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Multi-resolution, Multi-scale Modeling for Scalable Macroalgae Production

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Public Executive Summary

Macroalgae harvested along coastlines and in the open ocean has traditionally been used as food for human consumption, animal feed, and fertilizer. The U.S. ARPA-E MARINER Program estimates that the nation has suitable conditions and geography to produce at least 500 million dry metric tons of macroalgae per year, yielding approximately 2.7 quadrillion BTUs of energy in the form of liquid fuel, which is roughly 10% of the nation's annual transportation energy demand. Adverse environmental effects of nutrient overload and ocean acidification may also be reduced by large-scale macroalgae cultivation in many coastal ocean regions. However, the successful deployment of large-scale marine macroalgae farms for fuel production depends on ambient hydrodynamic conditions and nutrient availability, as well as their interactions with macroalgae farm structures. Pacific Northwest National Laboratory led an ARPA-E MARINER project to develop a set of numerical modeling tools capable of simulating ocean hydrodynamic and biogeochemical processes, macroalgae trajectories for free-floating systems, macroalgae growth and biomass yields, and hydrodynamic load on macroalgae canopies and farm structures using a multi-resolution and multi-scale approach. This set of modeling tools provides a suite of information essential for system design, optimal project siting, risk analysis, and management of macroalgae production systems in the ocean. Better clarity can also help macroalgae system developers reduce deployment costs, operational risk, and potential impacts on the local marine environment.

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Objectives and Accomplishments

Objectives

The overall objective of the project was to develop a set of numerical modeling tools capable of simulating biogeochemical (BGC) processes, macroalgae trajectories for free-floating systems, macroalgae growth and biomass yields, and hydrodynamic loading on macroalgae canopies and supporting structures using an unstructured-grid, multi-resolution, and multi-scale approach. Specific objectives of the project include:

1. Simulation of free-floating system trajectory using NOAA's particle tracking model (GNOME, General NOAA Operational Modeling Environment) and surface current and wind fields from the community reanalysis products;
2. Simulation of regional-scale phytoplankton and nutrient flux using the flexible mesh global Model for Prediction Across Scales-Ocean and its biogeochemistry model (MPAS-O/BGC);
3. Developing a standalone macroalgae growth model to simulate growth rate and biomass yield for free-floating macroalgae systems;
4. Developing a dynamically coupled macroalgae growth and nutrient uptake model to simulate the nutrient consumption and macroalgae dynamics at farm scale;
5. Conducting laboratory experiments and numerical modeling analyses of hydrodynamic loads and interactions with macroalgae farm structures; and
6. Application of the integrated modeling tools to assess macroalgae growth and production potential, nutrient distributions, and system load responses to various hydrodynamic conditions.

Accomplishments

A number of tasks and milestones were laid out in Attachment 3, the Technical Milestones and Deliverables, at the beginning of the project. The actual performance against the stated milestones is summarized below in Table 1.

Table 1. Key Milestones and Deliverables

Tasks	Milestones and Deliverables
Task 1: Development of workplan 1.1 Modeling framework	**M1.1: Final SOPO** - Finalize Statement of Project Objectives (SOPO), technical tasks, milestones and deliverables. *Actual Performance*: (Completed 6/14/2018) PNNL finalized the SOPO in consultation with the ARPA-E MARINER Program. **M1.2: NOAA-PNNL collaboration workplan** - Develop a workplan that outlines the pathways for coordination and collaboration between PNNL and NOAA to ensure mutual support and eliminate any duplicative work. *Actual Performance*: (Completed 9/5/2018) Collaboration workplans were signed with NOAA for GNOME trajectory modeling (Chris Baker, signed 8/20/18) and marine spatial planning/data exchange (James Morris, signed 9/5/18). **M1.3: Completion of model integration** - Complete validations by Q6 for all models, including regional ocean model, MPAS-O/BGC, GNOME,

Tasks	Milestones and Deliverables
	wave and storm surge, Finite Volume Community Ocean Model (FVCOM)-Macroalgae and fluid-structure interaction (FSI) model. *Actual Performance*: (Not complete) Model integration for HYCOM, MPAS-O/BGC, and GNOME has been completed through the Cat1 NOMAD project. Initial model integration for HYCOM, MPAS-O/BGC, and FVCOM has been tested in Saco Bay. Integration of wave output with FSI has been completed for free-floating system (NOMAD) but is not completed for a fixed system because lab experiments for FSI model applications were not conducted. Further work for this task has been suspended at the direction of ARPA-E.
Task 2: Regional hydrodynamic modeling analysis 2.1 Model data inquiry and processing 2.2 Verification and analysis of model results	**M2.1: Coordination with NOAA** - Coordinate with NOAA to identify data sources and model coverage to ensure no duplication in effort. Explore opportunities to leverage existing data. *Actual Performance*: (Complete 9/5/2018) Task completed upon establishment of collaborative workplans with NOAA. **M2.2: Framework for model validation method** - Develop the framework for the model/data verification. Includes identification of all the relevant data sources to ensure no gaps in coverage. *Actual Performance*: (Completed 6/14/2018) The validation framework for the model data was completed. The velocity was compared with extensive surface drifter data and the vertical profiles of temperature and salinity were compared with ARGO drifter data. **M2.3: Completion of ocean model data analysis** - Complete QA/QC of model data records and evaluate the model SCORE metric based on the method of Haas et al. (2013) for predicting velocity and temperature, ensuring that all regions of scores of 3.0 or higher. *Actual Performance*: (Completed 2/15/2019) The performance of HYCOM Reanalysis was assessed by calculating statistical metrics comparing model prediction with field measurement in the U.S. Exclusive Economic Zone (EEZ) over a 20-year period. The model makes a reasonably good prediction in current speed and works exceptionally well in simulating temperature and salinity. A technical report entitled "ARPA-E: Regional Hydrodynamic Modeling Analysis: Data Validation Report" submitted as an attachment to the Q4 quarterly report. **M2.4: Data maps of ocean current and temperature completed** - Generate maps and data layers for ocean current and sea temperature/salinity will be generated by the end of Year 1 to support free-floating system tracking simulations and farm-scale coupled hydrodynamic-macroalgae modeling. *Actual Performance*: (Completed 6/10/2019) Ocean current and temperature data for the West Coast and Gulf of Mexico regions were obtained from HYCOM simulations. Hydrodynamic data on the West Coast were used to support simulating trajectories and macroalgae growth of NOMAD longlines and data in the Gulf of Mexico were used to simulate the sargassum trajectories and biomass growth in the vicinity of ocean gyres.
Task 3: Regional biogeochemistry modeling 3.1 MPAS-O/BGC model setup and calibration 3.2 Regional BCG model results and analysis	**M3.1: Identification of BGC parameters for FVCOM-macroalgae boundary conditions** - Identify parameters (e.g., N, P, and photosynthetically active radiation) to be produced by the MPAS-O/BGC system as needed by FVCOM-macroalgae for boundary conditions in order to provide an oceanic "farmer's almanac" suitable for plot-scale modeling of macroalgae.

