Proposal submitted to Internal NOAA 2023 Request for Proposals from the OAR UxS Research Transition Office and OMAO UxS Operations Center

Plankton, Aerosol, and Cloud Measurements using the FVR-90 Uncrewed Aerial System (UAS)

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Proposed period of performance

01 May 2023 – 30 Apr 2025, Subaward ends 12/25

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Signature and Date	Signature and Date	Signature and Date

Budget Request:

Institution/Item	Year 1	Year 2	Total
University of Washington/CICOES	$241,251	$182,573	**$423,823**
NOAA PMEL	$23,667	$24,615	**$48,282**
Total	$264,918	$207,187	**$472,105**
FVR-90 Lease*	-	$300,000	**$300,000**

* The project has been advised to list the lease of the drone separately.

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Abstract

The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) satellite, set to launch in January 2024, will greatly advance our understanding of global biogeochemistry, ecology, and atmospheric aerosols. The primary sensors on PACE are a hyperspectral sensor for assessing phytoplankton community distributions, including Harmful Algal Blooms (HABs), and multi-angle polarimeters for characterizing aerosols. However, PACE will have limited utility in the U.S. Arctic due to persistent cloud cover and limited spatial resolution (1 km). To extend PACE measurements to remote and underserved regions in Alaska, this project proposes to integrate multiple sensors into the FVR-90 Uncrewed Aerial System (UAS) from L3Harris and test the system's multi-mission capabilities off California in FY23 and FY24. Three nose-cone payloads will be tested: 1) hyperspectral observations of phytoplankton (HAB Payload), 2) clear-sky aerosols (Clear Sky Payload), and 3) aerosol-cloud interactions (Cloudy Sky Payload). The UxS Operations Center has funded flight time hours and pilot costs for Clear and Cloudy Sky operations in FY23. The primary focus of this proposal is the HAB Payload in FY23 and FY24, and funding for flight operations in FY24.

Hyperspectral data will be validated from coordinated ship-based measurements, and ocean-color algorithms for determining phytoplankton to genus and/or species will be tested and compared with the PACE data in FY24, as well as other available satellites. The readiness level (RL) of the observing system (UAS plus HAB Payload) will increase from RL4 to RL6/7 during this proposed work, and the system will be readied for future deployments in the operational environment of the U.S. Arctic. Results from the future Arctic deployments will be available to NOAA's National Centers for Coastal Ocean Science (NCCOS) and incorporated into the Alaska HAB Network (letters of support). This project aligns with NOAA's mission 1) *to conserve and manage coastal and marine ecosystems and resources* by contributing to the strategic objective of improving resilience of coastal communities and economies, and 2) *to understand and predict changes in climate, weather, oceans, and coastal regions* by fulfilling the OAR's mission of conducting research to understand and predict the Earth System. The proposed innovation will enhance our ability to understand and predict changes in the ocean and coasts, contributing to economic growth, ocean health, and ocean management in the U.S. Arctic. If successful, this system would benefit local and native communities in Alaska that have recently experienced a rapid expansion and increase in the abundance of HABs.

1 Purpose/Objective

1.1 Overview

The primary objective of this project is to assess the capability of the FVR-90 UAS in performing effective phytoplankton and cloud-aerosol surveys over marine coastal waters. Specifically, the project will assess the feasibility of FVR-90 as a multi-use platform by switching between three payload types that observe proxies for phytoplankton distributions (HAB Payload), clear-sky aerosols (Clear Sky Payload), and aerosol-cloud interactions (Cloudy Sky Payload). Operations of the Clear and Cloudy Sky Payloads in the FVR-90 have already been funded for Year 1 by NOAA’s Earth Radiation Budget (ERB) Program and the UxS Operations Center. Science funding for the Clear and Cloudy Sky Payloads will be provided by the ERB program in Year 2. This proposal only requests funds for integration of the HAB Payload into the FVR-90, travel for the field studies, ground-truth observations, and data analysis. Funds are requested for flight hours in Year 2.

1.2 Background

PACE satellite: The upcoming launch of NASA's PACE (Plankton, Aerosol, Cloud, ocean Ecosystem) satellite offers an opportunity to revolutionize our understanding of Earth's ecosystems and aerosols. The PACE observatory offers two advances that will enhance our understanding of these critical systems. First, PACE's Ocean Color Instruments (OCI) are hyperspectral moving beyond multispectral heritage ocean color instruments, which will allow for more detailed information on the spatiotemporal distribution of discrete phytoplankton communities. Specifically, hyperspectral data and new algorithms have been developed and vetted against phytoplankton cultures in advance of the launch of PACE. Second, PACE's addition of multi-angle polarimetry will provide dimensions of information beyond what is possible with OCI alone. The ability to view polarized light fields at multiple angles will provide a quantum leap forward in information content to reveal aerosol and cloud droplet microphysical properties. This will be crucial for improving our understanding of Earth's radiation budget, as well as the economic and societal applications of these measurements.

However, it is important to note that the PACE satellite will have low spatial resolution, which often hampers the observation of phytoplankton patches, and limitations in regions with persistent cloud cover, such as the U.S. Arctic waters. This could limit its utility in these areas, as OCI requires clear views of the ocean surface for signal retrieval and identification of specific phytoplankton communities, as well as clear-sky aerosol types. Therefore, it is essential to explore alternative approaches for studying regions with persistent cloud cover.

FVR-90: The FVR-90 UAS from L3Harris (Figure 1) is an exceptional platform that can stand harsh environmental conditions such as the Arctic region. Its modular nose cone design allows for the integration of advanced sensors and sampling equipment, enabling the UAS to collect high-resolution data on aerosols, clouds, and phytoplankton at high altitudes and over large areas. The FVR-90's long-endurance capability (up to 10 hours) and high-speed cruising (45–50 kts) also make it an ideal platform for rapid response surveys, allowing for the collection of timely and accurate data.

Harmful Algal Blooms (HABs): As the Alaskan Arctic continues to warm, there is a growing concern on the occurrence and potential threats of HABs in the Bering Sea and Chukchi Sea. A 2018–2019 survey revealed that the neurotoxin-producing dinoflagellate *Alexandrium* *catenella* was widely distributed and present at high concentrations in both surface waters and bottom sediments of the region (Anderson et al., 2021a). This is particularly concerning as *A. catenella* produces paralytic shellfish toxins (PSTs) that pose a significant threat to human and ecosystem health (Natsuike et al., 2017). A developing bloom with similar optical characteristics to dinoflagellate blooms (Craig et al. 2006, Gilerson et al. 2009, Soto et al. 2015) was observed during the most recent 2022 survey by R/V Norseman II over the northern Bering and Chukchi Seas (Figure 2a). Enhanced RGB imagery of the region on a rare cloud-free day (August 2, 2022, Figure 2b) shows near-shore runoff in bright green and an offshore phytoplankton bloom in red-brown. The unique optical properties of dinoflagellates were exploited in Figure 2c, which shows the likely distribution of a dinoflagellate bloom that could be *A. catenella.* It is important to mention that these images were captured by a multispectral satellite (Sentinel-3A) and determining the dinoflagellate species would only be possible with hyperspectral observations such as those of PACE-OCI and hyperspectral cameras. A subsequent survey in mid to late August 2022 (R/V Norseman II, Leg 2 northward) found exceptionally high and dangerous cell concentrations which were also observed by satellites (Sentinel-3), resulting in the issuance of multiple health risk advisories to local health officials and communities (Haecker, 2022). Future blooms of *A. catenella* are predicted to be large and frequent due to hydrographic and bathymetric features that support high cell and cyst accumulations, and warming temperatures that promote blooms from cysts that reside in bottom sediments. This situation is exacerbated by the fact that HAB species and biotoxin monitoring programs are often not feasible in the region (Goodrich, 2021).

Figure 1. The FVR-90 drone. Image courtesy L3Harris.

In addition, PSTs detected in shellfish have shown a marked increase in the frequency and severity of *Alexandrium*-induced harmful events along the U.S. west coast over the past 35 years (Horner et al., 1997; Jester et al., 2009; Moore et al., 2011; Anderson et al., 2021b), indicating the need for more comprehensive HAB monitoring in this region. Although sampling networks for *Pseudo-nitzschia* and *Alexandrium*, two dominant harmful species, have been established, there is still a significant gap in monitoring HABs, particularly dinoflagellate HABs, on a large scale. While the ultimate goal of this project is to enable UAS-based HAB monitoring in the Arctic, the U.S. west coast could also benefit from the success of its application in regions at times with heavy cloud cover.

<u>Aerosols:</u> Scattering and absorption of solar radiation by atmospheric aerosol particles affect Earth’s radiation budget, including cooling at the Earth’s surface. In addition, aerosol particles take up water and form cloud droplets which can increase cloud brightness and lead to a cooling of the Earth’s surface. The degree to which aerosol direct forcing and interactions between aerosols and clouds are cooling the planet and offsetting warming by greenhouse gases is highly uncertain. Vertical profiles of aerosol and cloud properties are required to improve models and decrease uncertainties, particularly over oceans due to the susceptibility of marine clouds to small changes in aerosol concentrations.

PMEL has been funded by NOAA’s ERB Initiative and UxS Operations Center to perform UAS flights for the measurement of vertical profiles of aerosol and cloud properties in

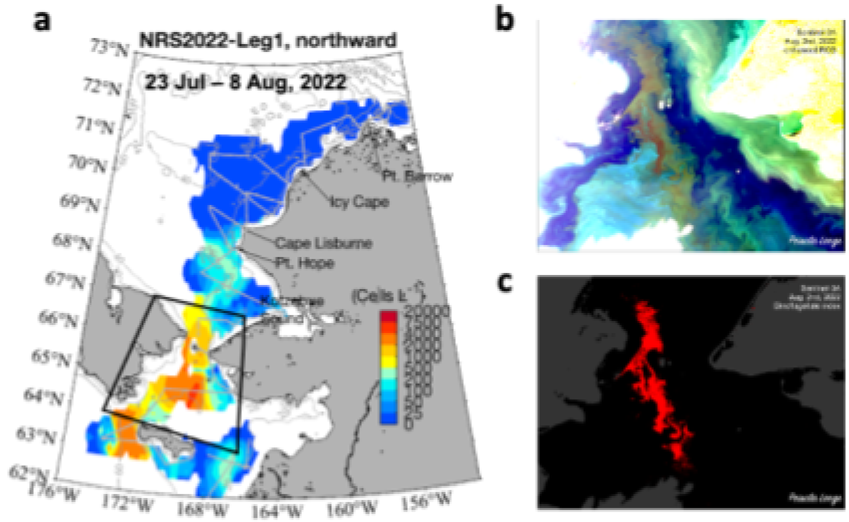

Figure 2. a) Ship-based measurements of A. catenella cells during the 23 Jul - 8 Aug 2022 period over the northern Bering and eastern Chukchi seas. A A. catenella bloom is in development. Image courtesy to Don Anderson. b) Enhanced RGB image of the Bering Strait area on 2 Aug 2022 from the Sentinel-3A satellite, displaying a clear sky. The black box in (a) indicates the area. c) Preliminary results from a new algorithm developed by the team defining the dinoflagellate index on the same date.

the marine boundary layer. The overall goal is to further our understanding of the impacts of aerosol on direct radiative forcing and cloud properties in the marine boundary layer. Clear and Cloudy Sky Payloads will be deployed for these measurements. Marine stratus clouds along the western coast of the U.S. will be targeted in the July/August 2023 time frame from Vandenberg Air Force Base. Investigations of how these UAS measurements can complement PACE satellite observations will be initiated.

