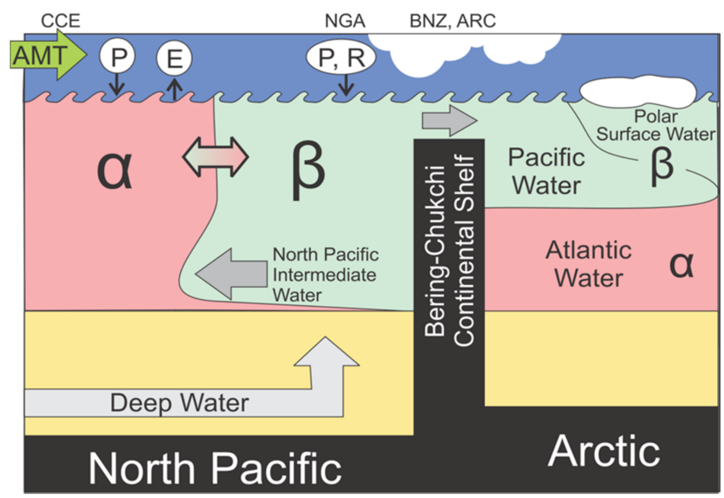



**Fig. 3D.** Upper ocean stratification regimes in North Pacific and western Arctic modified from Carmack (2007). Alpha regions (e.g., CCE) are thermally stratified, whereas freshwater stratifies beta regions (NGA). Contrasting timings and strengths of the solar and the freshwater cycles over the subtropical, subarctic and arctic gyres differently structures the marine ecologies at these different latitudes in a fashion that permeates from the stratification through the nutrient supply and productivity regimes. Abbreviations: P = precipitation, E = evaporation, R = eiver runoff, AMT = atmospheric moisture transport.

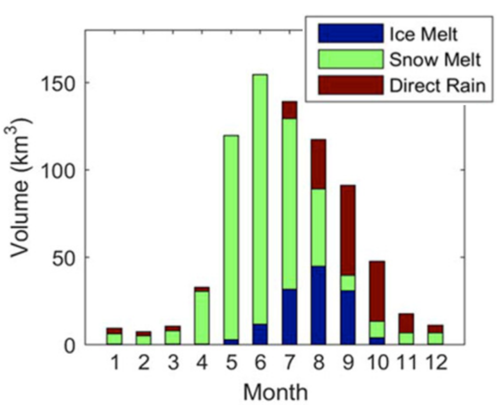



**Fig. 3E**. High-resolution model estimates of seasonal runoff cycle in the Gulf of Alaska, partitioned by freshwater source. (From Beamer et al. 2016)

## Fig. 4. Long-term change in the proposed NGA LTER

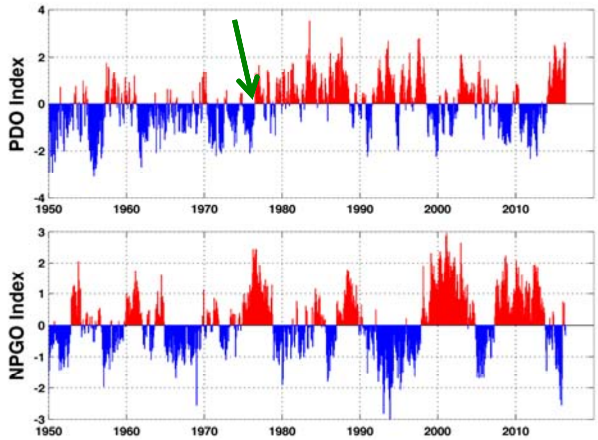



**Fig. 4A**. Long-term records (1950 – present) of North Pacific climate indices. Green arrow indicates timing of late-70s ecosystem regime shift.

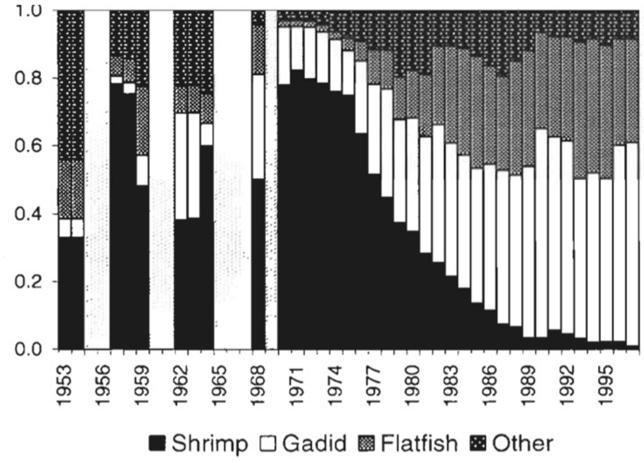
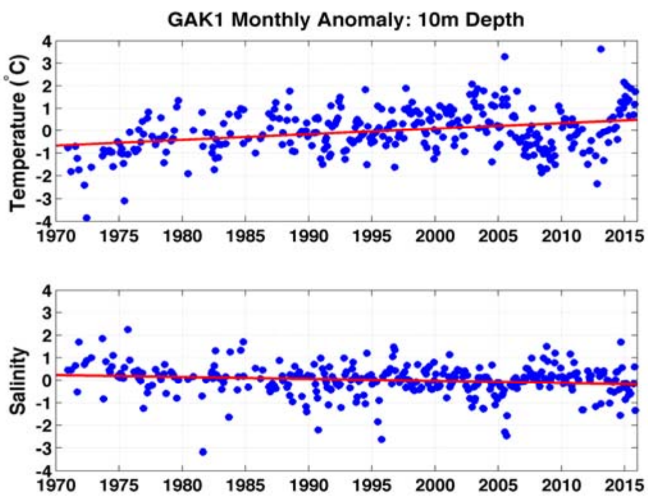



