Background

Ecosystems in the Bering and Chukchi Seas (i.e. the Pacific Arctic, **Figure 1B**; Baker et al., 2020) are changing (Huntington et al., 2020) and Alaskan communities reliant on marine resources are vulnerable to ecosystem shifts (Himes-Cornell et al., 2015). Recent regional observations, climatologies, and models have demonstrated declining sea ice (Frey et al., 2015; **Figure 1C**), warming surface temperature (Danielson et al., 2020), decreasing salinity (Woodgate et al., 2018), and more extreme weather (Walsh et al., 2020).

There is a history of physical oceanography in the Pacific Arctic with annual measurements of temperature since ~1955 (Danielson et al., 2020; **Figure 1D**). Notably, spatial and intra-annual observations have always been challenging due to seasonal weather and sea ice. Despite long-term efforts (e.g. Grebmeier et al., 2020), biogeochemical resolution remains poor (**Figure 1D-E**) obscuring how regional nutrient dynamics may be sensitive to changing environmental conditions (Hennon et al., *in prep*; Stabeno et al., 2019). Thus, even fundamental ecological linkages, such as the response of primary producers to changes in salinity, temperature, sea ice condition and nutrients are largely unconstrained. Uncertainty about lower trophic level (LTL: phytoplankton and zooplankton) response to environmental drivers impedes our ability to predict how subsistence and commercial resources, and thus Alaskans, will be impacted by changing climate.

Knowledge on potential impacts of the changing Pacific Arctic on higher trophic levels (HTL; e.g. fishes, pinnipeds) (Mueter et al., 2021) is important to Alaskans. Resources for HTLs are shaped by physical conditions, basal resource availability and LTL connectivity (Friedland et al., 2011, Marshak & Link, 2021). End-to-end models, connecting the ecosystem from nutrients to HTLs, remain difficult to parameterize considering HTL data availability (Maureaud et al., 2020; Pickens et al., 2021) and mechanistic connectivity to LTLs (Chenillat et al., 2021). Satellite analyses have highlighted that warming and earlier ice retreat leads to earlier blooms, longer growing seasons (Song et al., 2021) and increased primary production (by ~30%; Lewis et al., 2020) – and changes in primary productivity likely have implications for resource allocations to other parts of the ecosystem. Despite the great temporal and spatial coverage that satellites provide, analyses are restricted to surface waters and limited by cloud and ice cover. As a result, we still need to understand LTL mechanisms driving apparent changes.

NPRB's Arctic Integrated Ecosystem Research Program (Arctic IERP) – consisting of Arctic Shelf Growth, Advection, Respiration, and Deposition Rate Experiments (ASGARD) and Arctic Integrated Ecosystem Study (AIES) – generated multi-disciplinary data sets (physical, hydrochemical, and ecosystem function) in the Northern Bering and Chukchi Seas (2017–2019). These campaigns produced data that may be used to constrain environmental drivers like nutrient supply (e.g. advected or local), which is important for predicting LTL and HTL dynamics. Arctic IERP and other recent research has resolved several major points:

1. Climatologies indicate increasing heat transport into the Pacific Arctic which further enhances warming (Danielson et al., 2020).
2. Nutrients in the Chukchi Sea are resupplied by lateral advection through the Bering Strait (Mordy et al., 2020), but it is unclear if, or how, Bering Strait nutrient fluxes are changing (Hennon et al., *in prep*; Mordy et al., 2020) despite increases in terrestrial sources (Walvoord and Striegl, 2007; Mars and Houseknecht, 2007).
3. Regional increases in phytoplankton have been attributed to increased nutrient availability (Lewis et al., 2020), warming surface waters (Lomas et al., in prep), and reduced sea ice coverage (Kinney 2020).
4. Productivity is vertically stratified, even over shallow shelves (Stabeno et al., 2020), and summertime deep chlorophyll maxima are common (Bouman et al., 2020).
5. Unlike small phytoplankton, spring diatom production is regulated by light and nutrient co-availability and not grazing pressure (Krause et al., 2021).

These observations allude to a strongly coupled system where lateral connectivity and vertically partitioned processes prevail. Our understanding of how productivity in the Pacific Arctic is structured is often resolved by site-specific studies. Primary productivity in the Chukchi Sea is often nitrogen limited (Mills et al. 2018); yet, the source of nitrogen to surface communities is largely unquantified with respect to advection, local remineralization (Brown et al., 2015), and/or turbulent mixing (e.g. Zheng et al., 2021). Thus, a major synthesis effort is required to assess biological responses to ecological drivers region-wide. To connect local observations to regional trends, our project–*SEAS the Change*–aims to combine observations with state of the art modeling to improve our understanding of nitrogen transports into and within lower trophic levels, and to provide foundational improvements for future, HTL studies.

SEAS the Change will investigate ecosystem sensitivity to nutrient fluxes and changing environmental parameters in the Northern Bering and Chukchi Seas (**Figure 1B**). This project will leverage ASGARD and AIES datasets, in collaboration with dataset originators. We'll complement the ASGARD and AIES datasets spatially and temporally by utilizing previously collected biogeochemical and remote sensing data (**Table 1**). We will use a multifaceted modeling approach including a regional physical circulation model (ROMS) and a marine ecosystem model (COBALT; **Figure 2**) to assess regional linkages between nitrogen supply (as nitrate and ammonium) and productivity. Using observations, we will quantify nitrogen fluxes through the trophic system using a linear inverse ecosystem model (LIEM). Through the novel use of both regional ecosystem (ROMS/COBALT) and inverse (LIEM) modeling paradigms, assumptions required for one approach may be tested and validated by the other.

SEAS the Change responds to NPRB's Synthesis RFP by employing multiple tools to address regional questions (*see Objectives*; **Figure 1A**) using a collection of data sources, including previous NPRB studies. It aligns with the Arctic IERP mission by aiming to resolve mechanistic processes that influence marine primary producers and consumers – especially in light of changing climate. Our research will demonstrate how lateral supply of nitrogen informs spatial patterns and magnitude of LTL response in the Northern Bering and Chukchi Seas and will better inform the community on regional predictability. The SEAS the Change program supports early career development of 5 researchers in collaboration with well established investigators; it supports summer undergraduate researchers, community workshops, and outreach on demystifying models.

Objectives

1. [Physical Coupling]: Use model hindcasts and field observations to determine the degree to which allochthonous (i.e., advected) or autochthonous (i.e. local) nutrient supply supports primary production within the Northern Bering and Chukchi Seas.
2. [Physical Coupling]: Assess spatio-temporal co-variability of physical parameters (e.g. temperature, sea ice) with nutrients, chlorophyll, and net primary production.
3. [Ecosystem Processes]: Using in situ data and model hindcasts, assess the impacts that a changing physical environment (e.g., transport, light, temperature, stratification) has on pelagic communities by quantifying rates (e.g. nitrate uptake) of primary producers and the transfer of nitrogen between primary producers and lower trophic level consumers.
4. [Engagement]: Review the state of biogeochemical observations of the Arctic Ocean, especially the Pacific Arctic, through involvement of colleagues and stakeholders at day-long workshops held immediately prior to the Alaska Marine Science Symposium.
5. [Engagement]: Retrieve and implement improvements to the educational dashboard suggested by Alaska Tribal Conference on Environmental Management (ATCEM) participants.

