A novel, modular, and scalable approach to modeling and data integration in ocean sciences for carbon removal MRV

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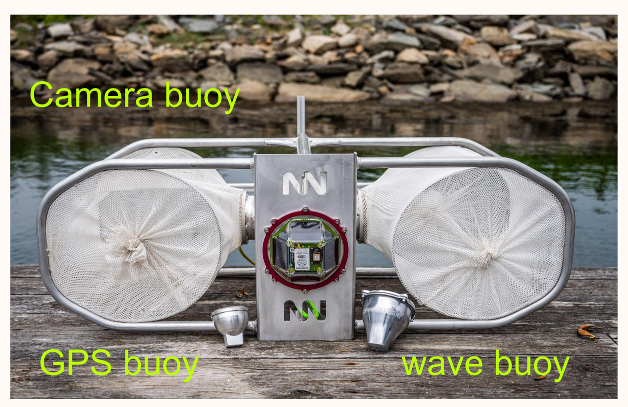
Running Tide is a carbon removal company with a goal to partner with nature to rebalance the carbon cycle. The IPCC has acknowledged the necessity of scalable carbon removal strategies in the effort to mitigate rising global temperatures. The ocean is a massive carbon sink, and is certain to play a vital role in any carbon removal pathway. In order to quantify our carbon removal deployments, we combine bespoke verification hardware with novel and modular fit-for-purpose models to create a conservative and statistically meaningful estimate of the carbon removed on a deployment-by deployment basis. This is how we model and verify the ocean surface transport of our material.

Verification hardware fleet:



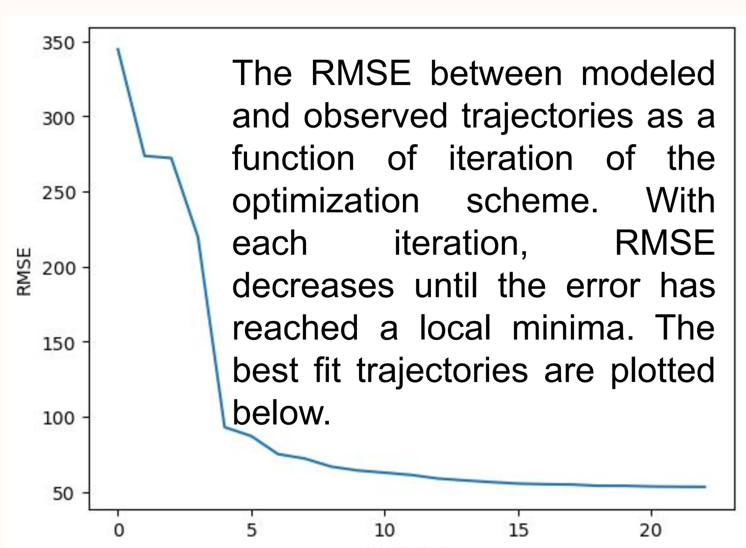
With every carbon removal deployment, we deploy a fleet of verification hardware to drift with and monitor the deployed material. This includes a number of GPS buoys, which are designed to respond similarly to ocean currents and waves as the deployed material.

We also send out our camera buoys, which send back GPS, sea surface temperature, and images of a subsample of the deployed material. The GPS and imaged data are ingested into our models and used to calibrate and validate our estimates of carbon removed.