**Fig. 4B.** Composition of small-mesh trawl catches in the Gulf of Alaska 1953-1997, showing major compositional shift associated with the late-1970s ecosystem regime shift (see Fig. 4A) (From Anderson and Piatt 1999)



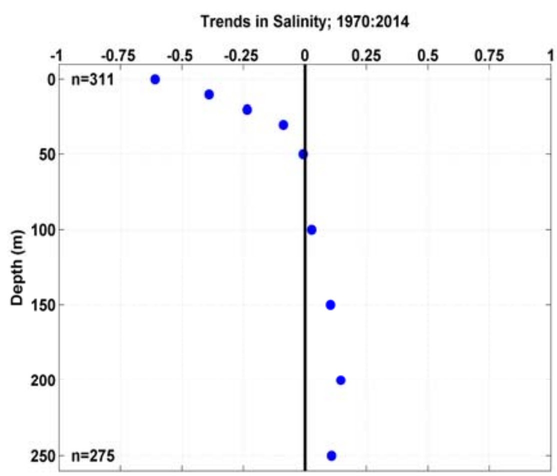
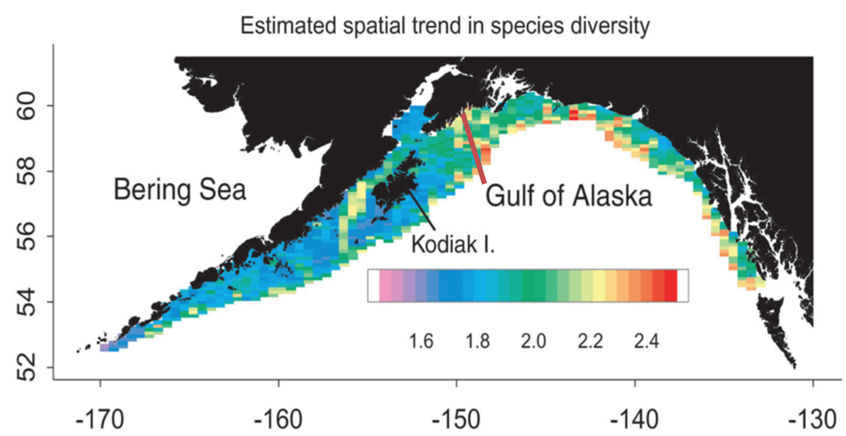



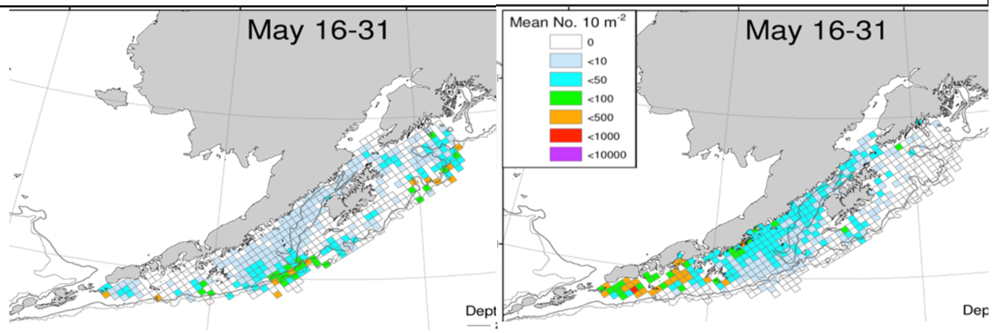

**Fig. 4C.** Left: Long-term records (1970-present) of temperature and salinity anomalies from 10 m depth at GAK1 on the Seward Line in the NGA. Right: depth profile of long-term salinity trend at GAK-1, showing freshening at the surface and increased salinity at depth.

**Fig. 4D.** East-west gradient in species diversity (Shannon-Weiner index) for Gulf of Alaska groundfish species (from Mueter & Norcross 2002). The Seward Line – backbone of the proposed NGA LTER - is located at the transition point between higher and lower diversity (red line)



## Fig. 5. Cross-shelf gradients in the proposed NGA LTER

**Fig. 5A**. Cross-shelf gradients in abundance of larval fish during late May (mean, 1981-2010). Left: arrowtooth flounder; right: Pacific cod (from Doyle & Mier 2016)



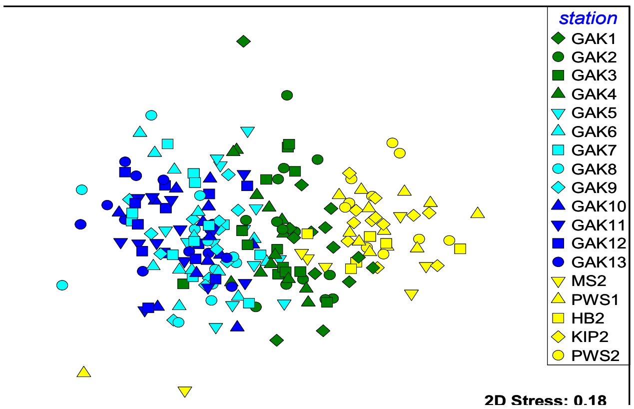




**Fig. 5B**. MDS plot of Seward Line mesozooplankton abundance and composition, 1998-2012. GAK stations with higher numbers are further offshore; yellow symbols are Prince William Sound stations. Data show a cross-shelf gradient with variable boundaries between inner, mid and outer shelf zones (from Hopcroft & Clarke in prep).