Design and Approach

A. Overview

Establishing linkages between the physical environment and lower trophic levels in the Pacific Arctic remains highly challenging primarily due to (1) complex physical processes and (2) a continuing lack of spatially and seasonally resolved observations of biogeochemical processes. This proposal seeks to improve our understanding about marine production in the changing Arctic, and we propose to leverage recent advances in physical and biogeochemical modeling to address key, data-driven questions about how Arctic marine LTLs respond to change across spatio-temporal scales. Through a multifaceted modeling approach, we will connect observations with circulation, transport, and physical drivers to resolve mechanistic linkages between the physical environment and phytoplankton productivity for the Pacific Arctic.

Data used in this study comes from a variety of sources extending back > 30 years, although most biogeochemical data is restricted to ~2005 and onward (**Table 1**), and is spatially or temporally (i.e. seasonally) limited. The modeling approach proposed here will help to extend our understanding of nutrient and LTL dynamics across space and time - especially during the more sparsely sampled seasonal transitions in spring and fall. We will use a space-for-time approach (Blois et al., 2013) when evaluating the impact that temporally variable drivers have on the ecosystem whereby independent stations data from across a natural gradient is used to inform how environmental changes impact the pelagic community. Additionally, spatial data (e.g. remote sensing) and a simplified linear inverse ecosystem model, along with results generated from this project, will be disseminated through an educational dashboard targeting high school and undergraduate aged students in order to demystify environmental modeling. Finally, community engagement, especially with Alaskan colleagues and partners, will be integrated through two scientific workshops focused on Arctic modeling resources and emerging issues and opportunities.

B. Hypotheses & Testing

Hypothesis 1: Overall Chukchi Sea primary production is determined by nitrogen availability and fluxes from the Bering Strait.

Primary production in the Chukchi Sea is often limited by nitrogen availability (Mills et al. 2018). Nitrogen sources may be lateral (supplied by physical movement of waters into the area), internal (local remineralization), or vertical (supplied by upward flux of nitrogen from remineralization/sediments) (Baer et al., 2017; Brown et al., 2014; Christman et al., 2011), and modulated by denitrification (Chang and Devol, 2009; Mordy et al., 2021). Hypothesis 1 aims to investigate the relative importance of lateral nitrogen supply to productivity in the Chukchi Sea. Lateral connectivity between the Northern Bering and Chukchi Seas will be assessed using a 10 year physical circulation hindcast of the region (ROMS - *Section C3*) by releasing an inert tracer at sites, with historical nitrogen data, in the Bering and Anadyr Straits (Danielson et al., 2017; 2020). This long-term tracer study will provide temporal context for the primary study years (2017-2019). To further assess how nutrient delivery impacts phytoplankton growth, output from a 2015-2019 hindcast simulation with the marine ecosystem model (COBALT - *Section C4*) will be used. Patterns in light, nutrient, and temperature limitations will be evaluated based on parameter values obtained from **H2** (below) using observational field data from the ASGARD and Arctic IES cruises. Rates of lateral supply will be compared with remineralization and denitrification rates derived from COBALT and the literature to ascertain the relative contributions of allochthonous (i.e. advected) or autochthonous (i.e. local) nutrient supply (Objective 1) within the euphotic zone and surface mixed layer.

Hypothesis 2: The recent increases in marine primary production is attributable to reduced sea ice extent and consequently enhanced light availability.

Previous research (largely from satellite studies) has demonstrated correlations between declining sea ice and increasing phytoplankton biomass (Kinney et al., 2020, Lewis et al., 2020); yet, it is unclear if increased primary production transfers to HTLs (Lomas et al., 2020), in part, because mechanisms sustaining increased productivity remain spatially unresolved and are likely variable in space and time. Finally, in situ observations suggest that changes in phytoplankton growth rate - rather than biomass – support increasing primary productivity in the Bering Sea (Lomas et al., 2020) suggesting a change in bottom up controls.

To address the primary production dynamics in the Pacific Arctic (**H2**), we'll use observations of environmental conditions (i.e. temperature, light, nutrients) and total and size-fractionated phytoplankton uptake rates (i.e. nitrate, ammonium, carbon) from ASGARD and AIES process cruises to estimate in situ nutrient uptake efficiencies and how well cells are adapted to changing light conditions (*Section C5*). Further application of an LIEM (*Section C5*) can provide information about nitrogen movement through the LTLs (**H5**).

Hypothesis 3: Earlier and more complete sea-ice retreat has led to earlier nutrient drawdown by phytoplankton in the Chukchi Sea leading to longer and more frequent occurrences of nitrogen limitation and subsurface chlorophyll maximums (DCMs) throughout the summer season.
Earlier blooms, fueled by earlier departure of sea ice, have been described in the Chukchi Sea (e.g. Song et al., 2021). Seasonal stratification over the shallow shelves may have profound effects on productivity (e.g. Churnside et al., 2020) and nutrient supply and availability (e.g. Mordy et al., 2020; Lin et al., 2019; Lowry et al., 2015) for the LTLs. Using observational data (Table 1), we will examine decadal and interannual trends of (A) surface nitrogen concentrations over time, (B) depth of DCM, (C) frequency of DCM occurrence, and (D) magnitude of DCM taken throughout the Northern Bering and Chukchi Sea. If significant, these trends would indicate (A) if nitrogen resupply is slower than growth in the surface and (B-D) if communities are moving to depths where nitrogen supply is greater.

Hypothesis 4: Intra-regional variability in primary production has increased over time leading to more sporadic spring and fall blooms and greater phytoplankton patchiness, especially in the Chukchi Sea where secular warming trends and sea ice retreat are pronounced.
Results from the 2018 ASGARD cruise indicated high variability in primary productivity among stations (Danielson et al., 2021). Patchiness in phytoplankton concentrations impacts zooplankton by sustaining zooplankton production in high productivity zones (Greer et al., 2020). Thus, by influencing zooplankton abundance, phytoplankton patchiness also influences micronekton prey availability. Patchiness can be calculated from field observations (stations, underway, towed instruments) and hindcast models (ROMS & COBALT). Physical patchiness (i.e. temperature, salinity) can be assessed within ROMS. Specifically, decorrelation length scales will be determined (Getis 2010; *Section C2*) in NPP, chlorophyll, and temperature signals; that is, how correlated is each signal with themselves over a certain distance within a specific region. In this analysis, short length scales are indicative of higher spatial variance and smaller patch size (i.e. higher patchiness; Mackas 1984; Johnson et al., 2008). Additionally, changes in temperature decorrelation length scales will reflect physical variability independent from biological response. We expect to see inter-annual increases in patchiness throughout the study region as sea ice declines (e.g. **Figure 1C**) and (sub)mesoscale variability increases.

Hypothesis 5: Seasonal shifts in planktonic community composition result from transitions between allochthonous nitrogen, internal recycling, and ambient nutrient depletion.
As noted in **H2**, phytoplankton growth rates may be limited by supply of nitrogen. Furthermore, the source of nitrogen (external or internal/regenerated) has the potential to vary with warm and cold conditions (seasonally; Lomas et al., 2020; Mordy et al., 2020). The planktonic community (phytoplankton and zooplankton) will respond to changes in resource abundance (i.e. nutrients, or prey; e.g. Greer et al., 2020; Hill et al., 2005; Spear et al., 2020). To address **H5**, observations (rate measurements made during ASGARD/AIES) and literature values (e.g. Brown et al., 2014, Christman et al., 2011; Baer et al., 2017) will be incorporated into a linear inverse ecosystem model (LIEM) designed to investigate the flow of nitrogen through the pelagic LTLs (*Section C5*). The LIEM will resolve primary production, excretion, respiration, grazing, remineralization through a microbial loop, and denitrification at several sites within the Chukchi Sea during the ASGARD cruises. From the model, rates of bacterial production and detrivory can be approximated for the mixed layer at each station. Using a space-for-time approach, we expect a seasonal shift from a community supported by externally supplied nitrogen in the early summer (i.e. locations with lower stratification and/or higher ice

coverage) towards recycled nitrogen and regenerative production later in the summer (i.e. warmer temperatures) as winter water is flushed off the shelf and replaced by nitrogen depleted summer water (Lin et al., 2019).