Tasks	Milestones and Deliverables
	Actual Performance: (Complete 6/14/2018) Fourteen (14) essential BGC parameters, 4 essential ocean state parameters, and 17 optional parameters were identified in collaboration with PNNL for their macroalgae growth modeling. Nine (9) of these parameters are critical, and prototype datasets from MPAS-O/BGC were provided to PNNL to facilitate development of their macroalgae growth modeling. **M3.2: BGC Model calibration/validation completed** - Complete model calibration and validation through model skill assessment using a set of model performance error statistical metrics, e.g., with a weighted average skill score via Nash Sutcliffe Model Efficiency of greater than 0.2 for each parameter, to quantify model BGC capability. *Actual Performance*: (Not complete) BGC model calibration and validation was completed using low resolution mesh. Skill assessment analyses were performed with results pointing to a) the need for improved observational data as the "best available" climatology is insufficient to represent local variability and b) suggesting increased value in higher resolution to better resolve eddies. While the model calibration and validation were completed using low resolution mesh, calibration and validation at high resolution was not completed, as the task was suspended at the direction of ARPA-E. **M3.3: Regional nutrient distributions and model outputs** - Initial set of maps of regional BGC parameters and model outputs for BGC open boundary conditions (currents and BGC parameters such as temperature, nitrogen, phosphorous, etc.) for the FVCOM-macroalgae model at the local domain. *Actual Performance*: (Not complete) Regional nutrient distributions and model outputs were provided to the PNNL team for the FVCOM-macroalgae model suitable for their modeling purposes within local domains. While regional nutrient distributions and model outputs were provided using low resolution mesh, nutrient distributions and model outputs at high resolution were not provided, as the task was suspended at the direction of ARPA-E. **M3.4: Finalized FVCOM-macroalgae "farmer's almanac"** - Finalization of refined BGC parameter maps and boundary conditions for FVCOM-macroalgae, i.e., "farmer's almanac" for plot-scale macroalgae farm. Complete sensitivity analysis to evaluate role of model parameters on "farmer's almanac." *Actual Performance*: (Not complete) BGC parameter maps and boundary information were provided for the FVCOM-macroalgae modeling efforts for plot-scale modeling efforts. Sensitivity analysis indicated a role of increased resolution in eddy transport of nutrients within the domain, and use of mixed Eulerian-Lagrangian methods highlighted riverine vs deep ocean nutrient origins for macroalgae mariculture. While BGC parameter maps and boundary information were completed using low resolution mesh, parameter maps, and boundary information at high resolution were not provided, as the task was suspended at the direction of ARPA-E.
Task 4: Trajectory simulations for free-floating systems 4.1 Development of the trajectory prediction framework	**M4.1: Collaboration with NOAA on GNOME modeling** - Reach out to NOAA GNOME team in Seattle and set up a meeting to seek inputs on model configuration, data source for model validation, and potential improvement to represent longline floating macroalgae system. *Actual Performance*: (Complete 6/14/2018) PNNL made a site visit to the NOAA GNOME model development team in May 2018 and had another