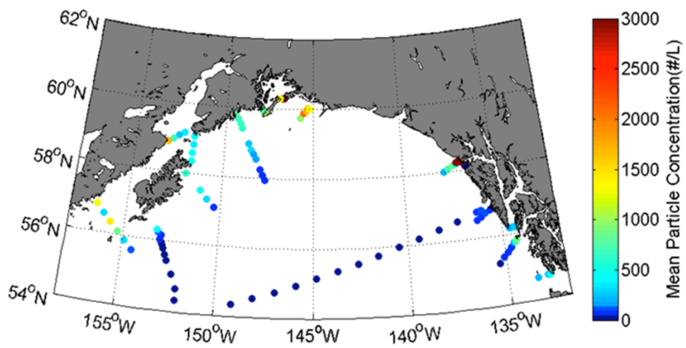
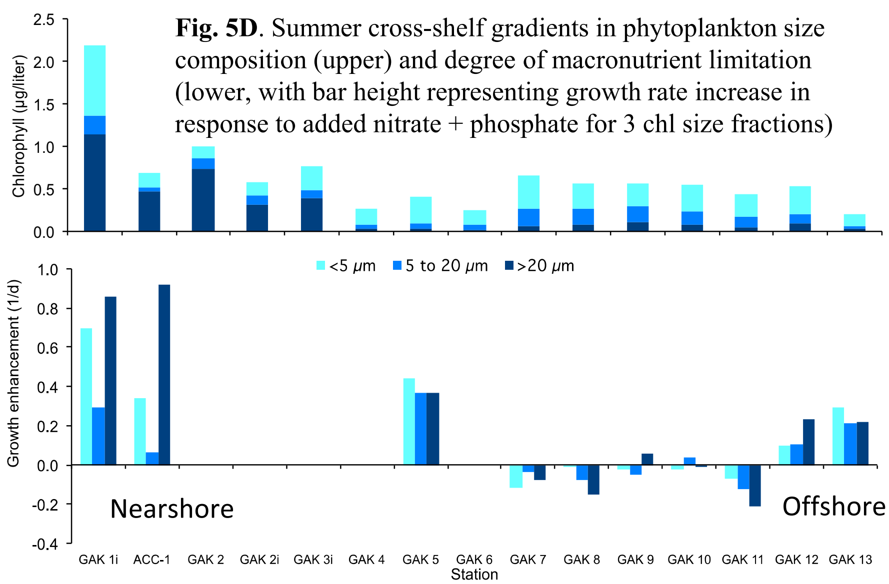



**Fig 5C**. Gradients in mean concentration of large particles (64 µm -2.5 cm) detected over the entire depth of the water column measured by the UVP5 (#/L) during cruises in June-August 2015. (From Turner et al., submitted)

**Fig. 5D**. Summer cross-shelf gradients in phytoplankton size composition (upper) and degree of macronutrient limitation (lower, with bar height representing growth rate increase in response to added nitrate + phosphate for 3 chl size fractions)



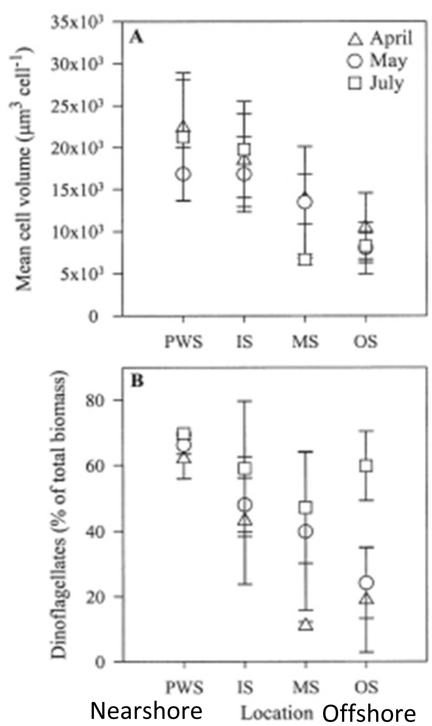




**Fig. 5E.** Cross-shelf gradients in spring and summer microzooplankton communities. Upper: mean cell volume; lower: proportion of dinoflagellates in community (from Strom et al. 2007)

**Fig. 6. Variability in production in the proposed NGA LTER**

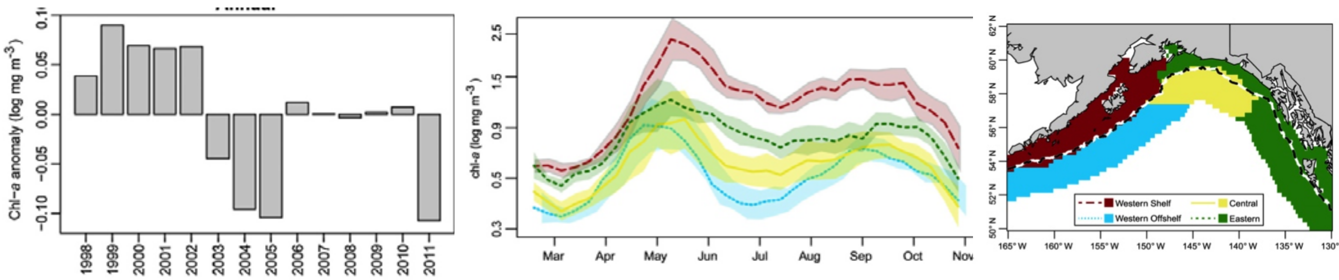



**Fig. 6A.** Heterogeneity in primary producer biomass in the coastal GOA. Left: Inter-annual variability in annual average chlorophyll concentration (as anomalies); Center: Seasonal chlorophyll cycle in 4 shelf and slope zones (see right pannel); Right: Unique figures of chl-a variability identified using cluster analysis (Waite & Mueter 2013).