C. Scientific Approach

C1. Overview: The SEAS the Change project will be broadly partitioned into three interrelated and synergistic efforts (ROMS, COBALT, LIEM) aimed towards providing broad-scale synthesis of existing data sets and products. First, the Pacific Arctic will be spatially partitioned into marine “provinces” (Longhurst et al. 2007) based on hydrographic and biogeochemical properties - this analysis will be compared to previous efforts (e.g. Stabeno et al., 2012; Ortiz et al., 2016, Sigler et al., 2017). A machine learning approach, self organizing maps (SOM), will be used to identify salient temporal patterns within each marine province and will be used to resolve how modes of variability change spatially throughout the Bering and Chukchi Seas. Second, through a combination of hydrodynamic modeling (circulation, mixing) and marine ecosystem modeling (nutrients, lower trophic levels; **Figure 2**), we will conduct model evaluation within each province and identify nitrogen supply and utilization across space and time. This aggregative approach minimizes issues with point-to-point matchup due to mesoscale variability. Finally, through linear inverse ecosystem modeling (LIEM), ecosystem linkages between production and consumption (including phytoplankton, zooplankton, bacteria) will be independently ascertained (**Figure 2**).

C2. Exploratory Data Analysis and Domain Partitioning: In consistency with the available data, our study will focus on the Northern Bering and Chukchi Seas between 2017 and 2019. Physical, hydrochemical, and ecosystem level data from ASGARD and AIES campaigns will be the primary datasets included. We will also leverage data from the Distributed Biological Observatory (DBO) when available during the ASGARD and AIES campaign years (2017-2019). When relevant we will use additional data (outside the 2017-2019 timeframe) from previous campaigns and programs (**Table 1**; see *List of Data Sources*) to add resolution and context for the 2017-2019 years.

Due to the expanse and geographic complexity of the Pacific Arctic, data organization will require several stages. First oceanographic provinces will be defined based on spatial clustering of gridded hydrographic variables and remote sensing fields (e.g. sea ice coverage; EUMETSAT Sea Ice Coverage). This exercise will determine if previous divisions of the region into Eastern, Western, and Northern Bering Sea and the Chukchi Sea still well-describe the area (e.g. Sigler et al., 2017). The use of spatial provinces will permit a simplified experiment design when relating observational and modeling data, while simultaneously reducing the impact of anomalous data through aggregation. Next, to characterize and discern patterns with data within each province, we propose to use self organizing maps. Self organizing maps (SOM) are a machine learning technique that uses competitive learning to reduce the dimensionality of large datasets for analysis and prediction and is widely used in spatial analysis (e.g. Reusch et al., 2007; Zeng et al. 2015). The primary goal of SOM is to identify and extract features through pattern identification within the training data set. SOM provides a natural and more powerful extension to empirical orthogonal functions (Liu 2005; Liu et al., 2006). A SOM will be generated from common field observations (including nutrients, chlorophyll, temperature, salinity, etc.) and trained on emergent ecosystem properties including primary production and nutrient uptake.

Spatial variability (i.e. patchiness) will be determined by spatial decorrelation length scales. Decorrelation length scales will be calculated for observations from each cruise independently and compared to fields retrieved from the biogeochemical model and remote sensing (SeaWIFS and MODIS). Chlorophyll fluorescence will be compiled from ship underway data, towed sensors, and in-situ chlorophyll-a bottle samples. Daily-averaged modeled NPP rates from the Northern Bering and Chukchi Seas over the duration of each cruise will be used to ensure similar timing between modeled and observed decorrelation length scales. If the model compares well to observations, then the marine ecosystem model will be used to improve spatial resolution of the decorrelation length scale during the cruise years while remote sensing will provide long term context.

C3. Physical Modeling: The Pan-Arctic Regional Ocean Modeling System (PAROMS) is a validated physical circulation model with a domain from south of the Aleutian Islands to the southern extent of Greenland. In the Pacific Arctic, PAROMS has ~5 km resolution and uses the Alaska Regional Digital Elevation Model (version 2) for bathymetry (**Figure 3**). The boundary conditions are informed by SODA (1980 - 2015) and Global HYCOM (2015-2019). Numerous rivers along the coastal boundaries bring in freshwater, which is done with a point-source river input via exchange of mass, momentum, and tracers at all depths of the coastal wall (Danielson et al., 2020). JRA55-do (Tsujino, 2018) provides daily fresh water fluxes which were mapped to the PAROMS coastal grid points and applied as a series of lateral fresh water sources. These freshwater sources contain nutrient concentrations from Global Nutrient export from Watersheds models (NEWS, Seitzinger et al., 2005) and carbon sources based on observations from the Bering/Chukchi region (McClelland personal communication).

Some physical fields in the model (e.g. temperature, velocity, sea surface height) are well-validated, though others (e.g. salinity, sea ice extent) are not as well constrained in certain regions or at fine spatial scales (Curchitser et al., 2018; Danielson et al., 2020b). Since our work is not predicated upon point-to-point comparisons, the impact of model imperfections is not expected to be severe. PAROMS has been successfully applied to a variety of Pacific Arctic biological studies (Rand et al. 2018; Lovvorn et al., 2020; Deary et al., 2021; Vestfals et al. 2021). We intend to use the model to investigate the degree and variability of nitrogen transport within the study region. Lagrangian float experiments will quantify the physical connectivity between each marine province over biologically relevant timescales (i.e. days to weeks), by releasing particles uniformly across each province during the summer months. By tracking positions over time, lateral connectivity between each province can be assessed and transport rates calculated. Tracer experiments allow for determination of nutrient dynamics in the absence of biological processes.

C4. Biogeochemical Modeling: Hindcast ecosystem modeling capabilities will be provided from an actively developing marine ecosystem model (COBALT, Stock et al. 2014; van Oostended et al., 2018; **Figure 2**) with physical conditions provided by PAROMS (see *C3* above). Evaluation of the model is currently underway through a funded NSF project (NSF #1603116) and is expected to be complete in summer 2022. Following evaluation by the NSF project, this study proposes to utilize monthly outputs between May - October (2015-2019) to provide an independent and synoptic realization of the region while serving as a testbed for simulating change. We'll be using the model through the summer months, as there are insufficient winter observations to fully evaluate the winter season. The proposed model is state of the art for depicting biogeochemical cycles and lower trophic level processes in the Pacific Arctic, and has been successfully deployed in the Gulf of Alaska (Hauri et al., 2020, 2021). Its use here will focus on providing insights into nitrogen uptake and supply as well as in providing biogeochemical context for field observations.

The COBALT model used in this study has been modified with an additional coastal chain-forming diatom to better represent biogeochemical processes in highly productive coastal areas (3PS-COBALT, Van Oostende et al., 2018). With 36 state variables, the model resolves nitrogen, carbon, phosphate, silicate, iron, calcium carbonate, oxygen, and lithogenic material cycles, including process such as remineralization, nitrification, and denitrification (Stock et al., 2014). Nitrogen is used as the currency of biomass and productivity and was initialized with data from the World Ocean Atlas 2013 (Garcia et al., 2013). Other state variables were initialized as described in Hauri et al., (2020). Diazotrophs, small phytoplankton (<5um), medium phytoplankton (5 - 20 um), and a larger, chain-forming diatom (> 20 um) (**Figure 2**) take up ammonia, nitrate, and in the case of diazotrophs, dinitrogen. Primary productivity for each phytoplankton group is calculated based on the most limiting nutrient, light, temperature, and metabolic costs. The dynamic chlorophyll-to-carbon ratio is based on light and temperature (Geider et al., 1997). While nitrate and phosphate limitations are dependent on their ambient concentrations in seawater, iron limitation depends on the internal cell quota. Like all tracer concentrations in the model, nitrate and ammonia are affected by diffusion, horizontal and vertical advection, and sources minus sink terms, including net phytoplankton uptake, detritus remineralization in water column and in sediments (through pools of Dissolved Organic Nitrogen [DON]), nitrification, denitrification, atmospheric deposition, and river fluxes. The feeding of the three zooplankton groups is modeled with Holling's type II functional response as described in Stock et al. (2008). The sea-ice model does not currently include a biogeochemical component; however, efforts are underway to switch to a more complex sea ice model and focus on parameterization of biogeochemical processes in the sea ice, including sea ice algae, formation of ikaite etc.

C5. Inverse Modeling: To assess how variable nitrogen supply impacts the LTL we will use linear inverse ecosystem model (LIEM) which is a statistical, data-driven tool that incorporates disparate field observations, metabolic constraints, and associated uncertainties into a rigorously defined model. We'll use the LIEM to determine the fluxes of nitrogen through various ecosystem fields (e.g. uptake by phytoplankton, consumption by zooplankton, remineralization, export as detritus; **Figure 2**) for multiple locations throughout the Northern Bering and Chukchi Seas. The LIEM is physically decoupled - and thus won't incorporate lateral advection. It instead investigates the zero-dimensional movement of nitrogen through the ecosystem. By comparing the LIEM-determined fluxes of nitrogen through the ecosystem to physical conditions at each site, we can describe how regionality (as the result of temperature, salinity, light penetration or current speed) influences LTLs--and how LTLs influence nutrient cycling.

A LIEM consists of (1) a hypothetical food web (**Figure 2**), (2) model constraints (i.e. matrix equations), and (3) a solution set of ecosystem fluxes, in this case for nitrogen. The hypothetical food web contains compartments (e.g. Figure 2 boxes/circles) and fluxes (e.g. Figure 2 arrows). By using observations and literature constraints, the LIEM statistically determines the most likely set of fluxes through the ecosystem. The LIEM will contain many more flux terms (i.e. unknowns) than observations (i.e. knowns), which means there are infinite possible solutions that satisfy all constraints (i.e. under-constrained system of equations). To determine the most likely solution and uncertainty for each unknown term, we will use a Markov Chain Monte Carlo (MCMC) sampling method (Kones et al., 2009; van den Meersche et al., 2009; van Oevelen et al., 2010, Soetaert et al., 2017), which explores the possible set of solutions to the model while attempting to reduce model-observation misfit (i.e. maximize likelihood). The MCMC is repeated millions of times to generate a statistically robust distribution of fluxes through the ecosystem.

An independent LIEM will be run for the mixed layer of each marine province with constraints provided by a compilation of all available field data taken within that area during a given cruise. While traditional implementations would run a separate LIEM for each station, this study aims to determine ecosystem flows across larger spatial-temporal scales. By consolidating the available data into groups of multiple stations, uncertainty in each measurement and the impact of non-steady state conditions are reduced. Literature values–taken from regional studies if available–and subsequent derived quantities (e.g. allometric scaling) will be shared among all LIEM runs. Results from the LIEM will be used to investigate how conditions at each site influenced ecosystem flows. The LIEM flows can be complemented and compared with COBALT modeled flows (from monthly outputs for each grid cell in the region) to provide additional spatial resolution.

As an additional product of inverse modeling (using the MCMC sampling method), we will assess how well observations match expected fluxes determined using common biogeochemical model equations (Bayesian parameter optimization; e.g. Yingling et al., 2021; Fiechter et al., 2013). Specifically we will investigate nutrient uptake and phytoplankton growth equations (**Table 2**) by optimizing these common functional relationships to field observations of ambient conditions (e.g. temperature, light, nutrient concentrations), phytoplankton biomass, and biological rates (e.g. primary productivity, nitrate and ammonium uptake). Calculated analogously to the LIEM, we will determine parameter sets that maximize the "likelihood" of the observations given these equations (i.e. Bayesian parameter optimization). Such a comparison will allow us to investigate how well literature-derived parameterizations, and the underlying equations, represent the Bering-Chukchi system.

D. Demonstration of Capability

D1. Numerical Modeling: Proposed numerical modeling activities include leveraging of previous model runs and new work. Existing PAROMS output fields (daily and monthly averaged) will be used for the majority of the proposed tracer and Lagrangian simulations. Optionally, additional PAROMS runs can be conducted by Collaborators Hedstrom and Danielson. Project co-PI Hennon has worked on PAROMS analysis (Danielson et al., 2020), while co-PI Hauri has recently published a COBALT-based biogeochemical model of the Gulf of Alaska (Hauri et al., 2020). PI Kelly has previously conducted Lagrangian circulation experiments in the Gulf of Mexico (Gerard et al., 2020) and California Current (Kelly et al., 2018) and actively maintains open-source libraries for oceanographic data analysis and Lagrangian simulations (Kelly, 2019).

D2. Ecosystem Response & Biogeochemistry: Ecological expertise and regional familiarity with planktonic communities will be led by PI Mordy and co-PI Nielsen, who primarily conducts fieldwork and analysis of Pacific Arctic food webs. Collaborator Nielsen is currently developing a carbon-based LIEM for Northern Bering and Chukchi Sea plankton food web and has extensively researched LTL dynamics in the Bering and Chukchi Seas (Nielsen et al., *in revision;* Nielsen et al., *in prep*). PI Kelly has published on LIEM development (Stukel et al., 2018) and implementation (Kelly et al., 2019). Co-PI Whitmore has published on geochemical tracers of water-sediment interactions (Whitmore et al., 2019; Whitmore et al., *in review*) and circulation (Whitmore et al., 2020) in the Pacific Arctic and has experience leading and participating in international synthesis efforts (Charette et al., 2020; Whitmore et al., *in review*; Whitmore et al., *in prep*).