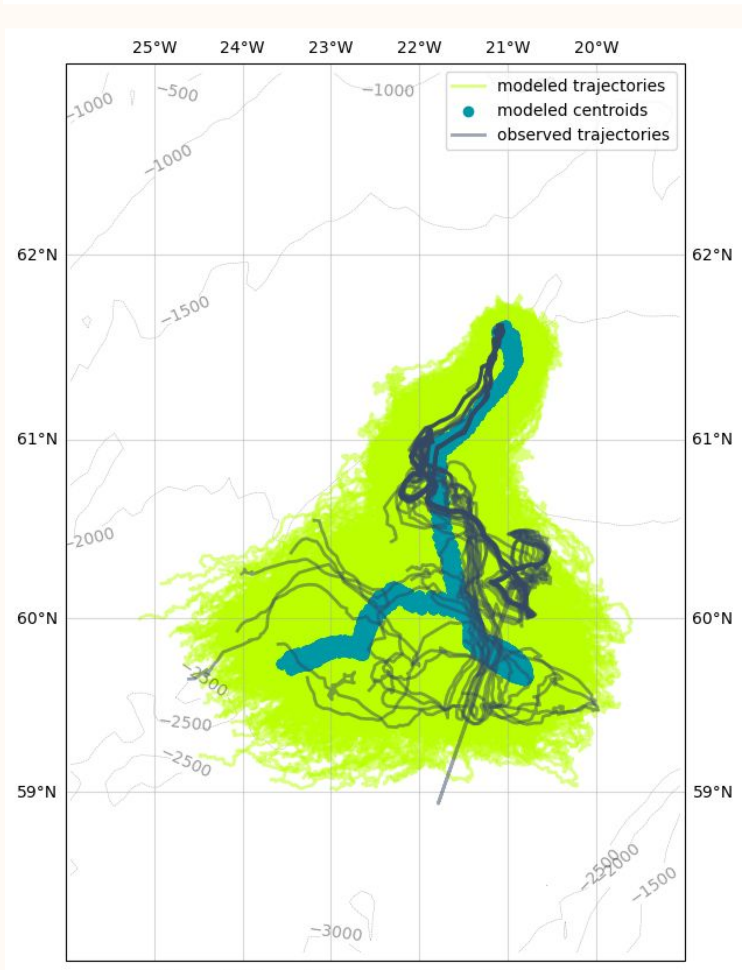
Tuning our models:

To simulate the movement of material on the surface, we use a Lagrangian simulator (Kehl et al., 2023) that weights ocean currents, waves, and wind reanalysis data to get the most accurate fit between modeled and observed trajectories. We've developed and implemented a gradient descent algorithm (bottom middle panel) that iteratively decreases the error between the modeled and observations and can reliably replicate the paths traveled by our GPS buoys.

After the appropriate weights have been identified through gradient descent, we apply a stochastic dispersion parameter that best fits the spread of the GPS buoys. This parameter accounts for small scale dynamics unresolved by the velocity fields used to force the Lagrangian simulator.



The RMSE between modeled and observed trajectories as a function of iteration of the optimization scheme. With each iteration, RMSE decreases until the error has reached a local minima. The best fit trajectories are plotted below.