Tasks	Milestones and Deliverables
4.2 Trajectory model validation 4.3 Application to selected pilot study sites	meeting during the ECM15 Conference in Seattle University in June 2018. NOAA provided PNNL an example GNOME application. PNNL implemented it on PNNL computers and further modified it to simulate trajectories of floating macroalgal cultivation systems. A detailed collaboration plan was also developed between PNNL and NOAA to facilitate the collaboration. **M4.2: Engagement with Cat1 awardees on trajectory modeling** - Engage with Cat1 awardees to investigate the applicability of trajectory modeling and simulation to other MARINER Cat1 free-floating macroalgae cultivation systems. *Actual Performance*: (Complete 6/14/2018) The project team worked closely with the PNNL Cat1 NOMAD project team and also reached out to another Cat1 team (Fearless Fund) in the Gulf of Mexico. PNNL's GNOME model domains covered both study sites (U.S. West Coast and the Gulf of Mexico). **M4.3: Trajectory model implementation** - Complete implementation of the trajectory model (GNOME) with input files of ocean current and wind forcing in proper formats and resolutions. *Actual Performance*: (Complete 1/31/2019) Eleven (11) years of current and wind forcing was collected for U.S. waters from global HYCOM and Climate Forecast System Reanalysis (CFSR). The data has been used to support simulations in both the eastern Pacific Ocean and the Gulf of Mexico and applied to answer specific questions posed by Cat1 project teams. **M4.4: Go/No-Go check point** - Validate the trajectory model against data obtained from NOAA Marine Debris Program and other sources. A set of error statistical metrics will be used to quantify the model performance. Error statistics include, at a minimum: (1) the deviation between modeled and observed trajectory locations normalized by both total travel distance and travel time; (2) correlation coefficients between modeled and observed trajectory locations relative to their origins. *Actual Performance*: (Complete 3/14/2019) PNNL conducted an extensive literature review and data inquiry for the trajectory model validation over the course of the project. The publicly available data for particle trajectory in the open ocean is extremely limited, and NOAA has conducted GNOME model validation using the existing data. For example, following the 2011 Japan tsunami, NOAA ran trajectories for 40,000 particles from eight (8) locations along Japan's coast, using the same global HYCOM currents that PNNL used. Results were validated by NOAA to reports of lost vessels, which are identifiable objects, and were compared with results from several other ocean tracking models. GNOME saw its best fit of 0.73 root-mean-square (RMS) when using windage of 1.5%. General timing of modeled particles aligned with vessel sightings after crossing the Pacific Ocean. The model validation conducted by NOAA using the 2011 Japan tsunami debris data suggested that GNOME is able to simulate the trajectories of free-floating particles with reasonable accuracy using HYCOM and CFSR wind data. PNNL also collaborated with Chaunmin Hu with the Fearless Fund project to identify satellite imagery of Sargassum that may be used for validation. While data was available, the infrequency of satellite overhead passes, the 1 km resolution, and interference by cloud cover made it impossible to determine the movement of individual rafts, so validation was not possible. Based on the literature review, previous

Tasks	Milestones and Deliverables
	NOAA studies, and availability of trajectory data, the model validation task was considered completed. **M4.5: Maps of trajectories of floating systems** - Generate maps of trajectories for the pilot study site as a function of releasing times and locations under different hydrodynamic (currents and wind forcing) and environmental (e.g., salinity and temperature) conditions. *Actual Performance*: (Complete 6/14/2019) Maps of trajectories were developed for free-floating projects (NOMAD and Fearless Fund).
Task 5: Regional wave and extreme events modeling 5.1 High-resolution wave modeling analysis 5.2 High-resolution storm surge modeling analysis	**M5.1: Completion of wave and storm surge model validation** - Validate the wave and storm surge models with NOAA buoy and tide gauge data to ensure the error statistical values are within commonly accepted criteria, such as overall normalized root mean square error (NRMSE) for significant wave height and storm surge level is less than 0.2 and the linear correlation coefficient is greater than 0.8. *Actual Performance*: (Completed 11/1/2019) Error statistics for model validation were generated. Storm surge simulations and validations for the East Coast, Gulf of Mexico, and Caribbean Sea were conducted for selected hurricane events. **M5.2: Maps and statistics of wave climates completed** - Complete maps and statistics of wave climates at selected regions/sites under extreme conditions based on long-term wave hindcasts. *Actual Performance*: (Not complete) Maps and statistics of regional wave climates were generated for West Coast, Alaska, and Hawaii regions. Further work for this task (e.g. obtaining wave climate data for the East Coast and Puerto Rico regions generated by Sandia National Laboratories) has been suspended at the direction of ARPA-E. **M5.3: Maps of storm surge and current distributions completed** - Complete maps of maximum water level and current speed distributions induced by tides and storm surge under extreme weather conditions. *Actual Performance*: (Not complete) Large ensemble storm surge simulations for the Gulf of Mexico were completed. Further work for this task, including results analysis for the Gulf of Mexico and ensemble simulations for the East Coast, has been suspended at the direction of ARPA-E.
Task 6: Farm-scale hydrodynamic and macroalgae dynamics modeling 6.1 Development of a macroalgae growth model 6.2 Coupling a macroalgae model with the hydrodynamics model 6.3 Application of coupled model to pilot study sites	**M6.1: Engagement with Cat1 awardees** - Engage with Cat1 awardees to identify opportunities to measure growth rates and nutrients on other systems. *Actual Performance*: (Complete 6/14/2018) The project team worked closely with the PNNL Cat1 NOMAD project team and also reached out to other Cat1 teams via email exchanges, informal meetings, and online surveys. **M6.2: Completion of growth model development** - Complete the portable growth model development and benchmark testing. *Actual Performance*: (Complete 12/14/2018) A stand-alone kelp growth model based on generic kelp kinetics formulations. The Droop Equation (Droop 1977) that allows for luxury nitrogen uptake and storage was also implemented. The growth was used to support the Cat1 NOMAD project. **M6.3: Completion of hydrodynamics-macroalgae model coupling** - Complete direct coupling between the macroalgae growth model and hydrodynamic model.