Data Sources

1. Arctic Shelf Growth, Advection, Respiration, and Deposition (NPRB), Available [https://arctic-ierp.dataportal.nprb.org/]
2. Arctic Integrated Ecosystem Survey (NPRB), Available [https://arctic-ierp.dataportal.nprb.org/]
3. Bering Ecosystem Study (BEST/ BSIERP), Available [https://data.eol.ucar.edu/project/BeringSea]
4. NASA Ocean Color Remote Sensing Products, Available [https://oceandata.sci.gsfc.nasa.gov/]
5. EUMETSAT Sea Ice Coverage, Available [https://osi-saf.eumetsat.int/]
6. U.S. GEOTRACES 2015, Available [https://www.geotraces.org/data/]
7. U.S. Distributed Biological Observatory, Available [https://arcticdata.io/catalog/portals/DBO]
8. Russian-American Long-Term Census of the Arctic, Available [https://arcticdata.io/catalog/data]
9. Bering Arctic Subarctic Integrated Survey (BASIS), provided by Calvin Mordy (PI)
10. Chukchi Ecosystem Observatory, provided by collaborator Seth Danielson [https://research.cfos.uaf.edu/ceo/]

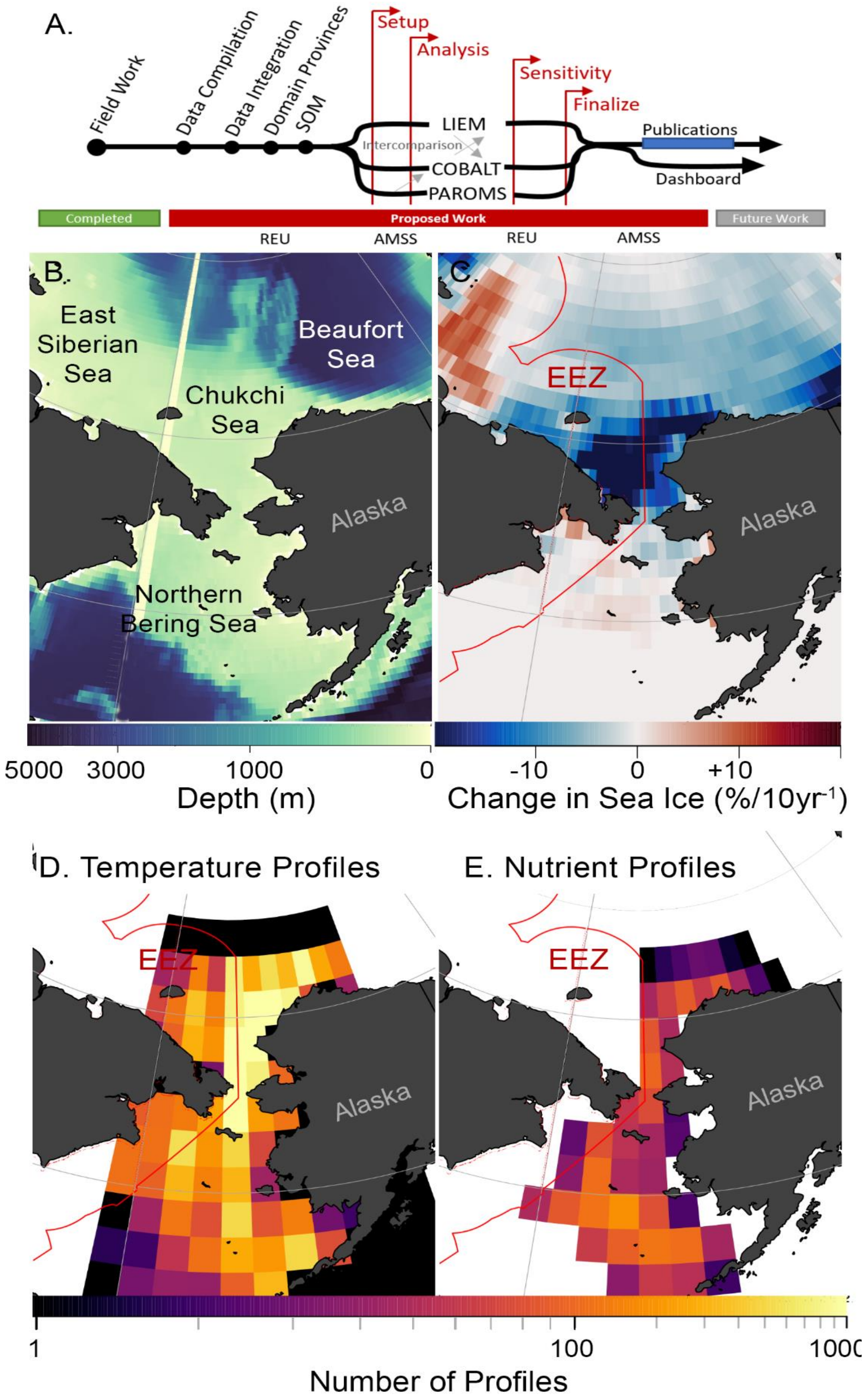


Figure 1. Project Overview. (A) Schematic of overall project structure and activities. Map of proposed study domain colored according to (B) depth with regional seas identified, (C) average change in sea ice coverage (%/10yr) for 1985-2015, number of casts where (D) temperature was measured (Danielson et al., 2020) and (E) nutrients were sampled (by BEST, DBO, AIERP). The Russian Exclusive Economic Zone (EEZ) is shown in red.