1.3 Goals and Objectives

The overall goal of the project is to evaluate the effectiveness of the FVR-90 UAS in conducting phytoplankton, aerosol, and cloud surveys over marine coastal waters in clear and cloudy conditions.

Objectives:

1) Evaluate the ability of the hyperspectral imagery system on the FVR-90 UAS (HAB Payload) to generate high spatial and temporal resolution spectral data of water-leaving radiance and reflectance for phytoplankton surveys.
2) Validate UAS-based data by conducting ship-based complementary measurements through coordinated overflights to ensure accuracy and consistency.
3) Develop and validate diagnostic algorithms for estimating phytoplankton genus/species and abundance, including HAB species, from the UAS-based hyperspectral data.
4) Compare hyperspectral data from the UAS with available satellite data including PACE to determine the effectiveness of the FVR-90 UAS in complementing satellite observations.
5) Develop and test methodologies for analyzing aerosol and cloud property data collected by the FVR-90 UAS under both clear and cloudy conditions (Clear Sky and Cloudy Sky Payloads, respectively), to assess the potential for complementing PACE satellite-based observations of aerosols.

1.4 Relevance to NOAA's mission.
The UAS-based algal bloom monitoring proposed in this project aligns with NOAA's mission *to conserve and manage coastal and marine ecosystems and resources*. The Ocean Climate Action Plan (OCAP) released by the White House in March 2023 has further assigned NOAA as the key agency to "reduce threats to coastal and Great Lakes ecosystems that are exacerbated by climate change, including invasive species and harmful algal blooms". UAS-based algal bloom monitoring will serve as an essential component of maintaining seafood security and shellfish health, particularly in regions with persistent cloud cover such as the U.S. Arctic. This project contributes to NOAA's strategic objective of *improving resilience of coastal communities and economies* by providing effective and timely monitoring of HABs, which are a threat to marine resources and coastal communities. Furthermore, the project aims to inform management and mitigation strategies to protect Arctic communities and their subsistence harvesting of marine resources. The UAS-based algal bloom monitoring system will be ultimately applied to the U.S. Arctic, which aligns with the key objectives of the NOAA/GOMO/Arctic Research Program strategy for 2022–2026, including *Observations, Modeling, Data and Products, Engagement, and Partnerships*. The project addresses these objectives through topics of airborne surveys, food security, and community engagement, with the involvement of numerous partnerships within NOAA and with academia.

At the direction of Congress in 2020, NOAA is leading a multi-year research initiative, the ERB program to investigate natural and human activities that might alter the reflectivity of the stratosphere and low-level marine clouds that form over certain ocean regions (the U.S. west coast being one such region). Strategies to mitigate warming due to greenhouse gases include "brightening" of the stratosphere and marine clouds. Understanding the mechanisms required for implementing climate intervention strategies and the full consequences of such actions require expanded atmospheric observations. The UAS aerosol measurements performed here with prior funding from the ERB program and the UxS Operations Center will provide a critical component to the marine boundary layer studies proposed in the new ERB initiative. In addition, measurements of aerosol and cloud vertical profiles are key observing requirements needed to fulfill OAR's mission "*to conduct research to understand and predict the Earth System*" and the NOAA-wide mission of *understanding and predicting changes in climate, weather, oceans, and coastal regions*.

1.5 Links to specific user requirements
We propose to work closely with end users to establish and integrate user requirements, including data quality, spatiotemporal coverage, and near-real-time data. The funded projects by the ECOHAB (Ecology and Oceanography of Harmful Algal Blooms) program of NOAA/NCCOS will be one of our cross-Line Office collaborators (see Section 7, Letter of Support from Dr. Kathi Lefebvre). Additionally, the Alaska HAB (AHAB) Network sponsored by Alaska Ocean Observing System (AOOS) will serve as the end user for the future Alaska deployment, providing valuable connections to Alaska coastal communities and ocean users. Distribution of information will be coordinated by the AHAB Network through their working groups, monthly member meetings, and online data portal. The AHAB Network will help to identify contacts during and after fieldwork and ensure that results are disseminated back to the local communities (see Section 7, Letter of Support from AOOS). Our collaboration with these end users will enable us to develop and refine drone-based monitoring methods to meet their specific needs, ultimately increasing the effectiveness and applicability of the technology in understanding and managing HABs in the region.

2 Technical Project Plan

2.1 Payload preparation and data acquisition

HAB Payload: A Pika L hyperspectral imagery system will be mounted on a standard nose cone provided by L3Harris. The Pika L imaging system, developed by Resonon, is a hyperspectral camera that is suitable for UAS-based algal bloom monitoring. This camera is capable of capturing high-resolution hyperspectral images in the visible and near-infrared spectrum range of 400-1000 nm. It has a spectral resolution of 3.5 nm, allowing it to capture detailed spectral signatures of various materials in the water, including different types of phytoplankton. The Pika L is also lightweight, compact, and easy to be installed on a UAS, making it an ideal tool for aerial surveys of marine coastal waters. The camera's high spatial resolution (up to 2448 pixels per line) allows for detailed mapping of algal blooms, which is critical for effective management and mitigation of HABs. Furthermore, the Pika L camera is capable of capturing images in different lighting conditions, including low light, making it suitable for use in various environmental conditions. The imagery system will include the imager, computer, solid state drive, a GPS/IMU unit (handling position along with pitch, roll, and heading information), and a downwelling detector. Communications between multiple engineering teams do not foresee any issues with mounting and power supply. Real-time data communication is not required, and the ethernet channel is used for communication radio only.

Figure 3 illustrates the data collection process. During UAS flights over the survey area, the hyperspectral camera will acquire radiance information with a spatial resolution of 2 m (cross-track) × 2 m (along-track) at a cruise speed of 50 knots and an altitude of 10,000 ft. The radiance will undergo atmospheric correction to account for attenuation and scattering by atmospheric constituents, including aerosols, and the resulting radiance data will be converted into water-leaving reflectance.

The water-leaving reflectance can be used in multiple ways to determine phytoplankton dominant taxa. In empirical algorithms such as Principal Component Regression, a Principal Component Analysis is used to decompose the reflectance spectra in dominant modes with specific spectral resolution. The sum of these spectral modes (or loadings, or eigenvectors, or principal components) in different proportions (or scores, or eigenvalues) result in the observed reflectance spectra (Bracher et al. 2015). Since the spectral modes show specific spectral characteristics that represent the contribution of optical properties of distinct water constituents (absorption of different pigments, CDOM absorption, particulate backscatter) and each phytoplankton species possesses a specific combination of pigments and backscatter properties, the scores of these spectral modes are used as predictors of the abundance or biomass of target phytoplankton species. In addition to these spectral

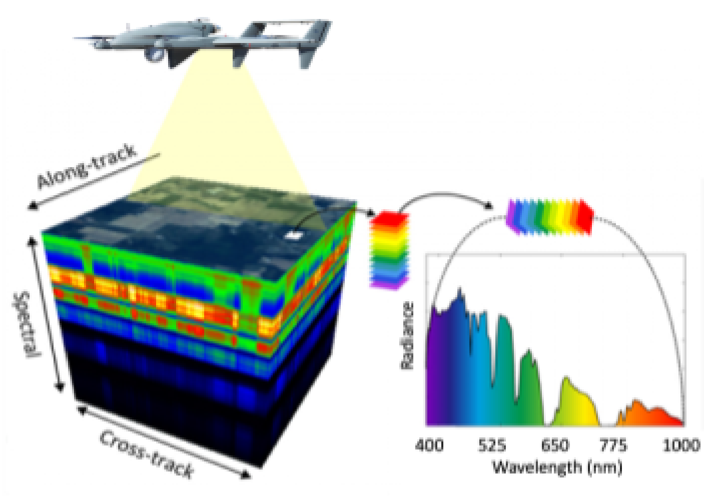

Figure 3. Data collection process using the hyperspectral imaging system of the HAB Payload. Image modified from https://www.neonscience.org/

modes, environmental variables such as sea surface temperature (SST) can be used as additional predictors in these models. This is particularly useful when different phytoplankton species present similar optical properties (which is the case of *Pseudo-nitzschia* and other needle-shaped diatoms), because often different diatoms are favored by distinct environmental conditions.

An alternative method to determine phytoplankton species from water-leaving reflectance is extracting the particulate (and then phytoplankton) absorption and backscattering spectra using inversion models (Zhu et al. 2019). Phytoplankton absorption spectra ($a_{ph}(\lambda)$) are determined exclusively by the concentrations of different pigments in the water. Therefore, pigment concentrations can be estimated from absorption spectra with relatively lower uncertainty when compared to empirical estimates directly from reflectance. Estimates of pigment concentrations from hyperspectral $a_{ph}(\lambda)$ can be done using a vast suite of methods such as gaussian decomposition (Hoepffner and Sathyendranath 1991, Chase et al. 2013), principal component regression and derivative analysis (Catlett and Siegel 2018). Once pigments are estimated, phytoplankton taxonomic groups can be retrieved using other statistical methods such as CHEMTAX (Mackey et al., 1996). Both methods have their caveats and benefits, and will be tested in this project.

Clear and Cloudy Sky Payloads: Prior to operations in July/August, Clear and Cloudy Sky payloads will be integrated into FVR-90 nose cones. An additional particle number sizing instrument will be added to Clear Sky to increase the size range of particles measured, fast total particle number concentration at a rate of 1 minute will be added to Cloudy Sky, and downward- and upward-looking radiometers will be added to both payloads. The addition of the radiometers will allow for a more complete assessment of the radiative impacts of aerosols and clouds and utility in low-orbit truthing of PACE satellite products.