Tasks	Milestones and Deliverables
	Actual Performance: (Complete 9/14/2019) Completed model coupling and continued testing the fully coupled hydrodynamic-macroalgal growth model using the simplified channel grid for major kinetic processes. **M6.4: Completion of hydrodynamic-macroalgae model validation** - Conduct model validation and evaluate model performance with a set of error statistical values to make sure model predictions reasonably match field observations. *Actual Performance*: (Not completed). The macroalgae growth model based on the Droop Equation was internally coupled with the hydrodynamic model FVCOM. The coupled hydrodynamic-macroalgae model has been tested and validated for an idealized channel case. The coupled model was also set up for a real-world site - Saco Bay, Maine USA and validated by comparing model results with field observation data, including water level, current, nutrients and macroalgae growth rate. However, a complete set of model validation error statistics have not been systematically calculated to assess model performance skill due to lack of performance time and redirection of the project by ARPA-E. Additional sensitivity tests to further improve model performance remain to be conducted. **M6.5: Completion of hydrodynamic-macroalgae model application** - Complete model application to selected Cat1 project sites and generate maps of nutrient distributions and macroalgae growth rates to support Cat1 projects. Seasonal variability of nutrient flux and macroalgae growth will be analyzed. *Actual Performance*: (Not complete) Further work for this task has been suspended at the direction of ARPA-E.
Task 7: Macroalgae and structure interaction experiment 7.1 Physical model configuration and setup 7.2 Experiments for different MAFS	**M7.1: Experiment configurations** - Develop new understanding of dynamics of MAFS under operating environment and extreme environment conditions. Create and archive benchmark data set for numerical modeling task. *Actual Performance*: (Not complete) The wave basin experiment was scheduled in the OSU Hinsdale Wave Research Laboratory for the Dec 2019/Jan 2020 timeframe. Experimental configuration was complete in early October 2019. However, the experimental set up was not performed as the experiment was suspended at the direction of ARPA-E.
Task 8: Farm-scale hydrodynamic load calculations 8.1 FSI model development for macroalgae 8.2 Application of FSI model to selected macroalgae farm systems and sea states 8.3 Prediction accuracy assessment	**M8.1: FSI model development** - Completion of incorporating macroalgae system properties into FSI model. *Actual Performance*: (Complete 6/14/2019) The system-scale FSI model development was completed. Specifically, the system-scale macroalgae farming system model was developed, and hydrodynamic loads analysis were performed using a free-floating configuration. **M8.2: Completion of FSI model validation** - Verification and validation of FSI model dynamic response and failure modes prediction using experimental data obtained in Task 7. *Actual Performance*: (9/14/2019) The physical and mechanical properties of both sugar kelp and bull kelp and longline under extreme environmental conditions were examined based on numerical simulations conducted. **M8.3: Load and response calculation** - Completion of structural load and response calculations and analysis for different farm structures. *Actual Performance*: (Not complete) This task was suspended at the direction of ARPA-E.

Tasks	Milestones and Deliverables
Task 9: Macroalgae production classification scheme 9.1 Collaboration with NOAA on marine spatial planning	**M9.1: Framework** - Literature review and development of framework for the production classification. *Actual Performance*: (Complete 3/14/2019) A framework was developed to further understanding of the optimal U.S. coastal areas for growing macroalgae at sea. Identification of these areas can help accelerate the establishment of an industry that will produce large amounts of macroalgae at competitive prices for food additives, specialized industrial chemicals, animal fodder, and biofuels. The framework was submitted as an attachment to the Q4 quarterly report. **M9.2: Inputs to NOAA's aquaculture mapping atlas** - Provide all data layers in geo-reference format to NOAA for incorporation into the existing Aquaculture Mapping Atlas. *Actual Performance*: (Not complete) All the hydrodynamic data from HYCOM have been generated but are not yet formatted in the geo-reference format. Wave data from regional SWAN hindcasts, except East Coast and Gulf of Mexico/Caribbean Sea, have been processed and provided to NOAA. BGC data are only available from the coarse resolution MPAS-O/BGC simulations and the high-resolution model simulations were not completed. This task was suspended at the direction of ARPA-E. **M9.3: GIS maps of classification scheme** - Generate data layers of rankings for macroalgae production based on a number of factors that the macroalgae biofuel industry can use to select favorable sites for macroalgae production. *Actual Performance*: (Complete 12/31/2019) GIS map layers were developed that took into consideration growing needs for five species of kelp. The layers included: bathymetry, distance to port, water temperature, salinity, dissolved oxygen, dissolved nutrients with emphasis on nitrogen and phosphorus constituents, vessel traffic routes and lanes, state and federal boundary lines in coastal and outer continental shelf areas, and ocean and tidal currents. These layers focused in eight regions of U.S. waters: Gulf of Maine, Mid-Atlantic, Southeast, Gulf of Mexico, Caribbean island area with a focus on Puerto Rico, West coast, Hawaii, and Alaska.
Task 10: Technology transfer and outreach 10.1 Outreach materials and processes 10.2 T2M	**M10.1: Stakeholder engagement** - One technical meeting and two webinars will have been held to inform the scientific community. *Actual Performance*: (Not complete) While the project team engaged with the scientific community and stakeholders at several relevant events throughout the period of performance of the project, one technical meeting and two webinars (specifically) were not conducted. **M10.2: TTO memo** - Technology Transfer and Outreach memo will be developed and submitted to ARPA-E. *Actual Performance*: (Not complete) This task was suspended at the direction of ARPA-E. **M10.3: T2M plan** - Tech to market plan will be developed for use of the modeling products. *Actual Performance*: (Not complete) This task was suspended at the direction of ARPA-E.

Computer Models

This project relied on several models to execute the project scope. Descriptions of the models, including key assumptions, validation details, and relevant peer reviewed publications, are provided below.