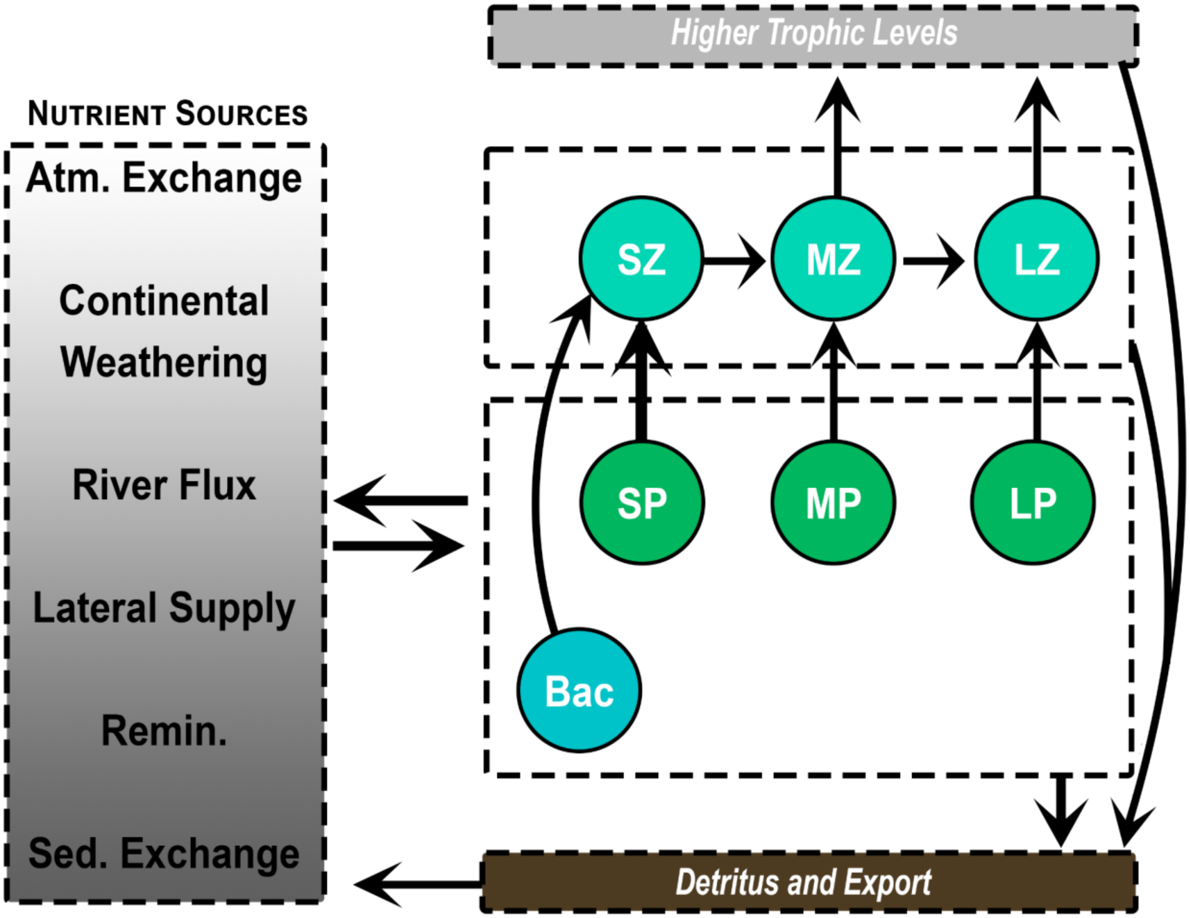


Figure 2. **Overview of COBALT biogeochemical model structure.** Model compartments shown for plankton: small phytoplankton (SP; <5 µm), large phytoplankton (MP; 5-20 µm), chain-forming phytoplankton (LP; >20 µm), bacteria (BAC), small zooplankton (SZ), medium zooplankton (MZ), and large zooplankton (LZ). Trophic linkages are as shown with all living compartments generating detritus, export, or excretion. Modeled nutrient sources are indicated on the left. Not shown are nitrogen losses due to denitrification.

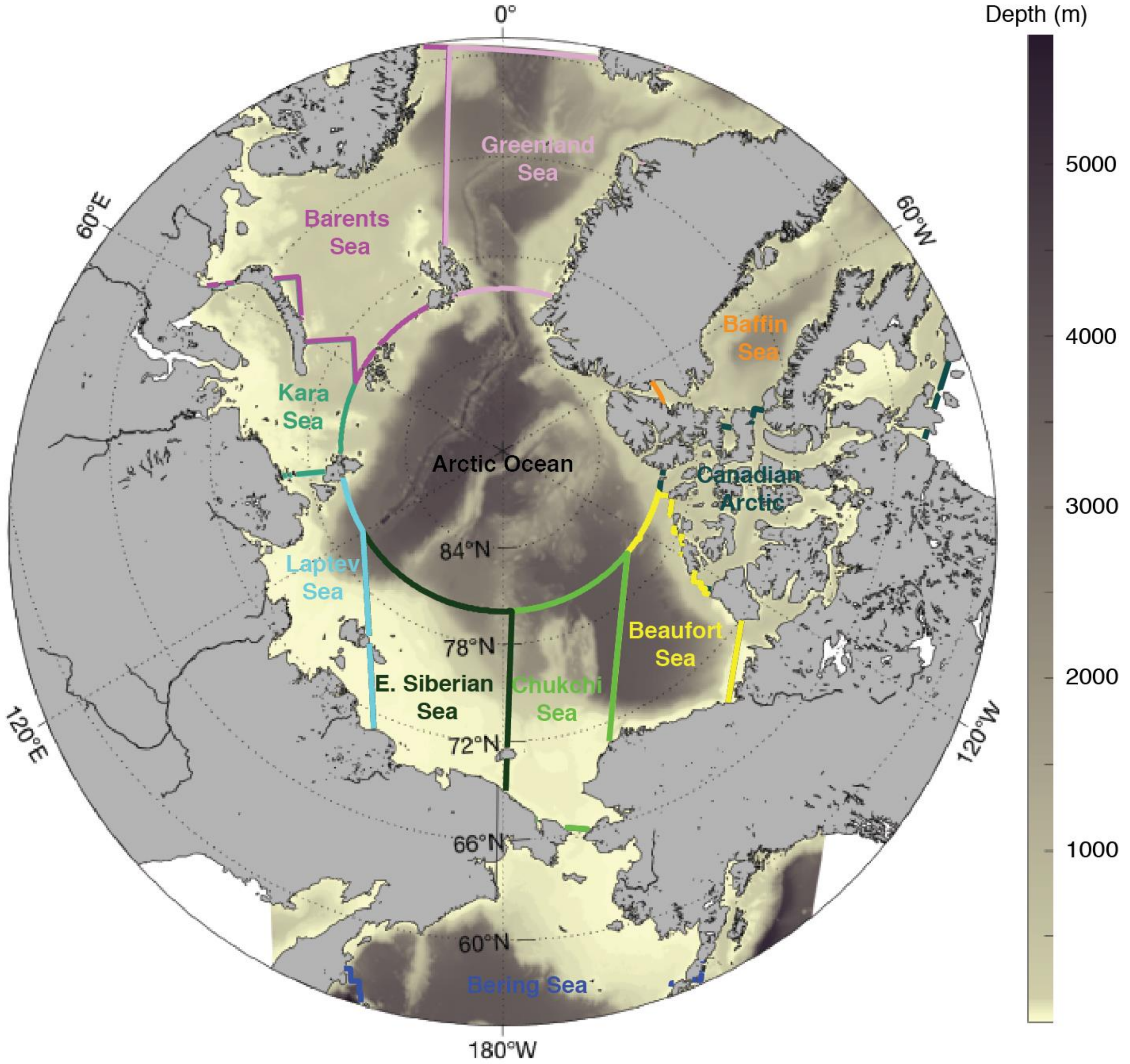
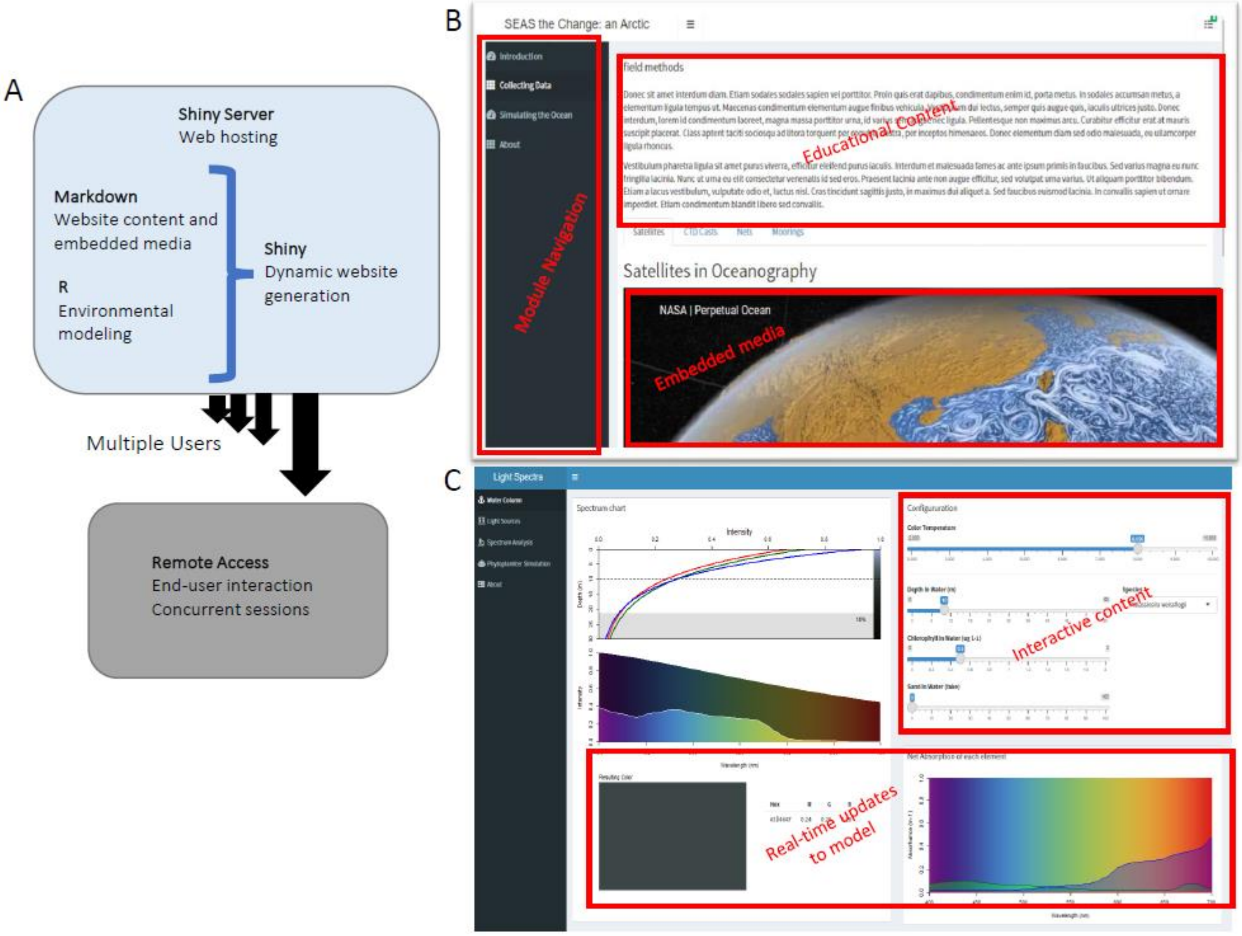