2.2 Field demonstrations

The OMAO AOC UAS division is currently making arrangements for flights of the FVR-90 in restricted air space over the ocean off the Vandenberg Space Force Base between July 17 and August 4, 2023 (18 days, 15 flight days). Portions of restricted areas R2516 and R2517 will be made available to us each day under the direction of the base air traffic control (Figure 4a). Traffic control will also coordinate with the Navy who controls the airspace west of the restricted areas. Vandenberg Air Force Base (AFB) will obtain permission to fly within the Navy's warning area W532S (Figure 4b). These flights will be constantly monitored by Air Force radars. During this flight window there will be separate flights for the HAB, Clear Sky, and Cloudy Sky missions. Each mission will have a unique instrument suite packaged within separate nose cones. Given the modularity of the nose cones, they will be switched out between flights while the UAS batteries are being recharged and the UAS is being refueled (typically 45 minutes) allowing for separate missions to conduct surveys on the same day.

Clear and Cloudy Sky Payload flights will be conducted between 400 and 10,000' in altitude for durations of 4 to 10 hours and up to 60 nm offshore. Weather conditions will determine which payload is flown on a given day. HAB Payload flights will be conducted at 10,000 feet allowing for maximum area coverage. We anticipate 7-8 flights (every-other day) each lasting ~ 4 hours. Survey grids will vary depending on approved airspace, weather conditions, recent satellite imagery, and proximity of any research vessels. In the past 5 years

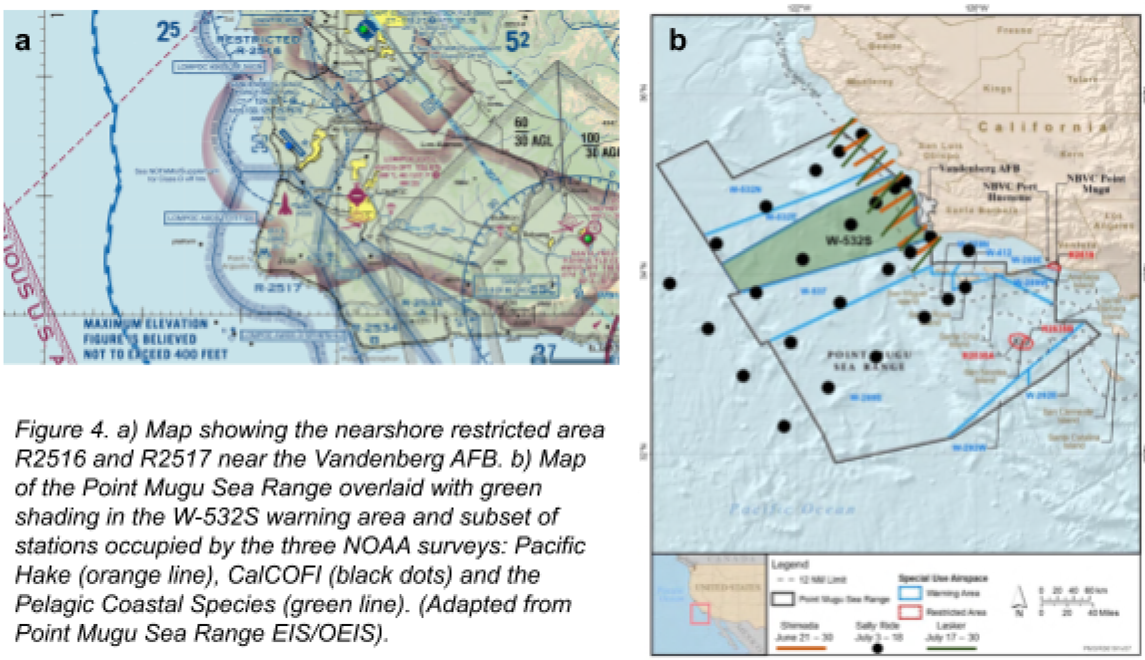

Figure 4. a) Map showing the nearshore restricted area R2516 and R2517 near the Vandenberg AFB. b) Map of the Point Mugu Sea Range overlaid with green shading in the W-532S warning area and subset of stations occupied by the three NOAA surveys: Pacific Hake (orange line), CalCOFI (black dots) and the Pelagic Coastal Species (green line). (Adapted from Point Mugu Sea Range EIS/OEIS).

~50% of the days between July 17 and August 4 in the nearshore flight region were cloudy, though it is unclear if these were low or high clouds, or the extent of foggy conditions.

In FY23, there are three NOAA fishery surveys that are scheduled in the study region: the Pacific Hake Acoustic-Trawl survey on the NOAAS *Bell Shimada* (June 21-30), the CalCOFI survey on the NOAAS *Sally Ride* (July 3-18), and the Coastal Pelagics Species survey on the NOAAS *Reuben Lasker* (July 17-30) (Figure 4b). Similar surveys are anticipated in FY24. Phytoplankton community compositions are usually measured on these surveys using imaging microscopes (Imaging Flow CytoBot, IFCBs). While the hake survey occurs ~1 mo prior to our HAB missions, together these data provide information on spatiotemporal variability of the phytoplankton community.

2.3 Risk mitigation

The table below lists specific risks and corresponding mitigation methods.

Risk	Level	Action	Mitigation
Spatiotemporal offset with ground-truth	Medium	Mitigation	Use IFCB data from Shimada, Ride, and Lasker to assess spatiotemporal variability in phytoplankton speciation. Use this information for uncertainty estimates in hyperspectral data.
Camera installation is delayed	Medium	Avoid	UW/CICOES has agreed to expedite processing of quotes for the purchase and installation of the camera.
Flights limited to within ~3 nm of shore (R2516 and R2517)	Medium	Mitigation	Vandenberg AFB will work with the navy to ensure flights offshore.

Low clouds / fog impede hyperspectral imagery	Medium	Avoid	Do not fly the camera during morning fog or during days with low clouds.
Launch of PACE is delayed	Low	Mitigation	Continue working with ground truth opportunities and other satellite products
FVR-90 grounded due to mechanical failure	Low	Mitigation	Work with L3Harris to resolve any mechanical issues.

2.4 Readiness Levels

Through this proposal it is anticipated that the readiness level of this integrated system will grow from RL4 to RL6 or RL7. The initial RL4 is justified through successful flight demonstrations of the FVR-90 airframe (Military & Aerospace Electronics, 2021), successful measurements of clear-sky aerosols and cloudy-sky aerosols from uncrewed aircraft (Bates et al., 2013), operational use of the Pika hyperspectral cameras for cyanoHABs detection in the Great Lakes (Vander Woude et al., 2019) and successful tests on small UASs (Martin et al., 2018), and successful data processing of oceanic hyperspectral data for assessing phytoplankton distributions (Ryan et al., 2014). This proposal is to integrate these subsystems and conduct tests in FY23 and FY24 in a relevant environment. The camera and aerosol subsystems will be integrated into the FVR-90 airframe and tested offshore of Vandenberg Air Force Base with hyperspectral data verified from ship-based measurements. It is expected that the FVR-90 will overcome two primary weaknesses of UAS-based remote sensing; mission duration due to limited battery life and sensor noise (McManus et al., 2018). After successful tests of these integrated subsystems we anticipate a Readiness Level of RL6 or RL7.

Subsequent to this project we intend to demonstrate the integrated system in the operational environment of the Arctic. Highlighting those efforts will be flights in extremely cold conditions and tuning hyperspectral algorithms for the dinoflagellate *A. catenella* (Figure 2c). While data processing of hyperspectral data has been optimized for cyanoHABs (Vander Woude et al., 2019) and phytoplankton assemblages off the west coast of the U.S. (Ryan et al., 2014), these algorithms are not tuned for Arctic assemblages. Once in the operational environment of the Arctic, the use of hyperspectral data will empower refinements to the current dinoflagellate index and allow for highly accurate remote sensing of *A. catenella*. Off-board processing of this data can then be delivered near real time to the AHAB Network and other end users (see letters of support).

3 Management Plan

3.1 Management structure and key personnel

- P. Quinn (PMEL) will serve as the lead PI in managing the overall project, communicating with the UxS program office, completing all required reviews and reports, and directing the field study. Funding for her participation will be provided by the NOAA's Earth Radiation Budget program.
- T. Bates (UW/CICOES) and D. Coffman (NOAA/PMEL) will operate the aerosol payloads. Funding for their participation will be provided by the NOAA's ERB program.
- J. Zhang (UW/CICOES) will devote 2.5 months per year to developing, calibrating, operating the HAB payloads during the field demonstrations, analyzing the data, publishing the data on the PMEL data archive, and leading the writing of a manuscript describing the results of the phytoplankton surveys.

- C. Mordy (UW/CICOES) will devote 1 month per year to coordinating ship-based ground-truth observations and managing the CICOES budget.
- P. Lange (Blue Marble) and M. Lomas (Biglow) will each devote 0.5 months per year to develop and validate ocean-color based algorithms for detecting extent and abundance of HABs. They will be funded through a subaward at UW/CICOES.
- M. Kavanaugh (OSU) will devote 0.5 months per year to process hyperspectral data and help develop algorithms for ocean-color based algorithms for detecting extent and abundance of HABs. She will be funded through a subaward at UW/CICOES
- T. Van Pelt (UW/CICOES) will devote 1 month per year for communication with end users including updates on the HAB mission meeting user requirements.
- H. Tabisola (UW/CICOES) will devote 1 month per year for tracking readiness levels of the project and record keeping in NRDD. She will also be the communications lead for the HAB mission with NOAA leadership.

3.2 Procurements, airspace access and clearances, travel and shipping needs
The OMAO/UAS division secured a lease with L3Harris for use of the FVR-90 in FY23. Costs for a similar lease in FY24 to be executed by the UAS division are included in this proposal and listed separately from the total cost. The UAS division is also making arrangements for flights in restricted airspace off the Vandenberg AFB (Figure 4a). Vandenberg AFB will obtain clearance with the Navy for flights in airspace further west (Figure 4b). PMEL funded the purchase of the nose cone, the Pika L hyperspectral camera, installation, and shipping costs. The proposal includes travel to Vandenberg AFB for the HAB mission. Travel and shipping costs for the Clear and Cloudy Sky missions are funded through NOAA's ERB program.