HYCOM (HYbrid Coordinate Ocean Model)

The HYbrid Coordinate Ocean Model (HYCOM) is a data-assimilative hybrid isopycnal-sigma-pressure (generalized) coordinate ocean model, developed and maintained by a consortium with a multi-institutional effort sponsored by the National Ocean Partnership Program (NOPP), as part of the U. S. Global Ocean Data Assimilation Experiment (GODAE). HYCOM was developed to address the shortcoming of the traditional vertical coordinate system (z-level, terrain-following, isopycnic) in resolving surface mixing and stratification in the ocean. In HYCOM, vertical coordinates remain isopycnic in the open, stratified ocean, but smoothly transition to z coordinates in the weakly-stratified upper-ocean mixed layer, to terrain-following sigma coordinate in shallow water regions, and finally back to level coordinates in very shallow water (Bleck 2002, Halliwell 2004). HYCOM's varying scale (2m ~ 1,000m) in the vertical axis allows for proper representation of thermodynamic and BGC processes in mixed zone, unstratified and weakly stratified zone, and open ocean. HYCOM Global Reanalysis has a global coverage, temporal resolution of three hours, and horizontal resolutions of 1/12.5°. A model with higher horizontal resolution of 1/25° is available for the Gulf of Mexico (GOM) called HYCOM GOM Reanalysis. The available model output includes u-velocity, v-velocity, temperature, salinity, and surface elevation every three hours from October 1992 to December 2012 for the global model and January 1993 to December 2012 for the Gulf of Mexico model. HYCOM has been extensively validated in world-wide applications (Chang et al. 2008, Kelly et al. 2007, Metzger et al. 2010, Mignac et al. 2015, Tanajura et al. 2020). In the present project, HYCOM Reanalysis data over all U.S. EEZ were acquired including West Coast, East Coast, Gulf of Mexico coast, Hawaii coast, and Puerto Rico coast regions. For validation, the model data was statistically compared to current speed from NOAA drifter buoy and temperature and salinity from Argo using a set of statistical metrics, and a score number was formulated to assess the overall performance of the model. Details of model validation for this study is provided in Jang and Haas (2019).

Publications produced as a result of this research are listed below. **Bold indicates ARPA-E MARINER project team members.**

- **Jang, M.**, **K. Haas, P. Wolfram,** and **Z. Yang.** 2020. "Automatic detection and analysis of surface eddies in the Gulf of Mexico." In preparation.

MPAS-O/BGC (Model for Prediction Across Scales-Ocean and Biogeochemistry Model)

To provide boundary conditions for farm-scale macroalgae modeling using FVCOM-Macroalgae, the Model for Prediction Across Scales-Ocean (MPAS-O − Ringler et al. 2013, Petersen et al. 2015) was configured with a global, multi-resolution mesh. MPAS-O is the ocean component of DOE's Energy Exascale Earth System Model (E3SM). The multi-resolution BGC model used in MPAS-O is the Biogeochemical Elemental Cycling (BEC) model, which consists of five key phytoplankton functional groups, one zooplankton group, multiple growth-limiting nutrients (nitrate, ammonium, phosphate, iron, and dissolved silicon), dissolved organic matter, and particulate inorganic and organic matter in order to access productivity (e.g., via ocean chlorophyll). The model also includes BGC processes of key elements, such as C, N, and P, and has been validated against extensive data sets. Calibration of the regional coastal BGC required consideration of regional and coastal results against observational data. Regional evaluations illustrated the need for improved representation of river forcing within the model, as the current configuration of MPAS-O/BGC within E3SM does not have realistic enough river forcing, including nutrient fluxes. Additionally, coastally refined resolution was used to understand the role of eddies in transport of nutrients within the Gulf of Mexico to illustrate free-floating farm system potential for macroalgae mariculture. Sensitivity analysis using different resolutions and mixed Eulerian and Lagrangian analysis was used to evaluate the role of source locations in nutrient distributions available for macroalgae mariculture. This multi-resolution approach, which used BGC simulations, provided key regional seasonal and climate information needed to model the growth and dynamics of macroalgae at the small scale using FVOM-Macroalgae. Results have been used to support Fearless Fund activities in anticipation of Phase 2 contributions to their efforts. More detailed descriptions of the model can be found in Moore et al. (2001; 2004) and Wang et al. (2015).

Publications produced as a result of this research are listed below. **Bold indicates ARPA-E MARINER project team members.**

- Dutta, S., R. Brady, **M. Maltrud**, **P. Wolfram**, and R. Bujack. 2019. “Leveraging Lagrangian Analysis for Discriminating Nutrient Origins.” Workshop on Visualisation in Environmental Sciences (EnvirVis), No. LA-UR-19-23951.
- Hoch, K., M. Petersen, **S. Brus**, D. Engwirda, A. Roberts, K. Rosa, and **P. Wolfram**. 2020. “MPAS-Ocean Simulation Quality for Variable-Resolution North American Coastal Meshes.” Journal of Advances in Modeling Earth Systems 12(3): e2019MS001848. https://doi.org/10.1029/2019MS001848.
- Johnson, S., F. Samsel, G. Abram, D. Olson, A. Solis, B. Herman, **P. Wolfram**, C. Lenglet, and D. Keefe. 2020. "Artifact-Based Rendering: Harnessing Natural and Traditional Visual Media for More Expressive and Engaging 3D Visualizations." IEEE Transactions on Visualization and Computer Graphics 26(1): 492-502. https://doi.org/10.1109/TVCG.2019.2934260.
- Samsel, F., **P. Wolfram**, P, A. Bares, T. Turton, and R. Bujack. 2019. “Color mapping Resources and Strategies for Organized Intuitive Environmental Visualization.” Environmental Earth Sciences 78 (9): 269. https://doi.org/10.1007/s12665-019-8237-9.

GNOME (General NOAA Operational Modeling Environment)

GNOME is an open-source predictive trajectory model developed by NOAA’s Office of Response and Restoration's (OR&R) Emergency Response Division to predict the movement of oil released during a spill based on winds, currents, diffusion, and shorelines (Spaulding 2017). The accuracy of predictions is based on the spatial and temporal resolution of model inputs (Duran et al. 2018) – HYCOM model outputs were often used for currents; CFSR model outputs were often used for wind. GNOME assumes massless particles with no inertia, and non-weathering particles were used to adapt the tracking of oil particles to macro-algae applications. The Trajectory Analysis Planner tool developed by NOAA (Samuels et al. 2013) allows a Monte Carlo approach where thousands of GNOME simulations can be processed and analyzed probabilistically by varying the start time and/or location, allowing predictions that vary seasonally or guide the starting location for operations.