Figure 3. Map of the PAROMS-COBALT domain showing the depth (m) of the ocean. Rough delineations for each region are also depicted.



field methods

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Satellites in Oceanography

Figure 4. Dashboard Modeling Mock-up. (A) Schematic demonstration of dashboard development and resources, (B) example of educational content, and (C) example of interactive modeling portal. See an interactive prototype at: https://tbrycekelly.shinyapps.io/model_watercolumn/.

Anticipated Products

1. Quantification of lateral and vertical nitrogen fluxes throughout the project domain (i.e. Pacific Arctic with focus on the Northern Bering and Chukchi Seas).
2. Observation-driven estimation of lower trophic level (LTL) interactions, including primary production, grazing, and nitrogen cycling.
3. Biogeographic provinces based on satellite, physical and LTL parameters.
4. “Modeling in oceanography” dashboard learning tool freely available as a live website and as downloaded source code.
5. Publish peer-reviewed and open access articles focused on change within the Pacific Arctic.

Table 1. Summary of primary data sources. List of datasets summarized by data type, time period and year of observations/estimates.

Project Name (Acronym)	Data Type(s)	Time Period(s)	Year(s)
Arctic COBALT Biogeochemical Model	Biogeochemical	Monthly	2015-2019
Arctic Integrated Ecosystem Survey (IES)	Physical, Biogeochemical, Biological Rates	August - September	2017, 2019
Arctic Shelf Growth, Advection, Respiration, and Deposition (ASGARD)	Physical, Biogeochemical, Biological Rates	Spring	2017, 2018
Bering Arctic Subarctic Integrated Survey (BASIS)	Physical, Biogeochemical	Late summer and fall	2003 - 2019
Bering Ecosystem Study (BEST/ BSIERP)	Physical, Biogeochemical, Biological Rates	Spring and summer	2006 - 2010
Chukchi Ecosystem Observatory (CEO)	Physical	Continuous (moored)	2014 - 2021
EUMETSAT Sea Ice Coverage	Remote Sensing	Continuous	1979 - 2021
NASA Ocean Color	Remote Sensing	Continuous	1997 - 2021
Pan-Arctic Regional Modeling System (PAROMS)	Physical	Monthly (1980-2018) Daily (2010-2019)	1980-2019
Russian-American Long-Term Census of the Arctic (RUSALCA)	Physical, Biogeochemical	Summer	2004 - 2014
U.S. Distributed Biological Observatory (DBO)	Physical, Biogeochemical	Semiannually, Continuous (moored)	2012-2021
U.S. GEOTRACES 2015	Physical, Geochemical	Aug–Oct	2015

Table 2. Summary of common phytoplankton growth equations. Equation parameters are indicated in red.

	Equation	Description
Equation 1. Nitrate Growth Limitation	$NL = \dfrac{NO3}{(\boldsymbol{K_{NO3}} + NO3)(1 + NH4/\boldsymbol{K_{NH4}})}$	Where $\boldsymbol{K_{NO3}}$ and $\boldsymbol{K_{NH4}}$ are the nitrate and ammonium half saturation constants, respectively.
Equation 2. Ammonium Growth Limitation	$AL = \dfrac{NH4}{\boldsymbol{K_{NH4}} + NH4}$	Where $\boldsymbol{K_{NH4}}$ is the ammonium half saturation constant.
Equation 3. Temperature Growth Coefficient	$TL = e^{\mathbf{k_t} \cdot T}$	Where $\mathbf{k_t}$is a temperature dependent rate constant.
Equation 4. Light Limitation	$LL = 1 - exp(\dfrac{\boldsymbol{\alpha} \cdot E}{TL \cdot \boldsymbol{\phi} \cdot \boldsymbol{P_{max}}})$	Where $\boldsymbol{\alpha}$ is the initial slope of the productivity-irradiance curve, $\boldsymbol{\phi}$ is a photo-acclimation constant, and $\boldsymbol{P_{max}}$ is the maximum growth rate.

Engagement Strategy

A. Student Involvement: SEAS the Change contains support for two Research Experience for Undergraduate (REU) students via the Northern Gulf of Alaska REU program. Student selection will prioritize applicants who lack prior research opportunities; REUs will be mentored on model output analysis, educational dashboard development, and their REU final presentation.

B. AMSS Workshops: We will invite academic colleagues and regional stakeholders to (1) assess the current state of biogeochemical observations in the Pacific Arctic and to (2) facilitate Arctic Ocean model development and evaluation. To accomplish this, two workshops will be held the Sunday prior to AMSS 2023 and AMSS 2024 in Anchorage, AK. Through discussion of the above points, the first workshop will identify opportunities for collaboration and current unmet needs for data sharing and analysis. The second workshop will develop a report (white paper or peer-reviewed publication) on the applicability and status of current regional modeling efforts and to identify validation opportunities for future field work.

C. Interactive Dashboard: Models are extensively used in climate science and are often, seemingly, complex. SEAS the Change's interactive "do-it-yourself" modeling dashboard (written in R using Shiny; Figure 4) aims to educate users about how models work, what we can learn from them, and what their limitations are. The guided platform will allow students to select a research question, explore data, and run model experiments by changing input variables. The arc of the dashboard (identifying research questions, data generation and exploration, and synthesis and modeling of data) mirrors the IERP strategy of: assessment, research implementation, and synthesis.