3.3 Timeline

May - June 2023	Prepare payloads. Work with engineering teams for mounting and ground testing. Define data form and format, and define or enhance metadata collection in situ.
July - Aug 2023	3 weeks of FVR-90 plus payload flights off the California coast. Coordinated overflights with ship/boat complimentary phytoplankton measurements.
Sep 2023 - May 2024	Data reduction and analysis, payload maintenance and calibration.
Jun - Aug 2024	3 weeks of FVR-90 plus payload flights off the California coast. Coordinated overflights with ship/boat complimentary phytoplankton measurements.
Sep 2024 - Apr 2025	Data reduction and analysis, metadata created, manuscript preparation, presentation of results at a national meeting. Manuscript preparations.

3.4 Milestones
Milestone 1: Successful routine autonomous land-based operation of the HAB Payload onboard the FVR-90 during 2023 and 2024 field demonstrations.
Milestone 2: Successful routine autonomous land-based operation of the Clear Sky and Cloudy Sky payloads onboard the FVR-90 during 2023 and 2024 field demonstrations.

Milestone 3: Successful completion of the comparison of the UAS-based and ship-based phytoplankton survey results in the 2023 and 2024 surveys.
Milestone 4: Successful completion of the comparison of the UAS-based and satellite-based phytoplankton distribution data in the 2024 survey.

3.5 Deliverables

Deliverables include beginning- and end-of-project technical reviews, semi-annual progress report briefings, a final project report at the end of the performance period, aerosol and cloud property data posted on the PMEL public web site, peer-reviewed publications highlighting the FVR-90 UAS plus payload performance and data regarding 1) phytoplankton distributions and 2) aerosol and cloud properties. Readiness Levels will be monitored and updates will be provided to NRDD.

3.6 Data management plan

The plan reflects the HAB payload only as the aerosol plan falls within funding provided by the NOAA's Earth Radiation Budget program. J. Zhang will be the responsible part for data management, and P. Sullivan will be the point of contact for this plan. Data collected during this work are images from the Pika L hyperspectral imagery system on HAB Payload of the FVR-90 UAS, and stored as 3D data or data cubes. Pre-defined ISO 19115 metadata are stored within the 3D data. Resources for processing and managing data have been identified and will fall within the funding and personnel budget of this project. Data storage will tap into an existing large multi-disk data-storage resource at NOAA/PMEL. The data workflow for the HAB payload is described in Section 2.1. Metadata will comply with EDMC directive and use of ISO 19115 standard. Metadata will be stored with the data within the PMEL ERDDAP environment and will be readable and accessible in the many formats that ERDDAP provides (https://data.pmel.noaa.gov/pmel/erddap/info/).

Data-collection with this new technology is experimental. Once the flights are scheduled and data-collection ends, data will be returned for processing, analysis and quality control (QC). If data collection and data integrity are acceptable, data will be made available within one year of the return of the data to the office setting. Data will be stored at PMEL on a large multi-disk storage area with built-in redundancy. The storage is robust and compliant with NOAA/OAR IT security standards. Additionally, contingent on successful collection and data integrity, these data with metadata will be submitted to NOAA/NCEI for archiving and assignment of DOI (https://www.ncei.noaa.gov/). A cloud-based storage solution will be examined to provide disaster recovery.

4 References

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5 Fiscal Year Budget Breakdown

Project Short Title: Joint FRV-90 Surveys
Primary PI: Patricia Quinn

		FY23		FY24		Total
CI (Sal, Ben)	**Monthly**	**Mo**	**Tot**	**Mo**	**Tot**	
J. Zhang	$8,901	2.5	$22,253	2.5	$23,143	$45,396
C. Mordy	$16,598	1.0	$16,598	1.0	$17,263	$33,861
T. Van Pelt	$10,442	1.0	$10,442	1.0	$10,861	$21,303
H. Tabisola	$9,399	1.0	$9,399	1.0	$9,775	$19,174
P. Sullivan	$11,988	0.7	$8,392	0.7	$8,727	$17,119
CI Travel						
Lakeland FL			$1,585			$1,585
Vandenberg CA			$4,430		$8,460	$12,890
CI Subawards						
Oregon State University			$50,000		$50,000	$100,000
Bigelow			$28,645		$29,204	$57,849
CI Supplies						
L3Harris Engineering			$30,000			$30,000
Training with Resonon			$10,602			$10,602
Indirect Costs						
Task II (CI, 26%)			$42,562		$20,340	$62,902
Task I Fee (CI, 2.7%)			$6,343		$4,800	$11,142
PMEL F&A on CICOES (28%)			**$23,667**		**$24,615**	**$48,282**
TOTAL PMEL and CI REQUEST			**$264,918**		**$207,187**	**$472,105**
L3Harris FVR-90 Lease					$300,000	**$300,000**

Cost Sharing	**FY23**	**FY24**	**Total**
P. Quinn (PMEL, 3 mo / yr)	$83,450	$83,450	$166,900
T. Bates (CI, 3 mo / yr)	$72,139	$72,139	$144,278
D. Coffman (PMEL, 4 mo / yr)	$75,700	$75,700	$151,400
Travel (PMEL and CI)	$13,290	$13,290	$26,580
L3Harris Lease (OMAO/UAS)	$300,000	-	$300,000
HAB Nose Cone (PMEL)	$9,000	-	$9,000
Pika L Camera (PMEL)	$41,491	-	$41,491
TOTAL COST SHARING	**$595,070**	**$244,579**	**$839,649**

Budget Justification:

UW/CICOES
Funds received by PMEL will be transferred to CICOES via the proposal agreement established between NOAA and CICOES.

Personnel Costs: Dr. J. Zhang is a NOAA affiliate working at the University of Washington through the Cooperative Institute for Climate, Ocean, and Ecosystem Studies (CICOES). Zhang will devote 2.5 months per year to developing, calibrating, operating the HAB payloads during the field demonstrations, analyzing the data, publishing the data on the PMEL data archive, and leading the writing of a manuscript describing the results of the phytoplankton surveys. Dr. C. Mordy will devote 1 month per year to coordinating ship-based ground-truth observations and managing the CICOES budget. T. Van Pelt will devote 1 month per year for communication with end users including updates on the HAB mission meeting user requirements. H. Tabisola will devote 1 month per year for tracking readiness levels of the project and record keeping in NRDD. She will also be the communications lead for the HAB mission with NOAA leadership. Salaries and benefits for all personnel include a 4% annual adjustment. The CICOES benefit and leave rates are in accordance with the UW's negotiated rates approved by DHHS and UW policy on 12/29/2022 (https://finance.uw.edu/maa/sites/default/files/fa/FA-FB-Rates-2022-12-29.pdf).

Travel: In Year 1 Dr. Zhang will travel to Lakeland FL for installation of the camera and training. Costs include $500 airfare, $785 for 5 days per diem, and $300 for transportation and other. In Year 1 and Year 2 she will travel to Vandenberg AFB for the HAB missions. Costs per trip include $400 airfare, $3,630 for 10 days per diem, and $400 for transportation and other.

Other Direct Costs: In Year 1 Dr. Zhang will be working with L3Harris on the camera installation and testing of the HAB nose cone. Charge for L3Harris engineering is $30,000. In Year 1 Dr. Zhang and P. Lange will also receive operational training and training on the use of hyperspectral data processing software from Resonon ($10,602). There are two subawards in the CICOES budget. A subaward to OSU is for Dr. M. Kavanaugh to provide ground-truth information on phytoplankton speciation and abundance collected during NOAA surveys and help develop algorithms for ocean-color based algorithms for detecting extent and abundance of HABs ($50,000 per year). A subaward to Bigelow is for M. Lomas and P. Lange who will work with M. Kavanaugh to develop ocean-color based algorithms for detecting extent and abundance of HABs ($28,645 in Year1 and $29,204 in Year 2).

Indirect costs: CICOES indirect costs are requested at the off-campus rate of 26% of Modified Total Direct Costs (direct costs minus capital equipment, graduate student tuition and subawards after the first $25K) for CICOES (Task II Fee). This rate is based on the federally negotiated agreement between the UW and DHHS dated 12/29/2022 (https://finance.uw.edu/maa/sites/default/files/fa/FA-FB-Rates-2022-12-29.pdf). The CICOES Task I Fee is 2.7% applied to the entire CICOES budget.

PMEL Indirect costs: As CICOES employees reside at PMEL, there is an additional indirect fee (PMEL F&A) applied to CICOES salaries, benefits and UW IDC at 28%.

6 Curriculum Vitae

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Education
Ph.D. Chemistry, University of Washington, Seattle, WA, 1988
B.A. Chemistry, Reed College, Portland, OR, 1982

Positions
Research Chemist, NOAA PMEL, 1993 – present
Affiliate Assistant Professor, Department of Chemistry, University of Washington, 1998 – present
Senior Fellow, Cooperative Institute for Climate, Ocean, and Ecosystem Studies, University of Washington, 1999 – present
Oceanographer II, Joint Institute for Atmosphere and Ocean, University of Washington, 1990 – 1993
Research Associate, Cooperative Institute for Research in Environmental Studies, University of Colorado, 1989 – 1990

Honors and Awards
U.S. Department of Commerce, Bronze Medal Award, 2022
AAAS Fellow, 2019
Highly Cited Researcher (Clarivate Analytics), 2016, 2017, 2018
Editor's Citation for Excellence in Reviewing, JGR-Atmospheres, 1993, 1998, and 2018
AGU Fellow, 2010
U.S. Department of Commerce, Bronze Medal Award, 2010
NOAA Administrator Award, 2008
NOAA PMEL Outstanding Scientific Paper, 2003