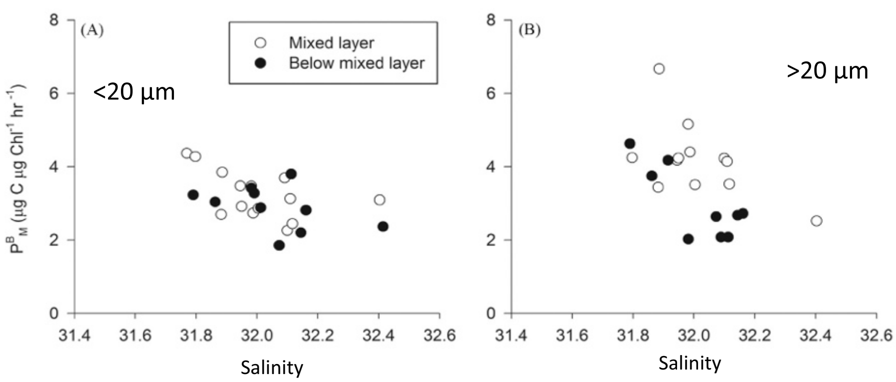



**Fig. 6B.** Maximum photosynthetic rate of spring 2011 NGA phytoplankton showed a negative relationship with salinity. Left panel: small (<20 µm) phytoplankton cells; right panel: large (>20 µm) cells. (From Strom et al. 2016)

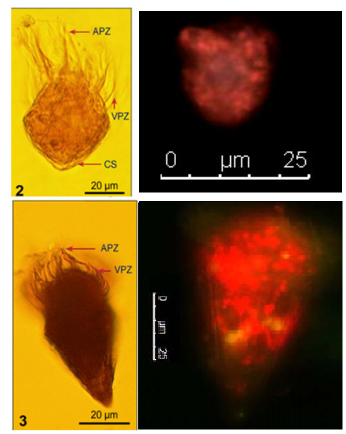



**Fig. 6C.** Chloroplast-retaining ciliates from spring 2016 on the Seward Line: right panels show red autofluorescence of sequestered chloroplasts in small (upper) and large (lower) *Strombidium* spp.; left panels show Lugols' fixed speciments of same species (courtesy D. Montagnes)

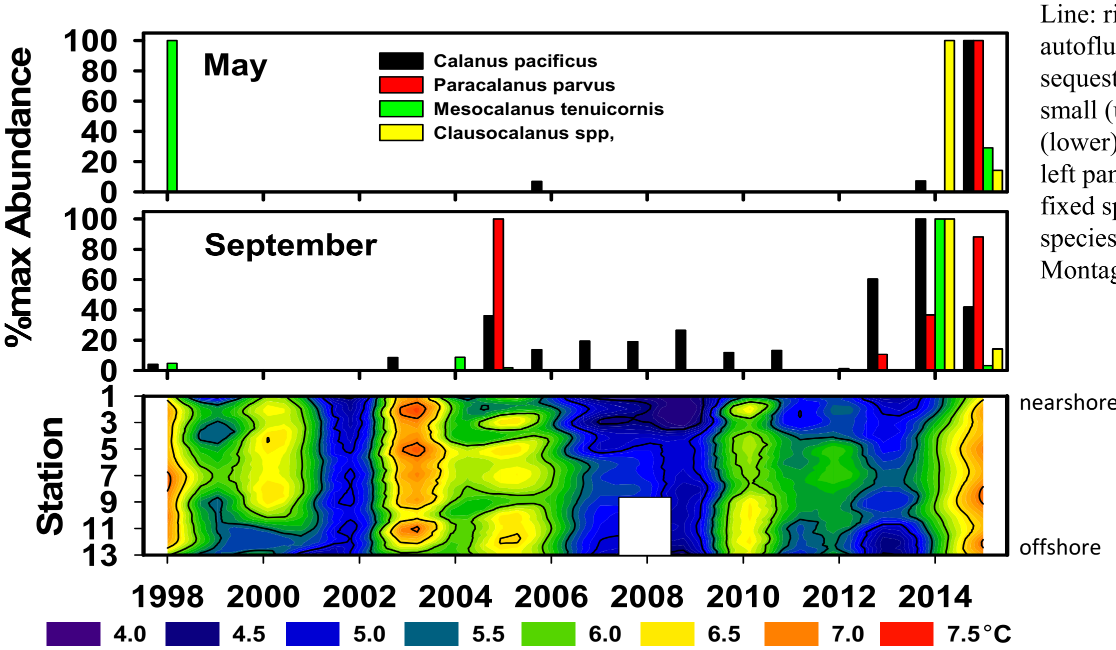



**Fig. 6D.** Observations of southern (CC) zooplankton species on the Seward Line during spring and fall over the 1998 – 2015 observation period, with 0-100 m average temperatures (bottom panel) shown for May along the Seward Line.

## Fig. 7. *Neocalanus* in the proposed NGA LTER

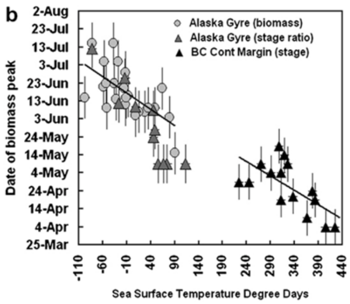
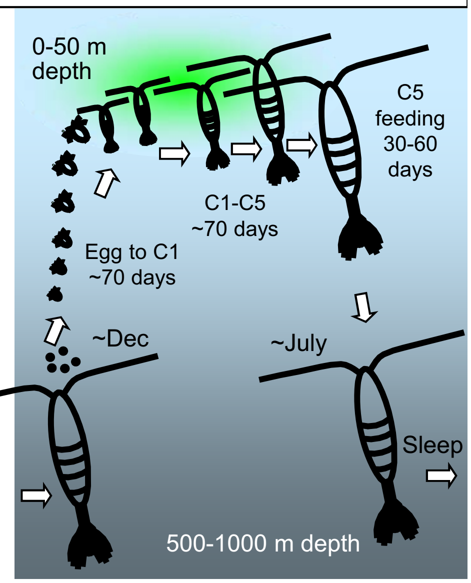