FVCOM (Finite Volume Community Ocean Model)

The Finite Volume Community Ocean Model (FVCOM) is a free-surface, three-dimensional primitive-equations model that fully couples ice-ocean-wave-sediment-ecosystem models with options for various turbulence closure schemes, generalized vertical terrain-following coordinates, and wetting-drying process (Chen et al. 2003). FVCOM solves the three-dimensional primitive Navier-Stokes equations to simulate water surface elevation, velocity, salinity, temperature, and other transport constituents. The unstructured-grid modeling framework and mass-conservative finite-volume numerical schemes give FVCOM a unique advantage for resolving complex coastlines and providing accurate hydrodynamic simulations with great computational efficiency (Chen et al. 2018, Nakamura et al. 2019, Qu et al. 2019, Rowe et al. 2019, Yang et al. 2020, Yang et al. 2014). In this study, a macroalgae growth model was developed and dynamically coupled with FVCOM to simulate the dynamic interaction of nutrient uptake, macroalgae growth, and flow fields.

MAGROM (MAcroalgae GROwth Model)

MAGROM is a standalone macroalgal growth model that was developed in this project to simulate nutrient uptake/storage, macroalgae growth, and biomass yield for free-floating macroalgae systems based on oceanographic and meteorological inputs. Parameterizations for different species of macroalgae, such as sugar kelp and sargassum were implemented in the model. Macroalgae growth rate is calculated based on nutrient inputs (nitrogen and phosphorus), sea surface temperature, light attenuation, and solar radiation. MAGROM assumes one-way coupling between macroalgae and ambient water (i.e. macroalgae growth will not affect ambient water conditions considering their low density near the ocean surface) following the same approach by Brooks et al. (2018). Coupled with current and wind forcing, MAGROM can be applied to simulate biomass growth for the free-floating macroalgae systems along the trajectories over time. Details for MAGROM development can be found in Whiting et al. (2020).

Publications produced as a result of this research are listed below. **Bold indicates ARPA-E MARINER project team members**.

- **Whiting, J.**, **T. Wang**, **Z. Yang**, and **M. Huesemann**. 2020. “Simulating Macroalgae Growth and Trajectory of Free-Floating Systems.” In preparation.

FVCOM-Macroalgae

A dynamically coupled model, FVCOM-Macroalgae, was developed in this project to simulate nutrient uptake, biomass growth, and interaction with ambient currents for conventionally moored macroalgae farms. The MAGROM model was embedded in the coastal hydrodynamic model FVCOM. The kinetics of nutrient transport and macroalgae growth are simulated dynamically in the same finite volume, unstructured-grid modeling framework as FVCOM. The model was tested and validated for an idealized channel case as well as for a real-world site - Saco Bay, Maine USA. Model validation was performed by comparing model results with field observation data on water level, current, nutrients, and macroalgae growth rate. Details for FVCOM-Macroalgae development and validation can be found in Wang et al (2020).

Publications produced as a result of this research are listed below. **Bold indicates ARPA-E MARINER project team members**.

- **Wang, T.**, **Z. Yang**, D. Fredriksson and **P. Wolfram**. 2020. "Macroalgae Growth and Interaction with Hydrodynamics – A Coupled Modeling Approach." In preparation.

WaveWatch III

WaveWatchIII is a multi-grid, third-generation phase-averaged wave spectral model, developed and maintained by NOAA's National Centers for Environmental Prediction (NCEP) as part of the marine operational forecast system (Tolman 2013). Its consists of a collection of physics packages, including curvilinear grids, structured and unstructured-grids, effects of sea ice, and various wind-wave interaction and dissipation packages, such as the source term 2 (ST2), ST4, and ST6 physics package options (Ardhuin et al. 2010, Roland et al. 2009, Tolman 2003, Tolman and Chalikov 1996). WaveWatchIII uses explicit numerical schemes, so the model time steps are constrained by the Courant–Friedrichs–Lewy (CFL) stability criteria. WaveWatchIII operates at 30-minutes resolution for the global and Arctic Ocean and at 10-minutes and 4-minutes for different ocean regions. In the present study, WaveWatchIII was run at 30-minutes resolution at a global scale to provide open boundary conditions to drive the high-resolution coastal region wave model SWAN.

SWAN (Simulating WAves Nearshore)

Similar to WaveWatchIII, SWAN is also a third-generation phase-averaged wave spectral model (SWAN 2015). SWAN uses implicit schemes, which allows much larger time steps for high computational efficiency. SWAN solves the action balance equation using implicit numerical schemes, so it is more computationally efficient for simulating wave climate in high-resolution model grids (SWAN 2015). SWAN models nearshore wave dynamics that include nonlinear wave interactions, refraction, and shoaling due to bathymetry or ambient currents, and whitecapping and depth-induced breaking. As a result, SWAN is the most commonly used model for wave resource characterization in the nearshore regions (Amrutha et al. 2016, Guillou and Chapalain 2015, Silva et al. 2015, Wu et al. 2019). The unstructured-grid version of SWAN was used to simulate wave climates in West Coast, Alaska Coast, Hawaii Islands, East Coast and Caribbean Sea (Allahdadi et al. 2019, Wu et al. 2019, Yang et al. 2019). Extensive model validations were conducted using NOAA's NDBC buoy data. Statistics of wave climates for the U.S. coastal regions were generated based on the regional SWAN simulations to support the present ARPA-E MARINER modeling project.