Recent Publications – First Authored
Quinn, P.K., T.S. Bates, D.J. Coffman, L.M. Upchurch, J.E. Johnson, A. Brewer, S. Baidar, I.L. McCoy, and P. Zuidema (2022): Wintertime observations of tropical Northwest Atlantic aerosol properties during ATOMIC: Varying mixtures of dust and biomass burning. *J. Geophys. Res.,* 127(8), e2021JD036253.
Quinn, P.K., E.J. Thompson, D.J. Coffman, S. Baidar, L. Bariteau, T.S. Bates, et al. (2021): Measurements from the RV Ronald H. Brown and related platforms as part of the Atlantic Tradewind Ocean-Atmosphere Mesoscale Interaction Campaign (ATOMIC), Seasonal variations in western North Atlantic remote marine aerosol properties. *Earth Syst. Sci. Data*, *13*(4), 1759–1790.
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Recent Publications – Co-authored
Chen, Q., J.A. Mirrielees, S. Thanekar, N.A. Loeb, R.M. Kirpes, L. Upchurch, A.J. Barget, N.N. Lata, A.R.W. Raso, S.M. McNamara, S. China, **P.K. Quinn**, A. Ault, A. Kennedy, P.B. Shepson, J.D. Fuentes, and K.A. Pratt (2022): Atmospheric particle abundance and sea salt aerosol observations in the springtime Arctic: a focus on blowing snow and leads. *Atmos. Chem. Phys*., 22(23), 15263–15285.
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Lewis, S.L., G. Saliba, L.M. Russell, **P.K. Quinn**, T.S. Bates, L.I. Aluwihare, and M.J. Behrenfeld (2022): Characterization of sea surface microlayer and marine aerosol organic composition using STXM-NEXAFS microscopy and FTIR spectroscopy, *Front. Mar. Sci.*, *8*, 720208.
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Bates, T.S., **P.K. Quinn**, D.J. Coffman, J.E. Johnson, L. Upchurch, G. Saliba, S. Lewis, J. Graff, L.M. Russell, and M.J. Behrenfeld (2020): Variability in Marine Plankton Ecosystems Are Not Observed in Freshly Emitted Sea Spray Aerosol Over the North Atlantic Ocean *Geophys. Res. Lett.*, *47*(1), e2019GL085938.
Lawler, M.J., S.L. Lewis, L.M. Russell, **P.K. Quinn**, T.S. Bates, D.J. Coffman, L.M. Upchurch, and E.S. Saltzman (2020): North Atlantic marine organic aerosol characterized by novel offline thermal desorption mass spectrometry approach: polysaccharides, recalcitrant material, and secondary organics, *Atmos. Chem. Phys.*, *20*, 16007–16022.
Lubin, D., D. Zhang, I. Silber, R.C. Scott, P. Kalogeras, A. Battaglia, D.H. Bromwich, M. Cadeddu, E. Eloranta, A. Fridland, A. Frossard, K.M. Hines, S. Kneifel, W.R. Leaitch, W. Lin, J. Nicolas, H. Powers, **P.K. Quinn**, P. Rowe, L.M. Russell, S. Sharma, J. Verlinde, and A.M. Vogelmann (2020): AWARE: The Atmospheric Radiation Measurement (ARM) West Antarctic Radiation Experiment, *Bull. Am. Meteorol. Soc.*, *101*(7), E1069–E1091.
Moffett, C.E., T.E. Barrett, J. Liu, M.J. Gunsch, L. Upchurch, **P.K. Quinn**, K.A. Pratt, and R.J. Sheesley (2020): Long‐term trends for marine sulfur aerosol in the Alaskan Arctic and relationships with temperature, *J. Geophys. Res.*, *125*(22), e2020JD033225.
Saliba, G., C.-L. Chen, S. Lewis, L.M. Russell, **P.K. Quinn**, T.S. Bates, T.G. Bell, E.S. Saltzman, K.J. Sanchez, R. Moore, M. Shook, L.-H. Rivellini, A. Lee, N. Baetge, C.A. Carlson, and M.J. Behrenfeld (2020): Seasonal differences and variability of concentrations, chemical composition, and cloud condensation nuclei of marine aerosol over the North Atlantic *J. Geophys. Res.*, *125*(19), e2020JD033145.
Wilbourn, E., D.C.O. Thornton, C. Ott, J. Graff, **P.K. Quinn**, T.S. Bates, L. Russell, R. Betha, N. Nelson, D. Siegel, M.J. Behrenfeld, and S.D. Brooks (2020): Ice nucleation by marine aerosols over the North Atlantic Ocean in late Spring *J. Geophys. Res.*, *125*(4), e2019JD030913.

Timothy S. Bates

Academic Training:

B.A.	Wittenberg University	Chemistry	1975
M.S.	University of Washington	Oceanography	1978
Ph.D.	University of Washington	Environmental Chemistry	1988

Professional Experience:

University of Washington

Research Scientist/Engineer –Senior Principal, Cooperative Institute for Climate, Ocean and Ecosystem Studies (CICOES formally JISAO)	2014-present
Senior Fellow, CICOES (formally JISAO)	1995-present
Affiliate Associate Professor, Department of Atmospheric Sciences	1994-2020
Affiliate Assistant Professor, Department of Atmospheric Sciences	1990-1994
Fellow, Joint Institute for the Study of the Atmosphere and Ocean	1991-1995
NOAA/Pacific Marine Environmental Laboratory, Research Chemist	1978-2014

Current Research Activities:

Atmospheric aerosol particles, global change and air quality.
The role of the ocean in the chemical composition of the atmosphere and climate change.
Uncrewed Aerial Systems (UAS) for studying aerosol-cloud interactions

Field Experience:

Forty one major oceanographic cruises totaling over 958 sea days.
Chief Scientist on twenty two NOAA cruises.

Awards:

NOAA Administrator's Award	2004
Thomson ISI Highly-Cited Researchers in Geosciences	2004
Fellow of the American Geophysical Union	2007
Editor's Citation for Excellence in Refereeing, American Geophysical Union	2007
NOAA Bronze Medal	2010
Editor's Citation for Excellence in Refereeing, American Geophysical Union	2021

Recent Publications:

Bates, T.S., P.K. Quinn, D.J. Coffman, J.E. Johnson, L. Upchurch, G. Saliba, S. Lewis, J. Graff, L.M. Russell, and M.J. Behrenfeld (2020), Variability in Marine Plankton Ecosystems Are Not Observed in Freshly Emitted Sea Spray Aerosol Over the North Atlantic Ocean, *Geophys. Res. Lett.*, 47, e2019GL085938. https://doi/org/10.1029/2019GL085938.

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Fung, K.M., C.L. Heald, J.H. Kroll, S. Wang, D.S. Jo, A. Gettelman, Z. Lu, X. Liu, R.A. Zaveri, E.C. Apel, D.R. Blake, J.L. Jimenez, P. Campuzano-Jost, P.R. Veres, T.S. Bates, J.E. Shilling, and M. Zawadowicz (2022), Exploring dimethyl sulfide (DMS) oxidation and implications for global aerosol radiative forcing, *Atmos. Chem. Phys.*, 22, 1549-1573, https://doi.org/10.5194/acp-22-1549-2022.

Quinn, P.K., T.S. Bates, D.J. Coffman, L.M. Upchurch, J.E. Johnson, A. Brewer, I.L. McCoy and P. Zuidema (2022),Wintertime Observations of Tropical Northwest Atlantic Aerosol Properties During ATOMIC: Varying Mixtures of Dust and Biomass Burning, *J. Geophys. Res.*, 127, 8, https://doi.org/10.1029/2021JD036253.

Lewis, S.L., L.M. Russell, G. Saliba, P.K. Quinn, T.S. Bates, C.A. Carlson, N. Baetge, L.I. Aluwihare, E. Boss, A.A. Frossard, T.G. Bell, and M.J. Behrenfeld (2022): Characterization of sea surface microlayer and marine aerosol organic composition using STXM-NEXAFS, *ACS Earth Space Chem.*, *6*(7), 1899–1913, doi: 10.1021/acsearthspacechem.2c00119.

Sanchez, K.J., B. Zhang, H. Liu, M.D. Brown, E.C. Crosbie, F. Gallo, J.W. Hair, C.A. Hostetler, C.E. Jordan, C.E. Robinson, A.J. Scarino, T.J. Shingler, M.A. Shook, K.L. Thornhill, E.B. Wiggins, E.L. Winstead, L.D. Ziemba, G. Saliba, S.L. Lewis, L.M. Russell, P.K. Quinn, T.S. Bates, J. Porter, T.G. Bell, P. Gaube, E.S. Saltzman, M.J. Behrenfeld, and R.H. Moore (2022): North Atlantic Ocean SST-gradient-diiven variations in aerosol evolution along Lagrangian cold-air outbreak trajectories. *Atmos. Chem. Phys.*, *22*, 2795–2815, doi: 10.5194/acp-22-2795-2022.

Berta, V.Z., L.M. Russell, D. Price, C.-L. Chen, A. Lee, P.K. Quinn, T.S. Bates, T.G. Bell, and M. Behrenfeld (2023): Non-volatile marine and non-refractory continental sources of particle-phase amine during the North Atlantic Aerosols and Marine Ecosystems Study (NAAMES). *Atmos. Chem. Phys.*, *23*(4), 2765–2787, doi: 10.5194/acp-23-2765-2023

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Education

2016: Ph.D. in Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, Madison, WI
2009: M.S. in Earth and Planetary Dynamics, Hokkaido University, Sapporo, Japan
2007: B.S. in Marine Sciences, Ocean University of China, Qingdao, China

Research and Professional Experience

2022–Present Research Scientist, University of Washington, affiliated with NOAA/PMEL
2020–2022 Postdoctoral Scholar, University of Washington, affiliated with NOAA/PMEL
2017–2020 Postdoctoral Research Associate, Los Alamos National Laboratory
2011–2012 Graduate Student Visitor, National Center for Atmospheric Research (NCAR)
2009–2016 Graduate Research Assistant, University of Wisconsin-Madison

Publications of past three years

Schoonover, J., Weijer, W., & **Zhang, J.** FEOTS: A new offline code for the fast equilibration of tracers in the ocean. *Geosci. Model Dev., in press*.

Zhang, J., Cheng, W., Steele, M., & Weijer, W. (2023). Asymmetrically stratified Beaufort Gyre: Mean state and response to decadal forcing, *Geo. Res. Lett.,* 50, e2022GL100457.

Zhu, C., **Zhang, J.**, Liu, Z., Otto-Bliesner, B.L., He, C., Brady, E.C., Tomas, R., Wen, Q., Li, Q., Zhu, C. & Zhang, S. (2022). Antarctic warming during Heinrich Stadial 1 in a transient isotope-enabled deglacial simulation. *J. Clim.*, 35, 3753-3765.

Li, L., Liu, Z., Lynch‐Stieglitz, J., He, C., Gu, S., **Zhang, J.**, & Otto‐Bliesner, B. (2021). Testing methods for reconstructing glacial Antarctic Circumpolar Current transport in an isotope‐enabled climate model. *Paleoceanogr. Paleoclimatology*, 36, e2020PA004183.

He, C., Liu, Z., Otto-Bliesner, B. L., Brady, E. C., Zhu, C., Tomas, R., Clark, P. U., Zhu, J., Jahn, A., Gu, S., **Zhang, J.** & others. (2021). Hydroclimate footprint of pan-Asian monsoon water isotope during the last deglaciation. *Sci. Adv.*, 7(4), eabe2611.

Zhang, J., Weijer, W., Steele, M., Cheng, W., Verma, T., & Veneziani, M. (2021). Labrador Sea freshening linked to Beaufort Gyre freshwater release. *Nat. Commun.*, 12(1), 1229.

Gu, S., Liu, Z., Oppo, D. W., Lynch-Stieglitz, J., Jahn, A., **Zhang, J.**, Lindsay, K., & Wu, L. (2021). Remineralization dominating the δ^{13}C decrease in the mid-depth Atlantic during the last deglaciation. *Earth Planet. Sci. Lett.*, 571, 117106.

He, C., Liu, Z., Zhu, J., **Zhang, J.**, Gu, S., Otto-Bliesner, B. L., Brady, E., Zhu, C., Jin, Y., & Sun, J. (2020). North Atlantic subsurface temperature response controlled by effective freshwater input in "Heinrich" events. *Earth Planet. Sci. Lett.*, 539, 116247.

Gu, S., Liu, Z., Oppo, D. W., Lynch-Stieglitz, J., Jahn, A., **Zhang, J.**, & Wu, L. (2020). Assessing the potential capability of reconstructing glacial Atlantic water masses and AMOC using multiple proxies in CESM. *Earth Planet. Sci. Lett.*, 541, 116294.

Related Activities

- PI of the Arctic AIR (Airborne Investigations and Research) project at NOAA/PMEL since 2022. Conducted multiple field ocean and atmospheric surveys on NOAA Twin Otter aircraft.
- Completed 34 verified journal reviews (https://www.webofscience.com/wos/author/record/1350275).
- Appointed as a member of the organizing committee for CAMAS (Consortium for the Advancement of Marine Arctic Science), focused on Arctic ocean modeling and ice-ocean-atmosphere interactions. Funded by DOE and ONR, the project runs from 2023 to 2026.
- Primary Chair for the session "The Changing Thermohaline Structure of the Arctic Ocean: Mechanisms and Impacts". Ocean Sciences Meeting 2020. *San Diego, California*, Feb 16–21, 2020.

Calvin W. Mordy

Oceanographer, Cooperative Institute for Climate, Ocean and Ecosystem Studies (206) 526-6870
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Professional Preparation:

Berry College	Mt. Berry, GA	Chemistry	B.S.	1982
University of Kansas	Lawrence, KS	Chemistry	M.S.	1986
Oregon State University	Corvallis, OR	Oceanography	Ph.D.	1992
University of Southern California	Los Angeles, CA	Sea Ice Microbial Communities		1992-1993

Appointments:

University of Washington	Research Engineer/Scientist	1993-present

Recent Publications:

Andrews, A., et al., (2019): Ecosystem Status Report 2019: Eastern Bering Sea, Stock Assessment and Fishery Evaluation Report. E. Siddon and S. Zador (eds.), North Pacific Fishery Management Council, Anchorage, AK.

Chiodi, A.M., C. Zhang, E.D. Cokelet, Q. Yang, C.W. Mordy, C.L. Gentemann, J.N. Cross, N. Lawrence-Slavas, C. Meinig, M. Steele, D.E. Harrison, P.J. Stabeno, H.M. Tabisola, D. Zhang, E.F. Burger, K.M. O'Brien, and M. Wang (2021): Exploring the Pacific Arctic Seasonal Ice Zone with Saildrone USVs. *Front. Mar. Sci.*, 8, 640690, doi: 10.3389/fmars.2021.640697.

Cynar, H., L.W. Juranek, C.W. Mordy, D. Strausz, and S. Bell (2022): High-resolution biological net community production in the Pacific-influenced Arctic as constrained by O2/Ar and O2/N2 observations. *Deep-Sea Res. II*, 206, 105214, doi: 10.1016/j.dsr2.2022.105214.

Danielson, S.L., J.M. Grebmeier, K. Iken, C. Berchok, L. Britt, K.H. Dunton, L. Eisner, E.V. Farley, A. Fujiwara, D.D.W. Hauser, M. Itoh, T. Kikuchi, S. Kotwicki, K.J. Kuletz, C.W. Mordy, S. Nishino, C. Peralta-Ferriz, R.S. Pickart, P.J. Stabeno, K.M. Stafford, A.V. Whiting, and R. Woodgate (2022): Monitoring Alaskan Arctic shelf ecosystems through collaborative observation networks. *Oceanography*, 35(2), 52, doi: 10.5670/oceanog.2022.119.

De Robertis, A., N. Lawrence-Slavas, R. Jenkins, I. Wangen, C.W. Mordy, C. Meinig, M. Levine, D. Peacock, and H. Tabisola (2019): Long-term measurements of fish backscatter from Saildrone unmanned sailing vehicles and comparison with observations from a noise-reduced research vessel. ICES *J. Mar. Sci.*, 76(7), 2459–2470, doi: 10.1093/icesjms/fsz124.

Goldstein, E.D., J.L. Pirtle, J.T. Duffy-Anderson, W.T. Stockhausen, M. Zimmermann, M.T. Wilson, and C.W. Mordy (2020): Eddy retention and seafloor terrain facilitate cross-shelf transport and delivery of fish larvae to suitable nursery habitats. *Limnol. Oceanogr.*, 65(11), 2800-2818, doi: 10.1002/lno.11553.

Hennon, T.D., S.L. Danielson, R.A. Woodgate, B. Irving, D.A. Stockwell, and C.W. Mordy (2022): Mooring measurements of Anadyr Current nitrate, phosphate, and silicate enable updated Bering Strait nutrient flux estimates. *Geophys. Res. Lett.*, 49(16), e2022GL098908, doi: 10.1029/2022GL098908.

Kuhn, C.E., A. De Robertis, J.T. Sterling, C.W. Mordy, C. Meinig, N. Lawrence-Slavas, E.D. Cokelet, M. Levine, H.M. Tabisola, R. Jenkins, D. Peacock, and D. Vo (2020): Test of unmanned surface vehicles to conduct remote focal follow studies of a marine predator. *Mar. Ecol. Prog. Ser.*, 635, 1-7, doi: 10.3354/meps13224.

Kuhn, C.E., J.T. Sterling, M. McCormley, B. Birkemeier, A. Sar, A. Flock, and C.W. Mordy (2022): Animal-borne video cameras reveal differences in northern fur seal foraging behavior related to prey size selection. *Front. Mar. Sci.*, 9, 1015594, doi: 10.3389/fmars.2022.1015594.

Ladd, C., S.W. Bell, D.G. Kimmel, C.W. Mordy, P.J. Stabeno, and S. Stalin (2020): Eddy-like features near St. Matthew Island, Eastern Bering Sea Shelf: Observations from the Oculus Coastal Glider. *Geophys. Res. Lett.*, 47(23), e2020GL089873, doi: 10.1029/2020GL089873.

Levine, R.M., A. De Robertis, D. Grünbaum, R. Woodgate, C.W. Mordy, F. Mueter, E. Cokelet, N. Lawrence-Slavas, and H. Tabisola (2021): Autonomous vehicle surveys indicate that flow reversals retain juvenile fishes in a highly advective high‐latitude ecosystem. *Limnol. Oceanogr.*, 66(4), 1139-1154, doi: 10.1002/lno.11671.
Lomas, M.W., L.B. Eisner, J. Gann, S.E. Baer, C.W. Mordy, and P.J. Stabeno (2020): Time-series of direct primary production and phytoplankton biomass in the southeastern Bering Sea: Responses to cold and warm stanzas. *Mar. Ecol. Prog. Ser.*, 642, 39-54, doi: 10.3354/meps13317, View online.
Mordy, C.W., S. Bell, E. Cokelet, C. Ladd, G. Lebon, P. Proctor, P.J. Stabeno, D. Strausz, E. Wisegarver, and K. Wood (2020): Seasonal and interannual variability of nitrate in the eastern Chukchi Sea: Transport and winter replenishment. *Deep-Sea Res. II*, 177, 104807, doi: 10.1016/j.dsr2.2020.104807.
Mordy, C.W., L. Eisner, K. Kearney, D. Kimmel, M.W. Lomas, K. Mier, P. Proctor, P.H. Ressler, P. Stabeno, and E. Wisegarver (2021): Spatiotemporal variability of the nitrogen deficit in bottom waters on the eastern Bering Sea shelf. *Cont. Shelf Res.*, 224, 104423, doi: 10.1016/j.csr.2021.104423.
Nielsen, J.M., L.A. Copeman, L.B. Eisner, K.E. Axler, C.W. Mordy, and M.W. Lomas (2023): Phytoplankton and seston fatty acids dynamics in the northern Bering-Chukchi Sea region. *Deep-Sea Res. II,* 208, 105247, doi: 10.1016/j.dsr2.2022.105247.
Stabeno, P.J., C.W. Mordy, and M.F. Sigler (2020): Seasonal patterns of near-bottom chlorophyll fluorescence in the eastern Chukchi Sea: 2010–2019. *Deep-Sea Res. II*, 177, 104842, doi: 10.1016/j.dsr2.2020.104842.
Tabisola, H., J. Duffy-Anderson, C. Mordy, and P.J. Stabeno (2021): EcoFOCI: A generation of ecosystem studies in Alaskan waters. *Oceanography*, 34(4), 34–35, doi: 10.5670/oceanog.2021.supplement.02-15.
Zhang, C., A.F. Levine, M. Wang, C. Gentemann, C.W. Mordy, E.D. Cokelet, P.A. Browne, Q. Yang, N. Lawrence-Slavas, C. Meinig, G. Smith, A. Chiodi, D. Zhang, P. Stabeno, W. Wang, H. Ren, A. Peterson, S.N. Figueroa, M. Steele, N.P. Barton, A. Huang, and H.-C. Shin (2022): Evaluation of surface conditions from operational forecasts using in situ saildrone observations in the Pacific Arctic. *Mon. Weather Rev.*, 150(6), 1437–1455, doi: 10.1175/MWR-D-20-0379.1.
Zhao, J., Y. Wang, W. Liu, H. Bi, E.D. Cokelet, C.W. Mordy, N. Lawrence-Slavas, and C. Meinig (2022): Sea surface salinity variability in the Bering Sea in 2015-2020. *Remote Sens.*, 14(3), 758, doi: 10.3390/rs14030758.

Related activities:

Co-PI on numerous integrated ecosystem research programs in Alaskan Waters. Lead PI for synthesis of the Bering Sea Ecosystem Study resulting in ~45 presentations, >30 publications, and NOAA Gold Medal.
Co-PI of the Innovative Technology for Arctic Exploration program (ITAE) which develops new platforms and sensors including the Saildrone which received a NOAA Bronze Medal.
Lead nutrient chemist in the GO-SHIP hydrographic program (along with chemists at Scripps and AOML), contributing author to Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report.
Science Advisory Boards, proposal review panels, and peer review.