**Fig. 7A**. Timing of *Neocalanus plumchrus* biomass peak in surface waters can vary by ~3 months depending on temperature (From Mackas et al. 2007)

**Fig. 7B.** *Neocalanus* annual life cycle showing ontogenetic vertical migration



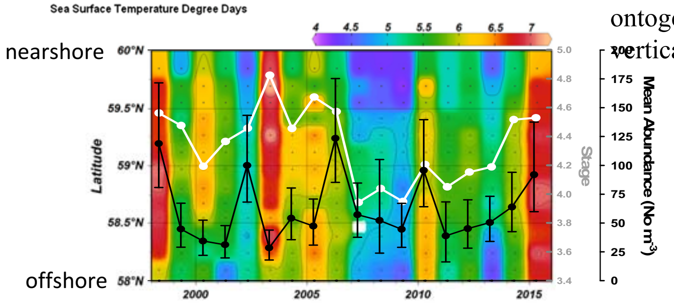
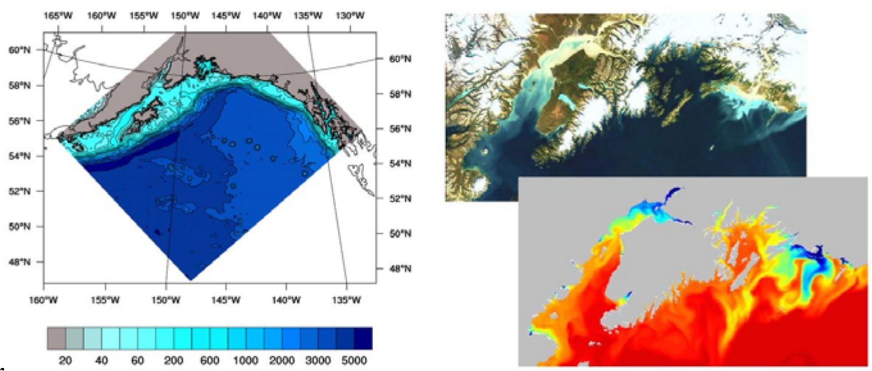




**Fig. 7C.** *Neocalanus* spp. mean abundance (black) and life stage (white) during early May (1998 – 2015) on the Seward Line. Temperature average of the upper 100 m (color).

## Fig. 8. NGA LTER Model

**Fig. 8A**. Proposed model domain. Left: the geographical extent of the ROMS domain and horizontal model resolution were specifically chosen to be capable of resolving both eddy activity offshore, and nearshore coastal dynamics associated with river discharge. Color represents bottom topography in meters. Right: simulated surface salinity in the eastern NGA domain showing regions influenced by freshwater discharge (blue-green colors), such as Cook Inlet and the Copper River plume



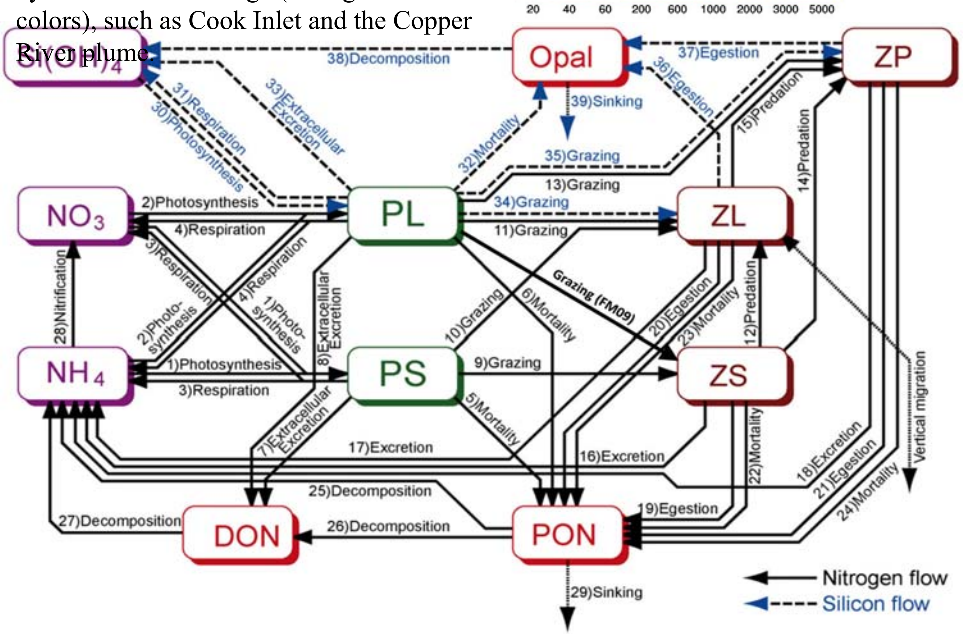



**Fig. 8B**. Schematic for the NEMURO biogeochemical model in its default configuration (from Kishi et al. 2007) with added microzooplankton grazing on large phytoplankton (Fiechter and Moore 2009 (FM09)) . The specific formulation that will be used for the LTER project also includes carbon and oxygen cycling as described in Fiechter et al. 2014.

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## Project Management Plan

Intellectual coordination and governance of the project will be principal investigators (Table 1). Decision-making will be by consensus within this group, including such potential issues as inclusion of new investigators, modification to the proposed research plan, and re-allocation of funds. Associates (Table 1) can contribute to these discussions. Communication will occur through bimonthly phone conferences, frequent email exchanges, and an annual project meeting. The annual project meeting will generally be held in conjunction with a widely attended national meeting (e.g., Ocean Sciences, Aquatic Sciences, LTER All-Investigator meeting), and will serve to present findings and review accomplishments from the previous year, plan the coming year's work, and discuss site management related issues. This meeting will be open to our NOAA fisheries and USFWS collaborators, graduate students whose research involves significant intellectual engagement with NGA, and colleagues involved in the Seward Line observational program. Effort will be made to allocate travel funds to graduate students for participation in project meetings. Hopcroft and Danielson are members of the Gulf Watch Alaska scientific management committee, ensuring co-ordination of NGA with their activities and scientists through quarterly phone conferences and annual meetings. Participation in Gulf Watch Alaska provides links to the majority of programs underway in the NGA and PWS, including projects from nearshore invertebrates to great whales.

**Table 1.** Participants for the NGA LTER site

| Name | Role | Institution | Interest |
|---|---|---|---|
| Russ Hopcroft | Lead PI | UAF | Zooplankton Ecology |
| Ana Aguilar-Islas | co-PI | UAF | Iron Biogeochemistry |
| Seth Danieldson | co-PI | UAF | Circulation and water masses |
| Jerome Fiechter | co-PI | UCSC | Biophysical Modeling |
| Suzanne Strom | co-PI | WWU | Phytoplankton and Microzooplankton Ecology |
| Rob Bochenek | Associate | Axiom | Information Systems |
| Claudine Hauri | Associate | UAF | Biophysical Modeling |
| David Hill | Associate | OSU | Environmental Fluid Mechanics |
| Andrew McDonnell | Associate | UAF | Particulate Matter Dynamics |
| Marylin Sigman | Associate | UAF | Education and Outreach |

**Specific PI responsabilities**

Lead PI Hopcroft will oversee the sampling program, act as chief scientist on most cruises, aided by Danieldson, Strom or Aguilar-Islas in the role of co-chief scientist, and be responsible for synthesis and preparation of the reports – a roll he fulfills with the existing Seward Line consortium. He will serve as the site representative on the LTER council. A project manager will be hired (2 months per year) to assist with administrative tasks as well as to maintain and update the project website. UAF has several senior scientific staff members capable of performing this function, final choice will be determined prior to project initiation. Financial administration will be handled by Hopcroft's departmental grant technician at no specific cost to this project as part of UAF's F&A costs.

Hopcroft has worked on planktonic communities for 30 years, and within Alaska waters for nearly 15 years. He has worked on numerous large multidisciplinary projects, including NPRB's Gulf of Alaska Program, often performing coordination roles in addition to his scientific duties. He has worked closely with most of this proposal's co-PIs for the past decade. He is broadly trained in most oceanographic disciplines, and in the operation, maintenance and trouble-shooting of most equipment to be used in this project. Within the disciplines, Hopcroft will be responsible for daytime operations of CTD and zooplankton sampling. His laboratory technicians have decades of experience with Alaska waters zooplankton.

Danielson will process data streams from physical parameters and assist in data interpretation and cross-disciplinary synthesis activities. Danielson is a physical oceanographer with over 20 years of experience in Alaska regional oceanography, focusing on causes and effects of shelf circulation and thermohaline variations. Danielson has been involved with Seward Line sampling since 1997, acting as chief scientist on nearly a third of the monitoring cruises between 1998 and 2004. In addition, he is involved with the moored time-series at GAK1 (the inner-most Seward Line station) and assists the National Park Service with their Vital Signs Monitoring oceanographic surveys in Glacier Bay waters (1993-present). He will be involved in graduate student training and mentoring.

Strom will be responsible for chlorophyll analysis, as well as phyto- and microzooplankton identification, quantification, and process studies. She has been working on phyto- and microzooplankton in the Gulf of Alaska for ~25 years, with recent projects focused on coastal waters. She has participated in numerous cruises to the region, including several as chief scientist, and has served in leadership roles (e.g., science steering committee) for several multi-disciplinary programs in the region. Her expertise includes lower trophic level productivity, environmental effects on marine plankton, and trophic interactions among phyto-, microzoo- and mesozooplankton. Strom's laboratory technicians have decades of experience with Gulf of Alaska phyto- and microzooplankton. Strom will be involved in student mentoring and training.

Aguilar-Islas will be responsible for all aspects of sampling, processing and analysis of iron species. She will also oversee collection of samples for macronutrient analysis and will coordinate with ODF the analysis of these samples. She will be directly involved in the design and execution of onboard experiments that include iron and macronutrient manipulation. She will mentor a graduate student as part of this project, and will be involved in synthesis and publication of results. She has expertise in trace metal chemistry and focus in high latitude systems. She has participated in several multidisciplinary projects including work in the Gulf of Alaska shelf (NPRB GoA Project), the Bering Sea Shelf (BEST-BSRP), and the Columbia River Plume (RISE). She is an active participant in GEOTRACES program – and international study of marine biogeochemical cycles of trace elements and their isotopes – including involvement in sample collection and distribution to the community, intercallibration work, and membership in the scientific steering committee for the US.

McDonnell has extensive experience studying sinking particulate matter as it relates to the ocean's biological carbon pump and has developed and advanced several methodologies in this field. McDonnell will be responsible for overseeing the particulate matter component of this LTER project. This includes the operation of the moored sediment trap to obtain a new time-series of particulate matter fluxes, as well as assessments of the particle concentration and size distribution from the in situ optical instruments (UVP and LISST). McDonnell will be responsible for processing the samples and data from these instruments and will participate in the analysis and publication of these results.