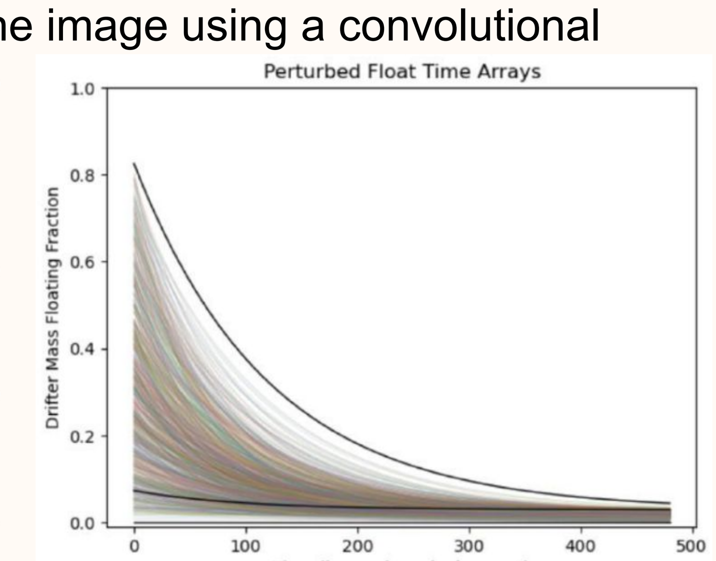


Abstract: It has become generally accepted that modeling will play a primary role in the monitoring, reporting, and verification (MRV) work necessary for successful and transparent marine carbon removal projects. While many of the models proposed for such work have been developed and validated over the course of the last several decades, the development of oceanographic modeling tools that deliver the scalability, specificity, and transparency required for MRV is still in its nascency. The MRV framework at Running Tide is an iterative system consisting of global ocean general circulation models, specific empirical and process-based models (e.g. macroalgal growth and Lagrangian drift simulations), and observations via a suite of in-situ sensors, including a first-of-its-kind open-ocean macroalgal growth observation platform. Our framework incorporates novel approaches to data integration using standard optimization techniques to guide parameterization and improvement of our models over time. Here, we describe in detail some of our data integration techniques, and demonstrate the capacity for model learning. In addition to discussing the use cases of such model infrastructure for carbon removal MRV, we will also highlight how this framework is integrated into our environmental and ecological exposures work.

Duration of material floating:

The float time of our carbon removal material is primarily dependent on four parameters: form factor, coating recipe, moisture content, and sea surface temperature (SST). Material float times are measured in two ways: laboratory tests and via our in-situ camera buoys. The data from each source can be fit to an exponential decay curve, the parameters of which are varied to produce a collection of float time curves that are fed into our quantification model. The images are processed to measure the fraction of biomass in the sample that remains floating on the surface. In order to compute floating fraction, we automatically segment each biomass within the image using a convolutional neural network model and compute the 2-dimensional pixel area for each detected biomass.

There is considerable variability between the two curves, most likely due to differences in measurement technique as well as moisture content and SST, but more testing is needed to fully map the sensitivity of float time curves to such parameters.



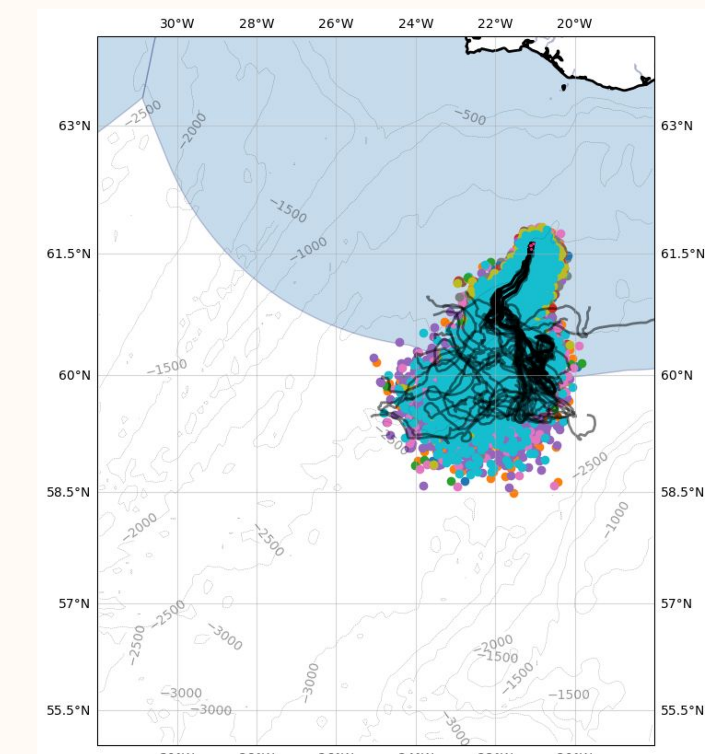
Implementation of gradient descent optimization:

The total velocity vector field used to force our Lagrangian simulator can be written as $\mathbf{u}_t = \alpha_h(t)\mathbf{u}_h + \alpha_s(t)\mathbf{u}_s + \alpha_w(t)\mathbf{u}_w$ where $\mathbf{u}_t$, $\mathbf{u}_h$, $\mathbf{u}_s$, $\mathbf{u}_w$ denote total, HYCOM, Stokes drift, and windage surface currents, respectively, and $\alpha_h(t)$, $\alpha_s(t)$, and $\alpha_w(t)$ are the time dependent weights applied to each of the velocity fields. The weight parameters are discretized in time and our model tuning optimizes these weights for the lowest error fit against our trajectory buoys. Our optimization algorithm is an implementation of a gradient descent, or steepest descent, (Polyak, 1987), a widely used optimization algorithm that finds the local minima of a differentiable loss or error function. It achieves this by computing all partial derivatives of the error function and moving the parameter space in the direction of steepest descent until the minimum is found, i.e. where the gradient of the error function approaches zero.