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Professional Experience

- Oceanographer, NOAA/PMEL, 1996 - Present

Education

- MS Atmospheric Sciences, University of Washington *1995*
- BS Atmospheric Sciences, University of Washington *1990*

Field Experience

- Twenty major oceanographic cruises totalling over 806 sea days
- Three UAS projects totalling over 30 flights

Publications

Quinn, P.K., T.S. Bates, **D.J. Coffman**, L.M. Upchurch, J.E. Johnson, A. Brewer, S. Baidar, I.L. McCoy, and P. Zuidema (2022): Wintertime observations of tropical Northwest Atlantic aerosol properties during ATOMIC: Varying mixtures of dust and biomass burning. *J. Geophys. Res.*, doi.org/10.1029/2021JD036253

Quinn, P.K., E.J. Thompson, **D.J. Coffman**, S. Baidar, L. Bariteau, T.S. Bates, S. Bigorre, A. Brewer, G. de Boer, S.P. de Szoeke, K. Drushka, G.R. Foltz, J. Intrieri, S. Iyer, C.W. Fairall, C.J. Gaston, F. Jansen, J.E. Johnson, O.O. Krüger, R.D. Marchbanks, K.P. Moran, D. Noone, S. Pezoa, R. Pincus, A.J. Plueddemann, M.L. Pöhlker, U. Pöschl, E. Quinones Melendez, H.M. Royer, M. Szczodrak, J. Thomson, L.M. Upchurch, C. Zhang, D. Zhang, and P. Zuidema (2021): Measurements from the RV Ronald H. Brown and related platforms as part of the Atlantic Tradewind Ocean-Atmosphere Mesoscale Interaction Campaign (ATOMIC). *Earth Syst. Sci. Data*, 13(4), 1759–1790, https://doi.org/10.5194/essd-13-1759-2021

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Lawler, M.J., S.L. Lewis, L.M. Russell, P.K. Quinn, T.S. Bates, **D.J. Coffman**, L.M. Upchurch, and E.S. Saltzman (2020): North Atlantic marine organic aerosol characterized by novel offline thermal desorption mass spectrometry approach: polysaccharides, recalcitrant material, and secondary organics. *Atmos. Chem. Phys.*, 20, 16007–16022, https://doi.org/10.5194/acp-20-16007-2020

Quinn, P.K., T.S. Bates, **D.J. Coffman**, L. Upchurch, R. Moore, L. Ziemba, T. Bell, E. Saltzman, J. Graff, and M.J. Behrenfeld (2019), Seasonal variations in western North Atlantic remote marine aerosol properties, *J. Geophys. Res.*, 124, 14,240-14,261, https://doi.org/10.1029/2019JD031740

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A. WORK EXPERIENCE

2023–present:	Research Scientist, Rede Nacional de Observação e Monitoramento Oceânico National Council for Scientific and Technological Development (CNPq), Brazil
2021–present:	Adjunct Scientist, Bigelow Institute for Ocean Sciences, United States
2018–present:	Affiliate Scientist, Blue Marble Space Institute of Science, United States
2020–2022:	Visiting Professor, Department of Meteorology, Federal University of Rio de Janeiro (UFRJ), Brazil
2018–2020:	Postdoctoral Researcher in ocean optics, Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission, NASA Goddard Space Flight Center, United States
2013–2017:	Research Scientist, Oxford Biological Oceanography Group, Department of Earth Sciences, University of Oxford, United Kingdom
2013–2017:	Research Scientist, Ocean Biogeochemistry and Ecosystems Research Group, National Oceanography Centre Southampton, United Kingdom
2013–2017:	Research Scientist, Remote Sensing Group, Plymouth Marine Laboratory (PML), United Kingdom
2012–2018	Research scientist, Atlantic Meridional Transect program, United Kingdom
2012:	Intern at the Phytoplankton Ecology Laboratory, Bermuda Institute of Ocean Sciences (BIOS), Bermuda
2002–2010:	Research scientist, Brazilian Antarctic Program, Brazil

B. EDUCATION

2013–2017:	D.Phil. (Ph.D.) in Earth Sciences, University of Oxford, United Kingdom.
2016:	IOCCG Summer Lecture Series, Observatoire Océanologique de Villefranche, France.
2011–2012:	NF-POGO Training Course in Operational Oceanography, Bermuda Institute of Ocean Sciences, Bermuda.
2009–2011:	Master of Science in Biological Oceanography, Universidade Federal do Rio Grande (FURG), Brazil.
2004–2007:	Biological Sciences Teacher (Licenciatura), UFRJ, Brazil.
2000–2004:	Bachelor of Science in Biological Sciences - Marine Biology, UFRJ, Brazil.

C. PARTICIPATION IN RESEARCH PROJECTS

2021–present:	Rede Nacional de Observação e Monitoramento Oceânico (ReNOMO), CNPq, Brazil. PI: Carlos Garcia
2021–present:	Satellite analysis of shifts in phytoplankton community composition and energy flow in the new Arctic, NOAA JPSS. PI: Lisa Eisner
2020–present:	Harmful Algal Bloom satellite detection system (FANSAT) for the State of Rio de Janeiro, Brazil, Universidade Federal do Rio de Janeiro (UFRJ). PI: Priscila K. Lange
2018–2020:	Plankton, Aerosol, Cloud, Ocean Ecosystem (PACE) mission, NASA GSFC. PIs: Jeremy Werdell and Ivona Cetinic
2013–2017:	Microbial ecology in the Atlantic Ocean, Atlantic Meridional Transect (AMT) and National Oceanography Centre Southampton (NOCS). PI: Mikhail Zubkov
2012:	Size-fractionated primary productivity in the Atlantic Ocean, AMT and Plymouth Marine Laboratory. PI: Gavin Tilstone

2009–201: Impact of anthropogenic activities in the Antarctic Environment: Water. National Institute of Science and Technology - Antarctic Environmental Research (INCT-APA), Brazilian Antarctic Program (PROANTAR). PI: Yocie Y. Valentin

2007–2009: Marine Antarctic Biodiversity in Relation to Environmental Heterogeneity at Admiralty Bay, King George Island, and Adjacent Areas at the Bransfield Strait (MABIREH), PROANTAR. PI: Lúcia S. Campos

2003–2007: Microphytoplankton as an instrument for monitoring environmental impacts in shallow coastal waters of Admiralty Bay, Antarctica, PROANTAR. PI: Lúcia S. Campos

D. RECENT PUBLICATIONS

Albernaz, D.R., **Lange, P.K.**, Santos, S., Carvalho, L.S. (2023). O mar está para peixes? - An interactive platform for open source fishery data in Rio de Janeiro. Anuário do Instituto de Geociências. *Accepted*.

Brewin, R.J.W., Dall'Olmo, G., Gittings, J., Sun, X., **Lange, P.K.**, Raitsos, D.E., Bouman, H., Hoteit, I., Aiken, J., Sathyendranath, S. (2022). A conceptual approach to partitioning a vertical profile of phytoplankton biomass into two communities. JGR Oceans. doi: 10.1029/2021JC018195

Lange PK, Werdell PJ, Erickson ZK, Dall'Olmo G, Brewin RJ, Zubkov MV, Tarran GA, Bouman HA, Slade W, Craig S, Poulton N, Bracher A, Lomas MW, Cetinic I (2020). Radiometric approach for the detection of picophytoplankton assemblages across oceanic fronts. *Opt Express*. doi: 10.1364/oe.398127

Lange PK, Brewin RJW, Dall'Olmo G, Tarran GA, Sathyendranath S, Zubkov MV, Bouman HA (2018). Scratching beneath the surface: a model to predict the vertical distribution of *Prochlorococcus* using remote sensing. *Remote Sensing* 10, 847. doi:10.3390/rs10060847

E. RELATED ACTIVITIES

- 15 oceanographic cruises over the last 16 years
- 17 lectures about marine sciences and ocean remote sensing over the last 16 years
- Lecturer in 11 disciplines for Undergraduate and Graduate courses in Meteorology and Biology
- Mentored 3 undergraduate and 2 graduate students, and elementary school students
- 11 Science outreach activities about phytoplankton over the last 15 years
- 15 peer-reviewed publications, 2 accepted publications, 3 in-prep publications
- 3 proposal review panels (NOAA and NASA grant calls)
- 5 panels of undergraduate and graduate projects (thesis, dissertations, etc.)
- 26 peer reviews
- 19 News featured reports and 10 interviews

Michael William Lomas

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I. Education

1999-2000 Assistant Research Scientist (post-doctoral position; advisor Dr. Todd Kana). Horn Point Laboratory - University of Maryland Center for Environmental

1999 Ph.D., Biological Oceanography. University of Maryland at College Park. Thesis Advisor, Dr. Patricia Glibert.

1994 B.Sc., Dual Degree, Marine Biology & Marine Chemistry. Long Island University, Southampton College (now called Stony Brook at Southampton).

II. Professional Experience, Mentorship & Teaching

2020 – pres. Director, Bigelow Center for Algal Innovation
2014 – pres. Director, Pravasoli-Guillard National Center for Marine Algae and Microbiota
2012 – pres. Senior Research Scientist, Bigelow Laboratory for Ocean Sciences.
2012 – pres. Adjunct Senior Scientist, Bermuda Institute of Ocean Sciences (formerly Bermuda Biological Station for Research, Inc.)
2001 – 2012. Assistant, Associate, Senior Scientist, Bermuda Institute of Ocean Sciences (formerly Bermuda Biological Station for Research, Inc.)

III. Products & Publications (total of 139)

Nielsen, J.M., Copeman, L.A., Eisner, L.B., Axler, K.E., Mordy, C.W., Lomas, M.W. 2023. Phytoplankton and seston fatty acid dynamics in the North Bering-Chukchi regions. *Deep Sea Research II (EIS special issue)* 208, 105247.

Pearson, H.C., Savoca, M.S., Costa, D.P., Lomas, M.W., Molina, R., Pershing, A.J., Smith, C.R., Villasenor-Derbez, J.C., Wing, S.R., Roman, J. 2023. Whales in the Carbon Cycle: can recovery remove carbon dioxide? *Trends in Ecology and Evolution,* 38, https://doi.org/10.1016/j.tree.2022.10.012.

Johnson, W.B., Soule, M.C.K., Longnecker, K., Lomas, M.W., Kujawinksi, E.B. 2023. Particulate and dissolved metabolite distributions along a latitudinal transect of the western Atlantic Ocean. *Limnology and Oceanography,* 68: 377-393.