ADCIRC (ADvanced CIRCulation Model)

ADvanced CIRCulation Model (ADCIRC) is an advanced coastal ocean modeling system that solves time dependent, free surface circulation and transport problems in two and three dimensions over an unstructured gridded domain (Bunya et al. 2010, Luettich et al. 2002, Westerink et al. 2008). ADCIRC utilizes the finite element method in space allowing the use of highly flexible, unstructured grids. ADCIRC has been extensively applied to simulate a wide range of coastal circulation and transport processes at various spatial and temporal scales, including tide and storm surge in deep-ocean, continental shelves, estuarine systems and coastal floodplains (Bunya et al. 2010, Chen et al. 2013, Dietrich et al. 2012, Joyce et al. 2019, Thomas et al. 2019). In present study, the ADCIRC model was applied in a three-dimensional mode to simulate tides and storm surge in the Atlantic Ocean, Gulf of Mexico and Caribbean Sea based on the community model configuration of ADCIRC for the region. Maximum velocity profiles through the water column were processed to support fluid-structure interaction modeling at the macroalgae farms.

OrcaFlex

OrcaFlex, a finite-element-based, multi-body/multi-mooring cable dynamic analysis software for offshore marine systems, was used to numerically predict the dynamics of farm-scale macroalgae systems subjected to extreme wave and current conditions. Specifically, OrcaFlex was used to model the hydrodynamic load and dynamic response of the Cat1 NOMAD system under extreme environmental conditions, where the longline was applied with polyculture bull kelp and sugar kelp. Here, hydrodynamic forces were calculated using Morison's equation. The kinematics and dynamics of the sugar kelp were simplified, and the group of kelps attached to the longline was modeled as a slender structure with the same length and an effective diameter such that the volumes were consistent with the real physical system. The simulations using OrcaFlex were used to identify potential failure modes for the preliminary NOMAD design. Additionally, OrcaFlex was used to develop a local-scale, fully non-linear coupled fluid-structural interaction sugar kelp model using a computational fluid dynamics (CFD) method. Sugar kelp was approximated as elongated rectangles with smoothed isosceles triangles at the ends to be consistent with available experimental data. Several different current speeds were simulated, and the resulting drag forces and calculated drag coefficients were validated by comparison with experimental data from the literature. The validated local-scale model was then applied to the modeled NOMAD system to determine the hydrodynamic coefficients of the simplified sugar kelp model for global dynamic analysis.

Publications produced as a result of this research are listed below. **Bold indicates ARPA-E MARINER project team members.**

- **Chen**, **M., S. Yim**, **D. Cox**, **T. Wang**, **M. Huesemann**, **Z. Yang**, T. Mumford, and G. Wood. 2019. "Hydrodynamic Load Modeling for Offshore Free-Floating Macroalgal Aquaculture Under Extreme Environmental Conditions." Proceedings of the 38th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2019). Glasgow, Scotland, UK. Paper-OMAE-2019-96803.
- **Chen**, **M., S. Yim**, **D. Cox**, **Z. Yang,** and T. Mumford. 2020. "Hydrodynamic Analysis of Macroalgae Local Model Using Computational Fluid Dynamics." Proceedings of the 39th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2020). Fort Lauderdale, FL, USA. Paper-OMAE-2020-19279.

Project Activities

Successful deployment of large-scale marine macroalgae farms for fuel production depends on ambient hydrodynamic conditions and nutrient concentrations, as well as their interaction with macroalgae farm structures. The overall objective of the project was to develop a set of numerical modeling tools capable of simulating BGC processes, macroalgae trajectories for free-floating systems, macroalgae growth and biomass yields, and hydrodynamic loading on macroalgae canopies and supporting structures using an unstructured-grid, multi-resolution, and multi-scale approach. Key elements of the project scope include:

- **Free-floating system trajectory simulations**. NOAA's multi-purpose particle-tracking model (GNOME) was used to conduct large ensemble simulations, driven by surface current and wind fields from the community reanalysis products HYCOM and CFSR.
- **Regional BGC and nutrient flux modeling**. The regional-scale phytoplankton and nutrient flux was simulated using the global MPAS-O and its BGC model, which allowed high-resolution simulations in the area of interest while maintaining a regional coverage.
- **Macroalgae growth and nutrient uptake modeling at farm scale**. A new macroalgae growth model (FVCOM-Macroalgae) was developed based on PNNL's FVCOM-Kelp model to simulate the nutrient consumption and macroalgae dynamics at farm scale with high spatial resolution.
- **Hydrodynamic load and interaction with macroalgae farm structure.** Structural response to hydrodynamic stress was calculated with wave climates and current inputs using a fluid-structure interaction numerical code. Laboratory experiments on wave and macroalgae interaction were to be conducted to support the hydrodynamic load calculations.

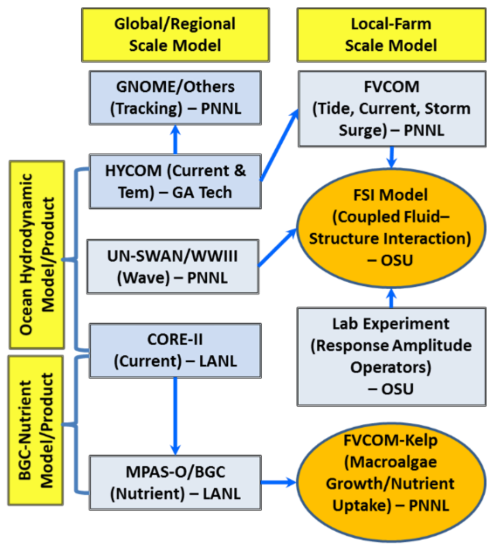

Figure 1. Modeling Approach and Roles of Team Members

Key modeling elements and team responsibilities are shown in Figure 1.