Fiechter will act as the lead investigator for the modeling component. His expertise is in coupled physical-biological and end-to-end ecosystem models applied to the Northeastern Pacific region (i.e., Gulf of Alaska and California Current System). More specifically, Fiechter has successfully used ROMS and NPZD-type models in both forward and data assimilative configurations to study the role of wind forcing and mesoscale eddies on phytoplankton community structure in the NGA. He has also explored innovative methods, such as ensemble calculations and Bayesian hierarchical models, to address questions related to uncertainty in biogeochemical model parameterization. Fiechter's main responsibilities will be to coordinate research activities (both within the modeling group and with the observational team), implement, run, and analysis output from the coupled ROMS-NEMURO model in its different configurations (see specific tasks listed under D.5.b), contribute to manuscripts and annual reports writing.

Hauri is specialized in using regional/global models and observations to study biogeochemical processes in Polar regions. As part of a currently funded NSF project she is developing a high-resolution coupled physical-biogeochemical model to identify the drivers and patterns of high $CO_2$ waters in the Gulf of Alaska. For this LTER project, Hauri will collaborate on all modeling aspects of the proposed work including implementation, evaluation, comparison with existing models, and preparation of future simulations. She will contribute to the analysis and publication of the results, especially as they relate to the impacts of climate change and ocean acidification on inorganic carbon dynamics and ecosystem processes.

Sigman will be responsible for outreach and education activities and products. She has two decades of experience managing outreach and education programs for Alaska marine ecosystems research, including the Gulf Watch Alaska program and Alaska Sea Grant research and education projects. She also served as an outreach consultant to numerous Gulf of Alaska researchers through the NSF-funded Alaska Center for Ocean Sciences Education Excellence.

Bochenek will serve as the technical manager of the data management system for this LTER program, supervising a technical staff of 15 at Axiom. He will serve as the primary spokesperson to communicate, work with, and respond to requirements and concerns of the PIs and LTER Council. Additionally, he will have oversight to ensure data accessibility and preservation needs are being met relative to LTER Network policies and submitted on schedule as stated in the RFP to make them publically accessible through the NIS Data Portal and the DataONE network.

The Seward Line observational program operates as a consortium led by Hopcroft. The consortium (Table 2) consists of funding through NPRB's Gulf of Alaska program, and through the EVOS Gulf Watch Program. Support from the latter is now in the $5^{th}$ year of a 5-year funding cycle that is conceived as the first phase of a 20-year program with renewals. Hopcroft receives annual funding through AOOS envisioned to cover the same 20-year duration. Funding from NPRB, through the agency's long-term monitoring program, is nearing the end of the second of a 5-year cycle. Nearly half of the support from these three sources is required to fund shiptime for the spring and fall surveys. UAF provides in-kind logistical support for cruises and a month of Hopcroft's salary annually. USFWS provides some portion of salary support for Kuletz. Hopcroft serves on the Science advisory team of the EVOS Gulf Watch program and through this structure, coordinates with all other members of the Gulf Watch oceanographic component: Weingartner/Danileson's GAK1 project, Batten's CPR program, Campbell's Prince William Sound and Doroff's Kachemak Bay oceanography. Kutlez is also a Gulf Watch PI working on seabirds within PWS & Cook Inlet. Co-PI McDonnell has received NSF support for particle flux. Given its duration, the Gulf Watch program already has guidelines in place on conflict resolution, and replacement of senior personnel upon retirement or failure to meet commitments. We expect these principles to be transferable to our LTER, with NSF program managers involved in consultation when appropriate.

**Table 2**. Funding streams supporting the Seward Line core observation program (spring and fall).

| Source | 2014/15 | 2015/16 | 2016/17 | 2017/18 | 2018/19 | TOTAL |
|---|---|---|---|---|---|---|
| NPRB (core) | $200,000 | $200,000 | $200,000 | $200,000 | $200,000 | 1,000,000 |
| UAF | $20,160 | $20,745 | $21,350 | $21,970 | $22,600 | |
| FWS | $27,000 | $27,810 | $28,644 | $29,504 | $30,389 | |
| AOOS | $100,000 | $100,000 | $100,000 | TBD | TBD | |
| EVOS | $100,497 | $104,007 | $107,703 | TBD | TBD | |

## Data Management Plan

**Data Management System**

Data management will be supplied by Axiom Data Science (www.axiomdatascience.com) and leverage the existing data system developed and supported by its partner, the Alaska Ocean Observing System (AOOS). Axiom is an informatics and software engineering firm focused on developing scalable cyberinfrastructure to integrate, curate, and provide access to real-time, modeled, GIS and remote sensing data. Through this data system, PIs will have access to the Research Workspace, which is a web-based project level data management system. The Workspace serves as central platform to store and collaboratively share preliminary data, sampling protocols, and other materials.The Workspace is coupled with an integrated editor for PIs to generate metadata records that comply with ISO 19115 standards. The Workspace and its metadata editor will be supported and cultivated throughout the project with several major modifications and upgrades planned. Data and metadata stored on the Workspace will then be packaged and sent to the DataONE member node maintained by Axiom/AOOS, and linked to the AOOS Gulf of Alaska Data Portal (http://portal.aoos.org/gulf-of-alaska.php) to be made publicly-accessible to broad community of scientists and decision-makers. A large task will be to work on compatibility of data streams from various projects, so that synthesized products and visualizations can be created. A web-based data visualization/integration tool will be deployed, which provides users with an interface to NGA LTER project level data and visualizations. This interface will allow users to query project profiles and metadata by time, parameter, species and spatial location. Significant work has already been undertaken by Axiom staff to design and develop this system as a component of the core AOOS data system. Long-term preservation of data in DataONE and the LTER Network Information System (NIS) Data Portal will be facilitated through the new, automated data-submission feature in development for the Workspace, scheduled for release concurrently with the Axiom/AOOS DataONE member node in November 2016. The NGA LTER website will also inform the public of the project and provide a link to the data visualization interface and archive.

The Axiom team will provide the NGA LTER with critical data management support to assist study teams in efficiently meeting their objectives and ensuring data produced or consolidated through the effort are organized, documented and available to be used by fellow LTER investigators and future research efforts. The data management team proposes to leverage AOOS's existing data system already in use by the Seward Line PIs to support data submission, metadata generation and data transfer to data repositories using the Research Workspace. The data management team will work closely with researchers to track data submissions to ensure they occur within 2 years of collection. It will review/audit metadata and data structure formats produced from NGA LTER projects and advise study team members in best practices for data formats and metadata authoring. Axiom software engineers will support and enhance existing web-based tools designed for the discovery and interactive exploration of visualized NGA LTER project data. The data management team will also guide and support PIs in the generation and update of data management plans, authoring metadata, and archiving project data to the NIS Data Portal and DataONE according to LTER Network policies.

**Types of Data**

This project will generate and assemble diverse types of data and products from moorings, cruises, and ocean circulation/biogeochemical modeling. Data from shipboard oceanographic sampling will include conductivity, temperature, depth, dissolved organic/inorganic carbon, chlorophyll a, micro- and macronutrients, phyto-, micro-, and zooplankton composition and biomass, primary production via stable isotope analysis, optically-derived particle size/flux, and seabird and marine mammal observations. Moorings will collect oceanographic data at multiple depths, including temperature, conductivity interpreted as salinity, acoustic recordings, acoustic backscatter, photosynthetically active radiation, iron speciation, current velocity, directional wave spectra, particle size spectra, colored dissolved organic matter, optical backscatter, pH, and variety of other data types depending on final instrumentation. Physical-biogeochemical model simulations will produce regional predictions of phyto- and zooplankton community responses to variations in seasonal climatology of freshwater input.

**Data and Metadata Standards**
Data management staff will assist with the creation of data management plans (DMP) specific to each NGA LTER project at its onset; thereafter, project PIs will update DMPs annually. NGA LTER projects will use well-defined, community accepted data and metadata formats and appropriate standards. We will use guidelines for data and metadata developed by the LTER Network and consistent with the Division of Ocean Science Sample and Data Policy that are designed to promote broad data access, standardization, and long-term data usability. Tabular data will be delivered to the Workspace as comma-delimited ASCII files (csv) which include header information that is uniformly formatted for each data type. Any geospatial products will be stored in the Workspace in their native formats and converted to shapefiles, geoTIFFs, or netCDF files for long-term preservation and sharing. Oceanographic models (& datasets) will be shared and preserved in netCDF to support a machine-independent format for representing data. Metadata documentation will be generated in either ISO 19115 or Ecological Metadata Language (EML) specifications that are adapted for a variety of data types and used universally in the oceanographic and ecological sciences. Metadata authoring will follow policies that meet the LTER standards for the NIS Data Portal. Data management staff will recommend and provide guidance on the metadata editor tool available through the Research Workspace. The Workspace metadata editor generates ISO 19115 standard metadata, with a roadmap for future developments including the ability to export metadata content as EML. In the interim, investigators that chose the EML format will be required to upload their EML record to the Workspace where it will be packaged, shared, and preserved with the data, and translated into ISO 19115 for discovery through the publicly-accessible portal(s).
**Data Submission Policy**
The NGA LTER site endorses the LTER Network Data Access Policy, which states that research data must be made available online within 2 years of collection and no later than publication of the main findings. The following guidelines will be followed to ensure the availability of NGA data to a broad research community: 1) Project data management plans must be submitted by the PI at the start of a new project and updated annually thereafter until completion; 2) Data and metadata must be submitted to the Research Workspace within 1 year of collection, and will be freely and publically available in the LTER NIS Data Portal and the AOOS Gulf of Alaska Data Portal not to exceed 2 years after collection. 3) Primary responsibility for data completeness and integrity (quality control) rests with the submitiing PI.
**Data Use, Archive, and Preservation**
Within 2 years of collection, NGA LTER site data will be freely available from the DataONE network, the LTER NIS Data Portal, and from the AOOS Gulf of Alaska Data Portal, along with descriptive metadata and supplemental documentation as appropriate. Data collected during NSF-supported oceanographic research cruises will be submitted to the R2R (Rolling Deck to Repository) program by the vessel operator. Prospective data users will be asked to identify themselves to the LTER PI and/or the PI responsible for the dataset to be used. Metadata for each dataset will include citation information as well as the following use statement: *This dataset is released to the public and may be freely reused. Please keep the NGA LTER site and the dataset contact person informed of any plans to use the dataset. Consultation or collaboration with the original investigators is strongly encouraged. Publications and data products that make use of the dataset must include proper acknowledgement. More information on LTER Network data access and use policies is available at: http://www.lternet.edu/data/netpolicy.html.*
**Milestones and Deliverables**
*2017 Dec*: NGA LTER Workspace group created, PIs have access, trainings scheduled for Jan-Feb 2018.
*2018 Oct*: Data inventory exists, submissions procedures shared with PIs and tracking by Axiom team.
*2018 Oct-2019 Oct*: Data from 1st year collection submitted to the Workspace with draft metadata describing projects and datasets; Axiom quality reviews data formats and metadata; repeated annually for data collected in subsequent years.
*2019 Oct - 2020 Oct:* Data from first collection year has been transferred to LTER NIS with complete metadata; repeated annually for data collected in subsequent years.
*2023 Oct*: All data and metadata, including model results and documentation, from initial 6 years of NGA LTER has been transferred to LTER NIS and DataONE.