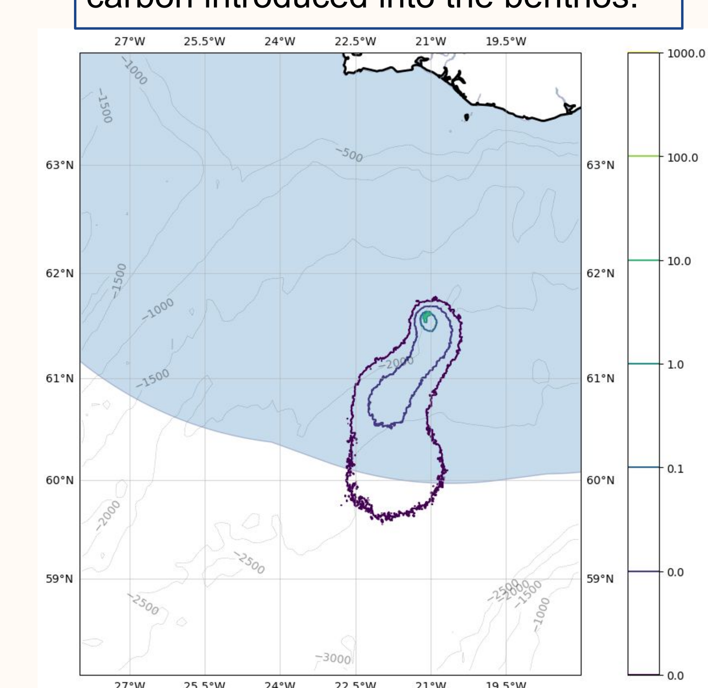
Estimates of terminal location of material on seafloor:

The output of the model runs are not only used to assess how much deployed carbon was sequestered, but also to estimate the amount of novel carbon introduced into the benthos. These estimates, along with comprehensive field experiments studying the degradation of Running Tide's carbon removal material in a benthic environment (see poster CM34A-1158 for more details) are used to assess the environmental impact of a carbon removal deployment.

Once all parameters have been appropriately fit and the float time curves have been generated, we run a Monte Carlo ensemble of 1,000 runs that introduce perturbations to the material float times and to the alpha values computed through model tuning. This additional variability is introduced to account for any dynamics not captured in the model, particularly the lateral transport of material as it sinks to the seafloor.



Above: the terminal locations of simulated material. Different colored dots represent results from different Monte Carlo runs. Black lines are observations.
Below: average estimates of novel carbon introduced into the benthos.



From each Monte Carlo simulation, we compute the fraction of the deployed material that was successfully sequestered below 1,000 m depth, and additionally we compute the spatial density of organic carbon introduced to the benthic region. We then report the median fractional value of the carbon sequestered which, throughout our 2023 deployment season, was approximately 93-97%. The average maximum density of novel carbon introduced into the benthos is estimated to be on the order of tens of grams of carbon per square meter.

References:

Kehl, C., Nooteboom, P. D., Kaandorp, M. L. A., and van Sebille, E. (2023). Efficiently simulating lagrangian particles in large-scale ocean flows – data structures and their impact on geophysical applications. Computers and Geosciences,175.

Polyak, B. T. (1987). Introduction to Optimization. Optimization Software, Inc., New York.

Velocity fields used in the Lagrangian simulator are from:

Cummings, J. A. and Smedstad, O. M. (2013). Variational data assimilation for the global ocean. In Park, S. and Xu, L., editors, Data Assimilation for Atmospheric, Oceanic, and Hydrological Applications, volume II. Springer, Berlin, Heidelberg.

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horanyi, A., Muñoz Savater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., and Thépaut, J.-N. (2023). ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS).