The impact of flow interaction on carbon sequestration potential in an idealised giant kelp forest

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February 26, 2024

Abstract

Macroalgae re- and afforestation are frequently proposed carbon dioxide removal (CDR) strategies, but the carbon storage is often uncertain. In nature, kelp forests grow on hard or sandy substrate leading to as little as 0.4% of their primary production being buried in the kelp's habitat (Krause-Jensen and Duarte, 2016) with the remainder exported. Export of dissolved and particulate carbon from kelp forests is strongly affected by the exchange of water between the kelp forest and the surrounding water. The permanence of storage of the exported carbon is determined by its destination, which is affected by the flow in and around the forest. Additionally, the potential for forests to grow can be limited by nutrients dissolved in the water, the availability of which is determined by the same water exchange rates.

Here, we use OceanBioME to build a numerical model of coupled flow/kelp interactions to study how tidal currents interact with a giant kelp (Macrocystis pyrifera) forest. We first validate our model using observations of currents within and surrounding a kelp forest in Southern California. By varying the kelp density within our model and tracking dissolved tracer released from the kelp forest, we analyse the timescales of water exchange to better understand how the flow influences carbon export and nutrient uptake. We find a density that maximizes the export of tracers which coincides with the density typical of natural kelp forests. Additionally, the drag results in a mean circulation through the forest and a mean displacement of the individuals suggesting that the physical dynamics of the kelp should be an important consideration in future studies and when planning re/afforestation projects.

Displayed at the AGUs Ocean Sciences Meeting 2024.
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Macrolalgae continually export carbon both dissolved in the water and as particulate detritus through erosion and breakage. However, the amount, final destination, and longevity of storage are unclear. As a first step to quantify these, we used modelling to better understand how water mixes with kelp forests, and how this limits their growth and carbon export. We are now expanding this to better capture intra-forest mixing, and coupling with biogeochemistry.

Limits to nutrient uptake and carbon export

To better understand how flow interaction with kelp forests influences the forests ability to grow (through nutrient limitation), and to export carbon, we arranged the kelp models as an idealised circular kelp forest exposed to complex flow. The kelp released a tracer with a saturation form:

$$ F_c = \frac{Z}{t} (1 - F_c) $$

Where $t$ is the characteristic timescale of release (1 hour), $F_c$ is the saturation value (0), and $Z$ is the scale factor for the kelp density. We then varied the kelp density in the forest to understand flow mixing in/out of the forest was limited.

- Peak tracer release at 1.5 individuals/m² (approximately similar to real life forests)
- Despite occupying less than 1% of the global ocean, macroalgae such as kelp contribute around 5.6% of primary productivity and potentially lead to 10% of the carbon sequestered by the ocean (Krishen, J., Lee, S., Hamdi, A., 2018). The outflow contribution is due to a combination of extremely fast growth, occupation of nutrient-rich waters, and high efficiency of nutrient utilisation. These estimates contain large uncertainties as the final destination of carbon assimilated in macro algae is unclear. Carbon is continually exported both as particulate and dissolved and only a small fraction (~4%) is buried in the benthic local.

At the lowest densities - 0.5 turbulent mixing occurs, limiting the tracer release to water which directly passes through the forest.

At intermediate density - mixing is enhanced by shear instabilities at the edge of the kelp forest.

At the highest densities - a von Karman vortex street develops further enhancing mixing.

To diagnose the factors dominating the peak tracer release at about 1.5 individuals/m², we took the volume averaged tracer evolution equation,

$$ \frac{1}{\Delta x} \int_{x+\Delta x}^{x} V(x) \, dz = \frac{1}{V} \int_{x}^{x+\Delta x} \frac{d}{dz} \left[ \int_{z}^{x+\Delta x} \frac{V(x')}{V(x)} \, dx' \right] \, dz $$

and defined the release and advection timescales: $r_x = \frac{\Delta x}{\sqrt{\frac{1}{V} \int_{x}^{x+\Delta x} \frac{V(x')}{V(x)} \, dx'}}$ and $r_a = \frac{L}{V}$ as well as defining the length scale characteristic of the distance a fluid parcel would travel before becoming more than 50% saturated, $L = \frac{V}{r_a} = \frac{V}{r_x}$.

For high kelp densities, the advection timescale is large as the speed of the flow through the forest is reduced. This causes the tracer to saturate prematurely in the total tracer released.

The kelp density at which kelp releases a tracer occurs when the release and advection timescales intersect. This also directly corresponds to when the saturation length scales $L/R$ becomes 1 in the forest core, suggesting that the fluid becomes saturated before it traverses through the kelp forest.

The key density at which tracer export/saturation is maximised corresponds to typical densities of kelp forests. This might suggest that forests are limited by the mixing of nutrients into the forest interior. These results also show that the flow within/around each kelp was important to their collective growth and export and that accurately representing transport processes is important when modelling the carbon sequestration caused by kelp forests. Additionally, these results may be used when considering kelp forests in relation to other carbon sinks.

To better understand the carbon drawdown potential of kelp forests, our next step is to couple the growth of kelp with the surrounding biogeochemistry. This will allow us to understand how these flow processes influence nutrient concentrations and primary production.

More realistic mixing processes

Our next step to quantify the carbon sequestration potential of kelp forests is to improve the realism of the mixing inside the forest and to add biogeochemical interactions.

During the summer months, strong temperature stratification is common in coastal waters. The stratification develops due to solar heating. Wind (and the corresponding stokes drift) causes a mixing layer near the surface to form, followed by a layer of strong stratification, and sometimes another well mixed layer above caused by the bottom topography.

Kelp forests may increase this stratification by altering the wave climate and insulating the water column. This might have an important effect on nutrient uptake in kelp forests as it can limit the amount of water mixed through the top of the forest where the majority of the nutrients are taken up.

In order to include the effect in our future work coupling kelp with the biogeochemistry, we have configured a LES to replicate shallow coastal summer time dynamics. This includes penetrative solar heating, surface heat exchange, wind stress, bottom wall stress, and wind driven Stokes drift.

We compared the LES with observations from near Motavak reef in California (Santa Barbara Coastal LTER, 2024) which showed good agreement with mean temperatures and diurnal stratification cycles (as shown in the left).

Constraining uncertain physical parameters

A key unconstrained parameter in our model of the kelp forest was the drag coefficient of the blades. In order to constrain this, we conducted an ensemble Kalman inversion (Shuster et al., 2020) where we generated an ensemble of synthetic observations of velocity inside and outside of the forest to compare to observations in Motavak reef (California) from Gaylord et al., 2007. We suggest that...