Neeley, A., Lomas, M.W., Mannino, A., Vandermeulen.R.. 2022. Impact of growth phase, evolution and climate change conditions on the pigment and carbon content of fifty-one phytoplankton isolates. *Journal of Phycology.*58: 669-690.

Martiny, A.C., Hastrom, G.I., DeVries, T., Letscher, R.T., Britten, G.L., Garcia, C.A., Galbraith, E., Karl, D., Levin, S.A., Lomas, M.W., Moreno, A.R., Talmy, D., Wang, W., Matsumoto, K. 2022. Marine phytoplankton resilience may moderate oligotrophic ecosystem responses and biogeochemical feedbacks to climate change. *Limnology and Oceanography. 67:378-389. doi.org/10.1002/lno.12029.*

Lomas, M.W., Bates, N.R., Johnson, R.J., Steinberg, D.K., Tanioka, T. Adaptive Biogeochemistry Leads to Counter-intuitive Carbon Export Response to Warming in the Sargasso Sea. *Nature Communications.* 13:1211 (10.1038/s41467-022-28842-3).

Tanioka, T., Matsumoto, K., Lomas, M.W. 2021. Drawdown of atmospheric pCO2 via dynamic particle export stoichiometry in the ocean twilight zone. *Geophysical Research Letters, 48:* e2021GL094924.

Lomas, M.W., Baer, S.E., Mouginot, C., Terpis, K.X., Lomas, D.A., Altabet, M.A., Martiny, A.C.. 2021. Varying influence of phytoplankton biodiversity and stoichiometric plasticity on bulk particulate stoichiometry across ocean basins. *Communications: Earth and Environment, 2:143.* DOI:10.1038/s43247-021-00212-9

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Krause, J.W., Lomas, M.W., Danielson, S. Diatom growth, biogenic silica production, and grazing losses to microzooplankton in the Northern Bering and Chukchi Seas. *DSRII Arctic IERP Special Issue.* https://doi.org/10.1016/j.dsr2.2021.104950.

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IV. Synergistic Activities

Mentored 42 undergraduate students from 1997 through 2022 of which 14 have gone on to graduate school, 12 have acquired technical research positions in marine science (one in my lab), 16 are still undergraduates or in other fields.

Primary Instructor in BIOS Centre of Excellence in Observational Oceanography, 2008-2011. Taught 40 graduate-level students from developing nations (from the point of view of oceanographic research) in Biological Oceanography and Scientific Writing.

Mentored 8 BIOS Centre of Excellence in Observational Oceanography students in their independent research projects, primarily related to the ecology and biogeochemistry of the Sargasso Sea.

Instructor for AWI Centre of Excellence in Observational Oceanography 2014-2015. Taught 20 graduate-level students from developing nations (from the point of view of oceanographic research) ocean biogeochemistry using the BATS data as a case study.

Co-organizer of the OCB Scoping workshop on US Ocean Time-series and other time-series special sessions at national meetings

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PROFESSIONAL PREPARATION
Undergraduate: Oregon State University, Zoology B.S., 6/2000
Graduate: Oregon State University, Marine Ecology/Statistics M.S., 3/2006
Graduate: Oregon State University, Oceanography/Statistics **Ph.D., 12/2012**
Postdoctoral: Woods Hole Oceanographic Institution, Computational Biogeochemistry 2016

APPOINTMENTS
2019: Assistant Professor, Ocean Ecology and Biogeochemistry, College of Earth, Ocean, Atmospheric Sciences, Oregon State University, Corvallis OR
2017 – 2019: Assistant Professor (Sr. Research), College of Earth, Ocean, Atmospheric Sciences (CEOAS), Oregon State University, Corvallis OR
2016 – 2017: Research Associate III, Woods Hole Oceanographic Institution, Woods Hole MA
2012 – 2016: Postdoctoral Scholar/Investigator, WHOI, Woods Hole, MA.
2007 – 2012: Graduate Research Fellow, CEOAS, Oregon State University, Corvallis, OR.

5 RELEVANT PUBLICATIONS
1. Kavanaugh, M.T., Bell, T., Catlett, D., Cimino, M.A., Doney, S.C., Klajbor, W., Messié, M., Montes, E., Muller-Karger, F.E., Otis, D. and Santora, J.A., 2021. SATELLITE REMOTE SENSING AND THE MARINE BIODIVERSITY OBSERVATION NETWORK. *Oceanography*, *34*(2), pp.62-79.
2. Kavanaugh, M.T., Church, M.E, Davis, C.O., Karl, D.M., Letelier, R.M. and S.C. Doney. ALOHA from the Edge: Reconciling three decades of in situ Eulerian observations and geographic variability in the North Pacific Subtropical Gyre. Frontiers of Marine Science. https://doi: 10.3389/fmars.2018.00130
3. Kavanaugh, M.T., Oliver, M., Chavez, F., Letelier, R.M., Montes, E., Muller Karger, F. and Doney, S.C. Quo Vadimus: Seascapes as a new vernacular for ocean monitoring, management and conservation. *ICES Journal of Marine Science 73* (7), 1839-1850
4. Kavanaugh, M.T., Abdala, F.N., Ducklow, H., Glover, D., Fraser, W., Martinson, D., Stammerjohn, S., Schofield, O. and Doney, S.C., 2015. Effect of continental shelf canyons on phytoplankton biomass and community composition along the western Antarctic Peninsula. *Marine Ecology Progress Series*, *524*, pp.11-26.
5. Kavanaugh, M.T., Hales, B. Lockwood, D., Emerson, S., Quay, P.D., Letelier, R.M. Physicochemical and biological controls on primary and net community production across NE Pacific seascapes. 2014. Limnology and Oceanography 59(6), 2013-2027 | DOI: 10.4319/lo.2014.59.6.2013

SIGNIFICANT PRODUCTS AND ADDITIONAL PUBLICATIONS (3 years)
1. NASA GEOBON: Global seascapes are produced operationally and hosted on NOAA CoastWatch: https://coastwatch.noaa.gov/cw/satellite-data-products/multi-parameter-models/seascape-pelagic-habitat-classification.html

2. Santora, J.A., I.D. Schroeder, S.J. Bograd, F.P. Chavez, M.A. Cimino, J. Fiechter, E.L. Hazen, M.T. Kavanaugh, M. Messié, R.R. Miller, K.M. Sakuma, W.J. Sydeman, B.K. Wells, and J.C. Field. 2021. Pelagic biodiversity, ecosystem function, and services: An integrated observing and modeling approach. *Oceanography* 34(2):16–37

3. Capotondi, A., Jacox, M., Bowler, C., **Kavanaugh, M.,** et al.., 2019. Observational Needs Supporting Marine Ecosystems Modeling and Forecasting: From the Global Ocean to Regional and Coastal Systems. *Frontiers in Marine Science*, *6*, p.623.
4. **Kavanaugh, M. T**., Rheuban, J. E., Luis*, K. M. A., & Doney, S. C. 2017. Thirty-three years of ocean benthic warming along the U.S. Northeast Continental Shelf and Slope: Patterns, drivers, and ecological consequences. Journal of Geophysical Research: Oceans, 122. https://doi.org/10.1002/2017JC012953
5. **Jamil, A., Y. Spitz and Kavanaugh, M.T.,** 2022. Drivers of Physical and Biological Frontal Variability in the Northern California Current *Journal of Geophysical Research -Oceans*
6. Benson, A., Murray, T., Canonico, G., Montes, E., Muller-Karger, F.E., **Kavanaugh, M.T.,** Triñanes, J. and Dewitt, L.M., 2021. DATA MANAGEMENT AND INTERACTIVE VISUALIZATIONS. *Oceanography*, 34(2), pp.130-141
7. Estes Jr, M., Anderson, C., Appeltans, W., Bax, N., Bednaršek, N., Canonico, G., Djavidnia, S., Escobar, E., Fietzek, P., Gregoire, M., Hazen, E. and **M.T. Kavanaugh** et al., 2021. Enhanced monitoring of life in the sea is a critical component of conservation management and sustainable economic growth. *Marine Policy,* 132, p.104699
8. E Montes, JS Lefcheck, E Guerra-Castro, E Klein, **MT Kavanaugh,** et al., 2021. Optimizing large-scale biodiversity sampling effort. *Oceanography* 34 (2), 80-91
9. Muller-Karger, F., **Kavanaugh, M**., Iken, K., Montes, E., Chavez, F., Ruhl, H., Miller, R., Runge, J., Grebmeier, J., Cooper, L. and Helmuth, B., 2021. Marine Life 2030: Forecasting Changes to Ocean Biodiversity to Inform Decision-Making: A Critical Role for the Marine Biodiversity Observation Network (MBON). *Marine Technology Society Journal*, *55*(3), pp.84-85
10. Woodill, J, **M.T. Kavanaugh**, M. Harte, and J. Watson. 2021. Ocean seascapes predict distant-water fishing vessel incursions into exclusive economic zones. *Fish and Fisheries.*
11. Schultz, C., Doney, S.C., Hauck, J., **Kavanaugh, M.T**. and Schofield, O., 2021. Modeling Phytoplankton Blooms and Inorganic Carbon Responses to Sea‐Ice Variability in the West Antarctic Peninsula. *Journal of Geophysical Research: Biogeosciences*, *126*(4), p.e2020JG006227.[B]
12. Bahlai, C.A., Hart, C., **Kavanaugh, M.T**., White, J.D., Ruess, R.W., Brinkman, T.J., Ducklow, H.W., Foster, D.R., Fraser, W.R., Genet, H. and Groffman, P.M., 2021. Cascading effects: insights from the US Long Term Ecological Research Network. *Ecosphere*, *12*(5), p.e03430.
13. Blaisdell, J., Thalmann, H.L., Klajbor, W., Zhang, Y., Miller, J.A., Laurel, B.J. and **Kavanaugh, M.T**., 2021. A Dynamic Stress-Scape Framework to Evaluate Potential Effects of Multiple Environmental Stressors on Gulf of Alaska Juvenile Pacific Cod. *Frontiers in Marine Science*, *8*, p.497.
14. Montes, E., Djurhuus, A., Muller-Karger, F.E., Otis, D., Kelble, C.R. and **Kavanaugh, M.T.,** 2020. Dynamic Satellite Seascapes as a Biogeographic Framework for Understanding Phytoplankton Assemblages in the Florida Keys National Marine Sanctuary, United States. *Frontiers in Marine Science,* 7, p.575.

7 Letters of Support

Two letters of support are provided by our end users.

- Letter of Support from Dr. Kathi Lefebvre, NOAA/Northwest Fisheries Science Center (cross-Line Office collaborators).
- Letter of Support from Alaska Ocean Observing System (AOOS).