With the intent of demystifying models through user exploration, the dashboard will be a useful tool for Teachers and Students as well as Stakeholders. By simplifying our synthesis efforts into four questions: "How does (1) *increasing temperature, (2) decreasing salinity, (3) declining sea ice, (4) or seasonality* impact the supply of food (as nutrients) to the base of the food web?" students can explore (through visualization, reading, and listening) how environmental changes impact the base of the ecosystem. During this project we will develop curriculum for undergraduate courses, including UAF's *The Oceans* and *Introduction to Marine Science II*. Each year, we will attend the Alaska Tribal Conference on Environmental Management (ATCEM) to, first, discuss and receive community feedback on how the dashboard can be useful to coastal communities and, second, to demonstrate the dashboard. In FY23 (in communication with AKDatUM) we will establish the website, refine curriculum (with Katie Gavenus), and create videos (contracted) about data generation. In FY24, we will improve the modeling interactive pages and deploy the dashboard in classrooms.

A voluntary survey at the conclusion of the module will assess efficacy and demographics of end-users. Google Analytics will record dashboard use and interactions. We will include a portal for teachers that includes pre- and post- exercise evaluations to evaluate learning outcomes. After the development of a self-sustaining website, we will aim to distribute the dashboard to additional NPRB Stakeholders/Audiences through local and state networks (CFOS, IARC, NPRB).

Project Management

A. General Management

All project PIs will contribute to the logistical and intellectual progress of the project through routine project meetings and semi-annual progress reports. Three project PIs will contribute to annual workshops, the Alaska Marine Science Symposium, and outreach activities. Coordination between UAF and NOAA PIs will be facilitated by project meetings and *ad hoc* Google Meet teleconferences to support LIEM implementation and development. A Github code repository will facilitate code sharing and collaboration amongst all project participants and all data and reports will be located in a dedicated Google Drive hosted by UAF. All data products will be submitted following NPRB policies, and results will be disseminated by publication in open access journals.

B. Individual Contributions

Dr. Thomas Kelly [biogeochemistry] is the SEAS the Change project lead. He has a history of participation and leadership in collaborative and multidisciplinary projects at the interface of observational approaches and modeling efforts, including previous LIEM and inverse model development and implementation, remote sensing algorithm development for biogeochemical processes, and biogeochemical model synthesis. Kelly has experience in teaching and mentoring middle school, high school, undergraduates, and graduate students.

Dr. Laura Whitmore [chemical oceanography] will lead the data exploration and nutrient transformation aspects of the project. She has field experience in the Arctic through the US GEOTRACES, MOSAiC, and NABOS programs. She has extensively studied geochemical tracers (nutrients, trace metals, and trace gasses) and has experience leading large-scale data-synthesis efforts including 30+ scientists. Dr. Whitmore will lead data management and submissions per NPRB data sharing requirements.

Dr. Tyler Hennon [physical oceanography] will lead the application of the physical model and nutrient supply estimations for the project. Dr. Hennon has investigated the Northern Bering and Chukchi Sea nutrient distributions and transports, and has considerable working experience with PAROMS hindcast analysis.

Dr. Jens Nielsen [plankton ecology] will co-lead development and implementation of the LIEM portion of the project and ecological context of the area. Dr Nielsen has participated in field studies (Arctic IERP) in the region and has worked extensively with the collected data.

Dr. Calvin Mordy [nutrient chemist] will manage the UW component of the project, provide previously unpublished data sets, and assist in determination of microbial rates and model evaluation. He has extensive expertise (>20 yrs) in the study area. He has been a Co-PI on numerous integrated ecosystem research programs including the Arctic IERP, and was a lead PI with M. Lomas (Bigelow) for NSF’s Synthesis of the Bering Sea Ecosystem Study (NOAA Gold Medal). He is a Co-PI of the Innovative Technology for Arctic Exploration program (ITAE) which develops new platforms and sensors including the Saildrone (NOAA Bronze Medal) and an *in-situ* nitrification analyzer.

Dr. Claudine Hauri [biogeochemistry and carbonate system] will guide the COBALT model output analysis and has extensive experience designing and utilizing coupled biogeochemical models in and around Alaska, including a recently published Gulf of Alaska simulation (Hauri et al., 2020). She has experience contributing to multidisciplinary projects with diverse modeling components.

C. Outline of Responsibilities

Dr. Thomas Kelly

- Conduct mandatory reporting
- Lead routine project meetings
- Assist with Linear Inverse Ecosystem Model
- Organize Alaska Marine Science Symposium workshops
- Attend Alaska Tribal Council on Environmental Management
- Perform domain partitioning and spatial clustering
- Apply Self Organizing Maps to compiled datasets

- Perform Bayesian parameter optimization

Dr. Laura Whitmore

- Assimilate datasets
- Lead data management and NPRB data reporting requirements
- Evaluate/assist with physical tracer and regional ecosystem model results
- Organize Alaska Marine Science Symposium workshops
- Attend Alaska Tribal Council on Environmental Management
- Attend Alaska Data for Undergraduate Education Modules (AKDatUM) Meetings
- Develop educational dashboard and activities
- Co-supervise summer student

Dr. Calvin Mordy

- Provide previously unpublished data sets
- Provide QC of the master nutrient data set
- Assist in Arctic COBALT model evaluation/interpretation

Dr. Tyler Hennon

- Analyze 40-year monthly PAROMS hindcast for physical patterns/characteristics
- Perform physical tracer model experiment
- Analyze Arctic COBALT nutrient distributions, transports, and variability
- Co-supervise summer student

Dr. Jens Nielsen

- Lead Linear Inverse Ecosystem Model
- Assist with Bayesian parameter optimization

Dr. Claudine Hauri

- Facilitate use of Arctic COBALT model
- Perform model-data comparisons between Arctic COBALT and other proposed analyses

D. Coordinate Efforts

PIs participating in this proposal are aware of a proposed effort to explore and integrate data regarding benthic-pelagic coupling within the Arctic ("Pelagic-benthic de-coupling? Ecosystem restructuring in the Northern Bering and Chukchi seas") led by Dr. Logerwall. We anticipate and will support any and all mutual activities common to the two proposals, if funded.

A Sea-scale Effort to Assess Sensitivity to Change in Nutrients and Ecosystems within the Pacific Arctic
October, 2022 - September, 2024

	Responsible Party	2022	2023				2024		
		Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Alaska Marine Science Symposyum	TK, LW, TH		X				X		
Final Report	TK								X
Data and Metadata Transfer	LW								X
Progress Report	TK		X		X		X		X
Objective# 1 [Physical Coupling]: Use model hindcasts and field observations to determine the degree to which allochthonous (i.e., advected) or autochthonous (i.e. local) nutrient supply supports primary production within the Northern Bering and Chukchi Seas.	TH, LW			X				X	
Objective# 2 [Physical Coupling]: Assess spatio-temporal co-variability of physical parameters (e.g. temperature, sea ice) with nutrients, chlorophyll, and net primary production.	TK, LW, TH			X			X		
Objective# 3 [Ecosystem Processes]: Using in situ data and model hindcasts, assess the impacts that a changing physical environment (e.g., transport, light, temperature, stratification) has on pelagic communities by quantifying rates (e.g. nitrate uptake) of primary producers and the transfer of nitrogen between primary producers and lower trophic level consumers.	JN, CM, TK	X	X			X			
Objective# 4 [Engagement]: Review the state of biogeochemical observations of the Arctic Ocean, especially the Pacific Arctic, through involvement of colleagues and stakeholders at day-long workshops held immediately prior to the Alaska Marine Science Symposium.	LW				X				X
Objective# 5 [Engagement]: Retrieve and implement improvements to the educational dashboard suggested by Alaska Tribal Conference on Environmental Management (ATCEM) partic	TK				X				X