In October 2019, the project was instructed by the ARPA-E MARINER Program Manager to redirect efforts to support the Cat1 Fearless Fund project during Phase 2. As a result, a new SOPO was developed to support Fearless Fund moving forward. Activities on several remaining tasks were suspended as a result of the project redirection, which is reflected in Table 1.

Project Outputs

Journal Articles

- Hoch, K., M. Petersen, S. Brus, D. Engwirda, A. Roberts, K. Rosa, and P. Wolfram. 2020. "MPAS-Ocean Simulation Quality for Variable-Resolution North American Coastal Meshes." Journal of Advances in Modeling Earth Systems 12(3): e2019MS001848. https://doi.org/10.1029/2019MS001848.
- Jang, M., K. Haas, P. Wolfram, and Z. Yang. 2020. "Automatic detection and analysis of surface eddies in the Gulf of Mexico." In preparation.
- Johnson, S., F. Samsel, G. Abram, D. Olson, A. Solis, B. Herman, P. Wolfram, C. Lenglet, and D. Keefe. 2019. "Artifact-Based Rendering: Harnessing Natural and Traditional Visual Media for More Expressive and Engaging 3D Visualizations." IEEE Transactions on Visualization and Computer Graphics 26(1): 492-502. https://doi.org/10.1109/TVCG.2019.2934260.
- Samsel, F., P. Wolfram, P, A. Bares, T. Turton, and R. Bujack. 2019. "Color mapping Resources and Strategies for Organized Intuitive Environmental Visualization." Environmental Earth Sciences 78 (9): 269. https://doi.org/10.1007/s12665-019-8237-9.
- Wang, T., Z. Yang, D. Fredriksson, and P. Wolfram. 2020. "Macroalgae Growth and Interaction with Hydrodynamics – A Coupled Modeling Approach." In preparation.
- Whiting, J., T. Wang, Z. Yang, and M. Huesemann. 2020. "Simulating Macroalgae Growth and Trajectory of Free-Floating Systems." In preparation.

Papers

- Chen, M., S. Yim, D. Cox, T. Wang, M. Huesemann, Z. Yang, T. Mumford, and G. Wood. 2019. "Hydrodynamic Load Modeling for Offshore Free-Floating Macroalgal Aquaculture Under Extreme Environmental Conditions." Proceedings of the 38th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2019). Glasgow, Scotland, UK. Paper-OMAE-2019-96803.
- Chen, M., S. Yim, D. Cox, Z. Yang, and T. Mumford. 2020. "Hydrodynamic Analysis of Macroalgae Local Model Using Computational Fluid Dynamics." Proceedings of the 39th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2020). Fort Lauderdale, FL, USA. Paper-OMAE-2020-19279.
- Dutta, S., R. Brady, M. Maltrud, P. Wolfram, and R. Bujack. 2019. "Leveraging Lagrangian Analysis for Discriminating Nutrient Origins." Workshop on Visualisation in Environmental Sciences (EnvirVis), No. LA-UR-19-23951.

Status Reports

Quarterly reports throughout the period of performance of the project were submitted to ARPA-E through the online ePIC portal.

Media Reports

None to disclose.

Invention Disclosures

None to disclose.

Patent Applications/Issued Patents

None to disclose.

Licensed Technologies

None to disclose.

Networks/Collaborations Fostered

- *NOAA Coastal Aquaculture Siting and Sustainability team* – The project team shared and exchanged research products with the NOAA Coastal Aquaculture Team throughout the project period. PNNL provided NOAA high-resolution regional wave climate datasets to support the development of NOAA's web-based OceanReports Tool. NOAA shared nutrient climatology and light attenuation GIS data layers with PNNL team to support the macroalgae model development.
- *NOAA GNOME development team* – The project team collaborated with the NOAA GNOME development team to implement the GNOME model and post-processing utility program TAPs on PNNL computers.

Websites Featuring Project Work Results

None to disclose.

Other Products (e.g., Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)

- *Models* – Two models were developed as direct products of this work, MAGROM and FVCOM-Macroalgae. Details on these two models are presented in the Computer Models section.
- *GIS layers* – GIS map layers of the classification scheme were developed that took into consideration growing needs for five species of kelp. The layers included: bathymetry, distance to port, water temperature, salinity, dissolved oxygen, dissolved nutrients with emphasis on nitrogen and phosphorus constituents, vessel traffic routes and lanes, state and federal boundary lines in coastal and outer continental shelf areas, and ocean and tidal currents. These layers focused in eight regions of U.S. waters: Gulf of Maine, Mid-Atlantic, Southeast, Gulf of Mexico, Caribbean island area with a focus on Puerto Rico,

West coast, Hawaii, and Alaska. GIS map layers can be made available to ARPA-E upon request.

- *Data maps* – Data layers and maps of ocean current and temperature were developed to support free-floating system tracking simulations and farm-scale coupled hydrodynamic-macroalgae modeling. Data layers and maps can be made available to ARPA-E upon request.

Awards, Prizes, and Recognition

None to disclose.

Follow-on Funding

In October 2019, the project was instructed by the ARPA-E MARINER Program Manager to redirect efforts to support the Cat1 Fearless Fund project during Phase 2. Follow-on funding received to support Fearless Fund during Phase 2 is provided in Table 2.

Table 2. Follow-on Funding Received

Source	Funds Committed or Received
ARPA-E	None

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