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

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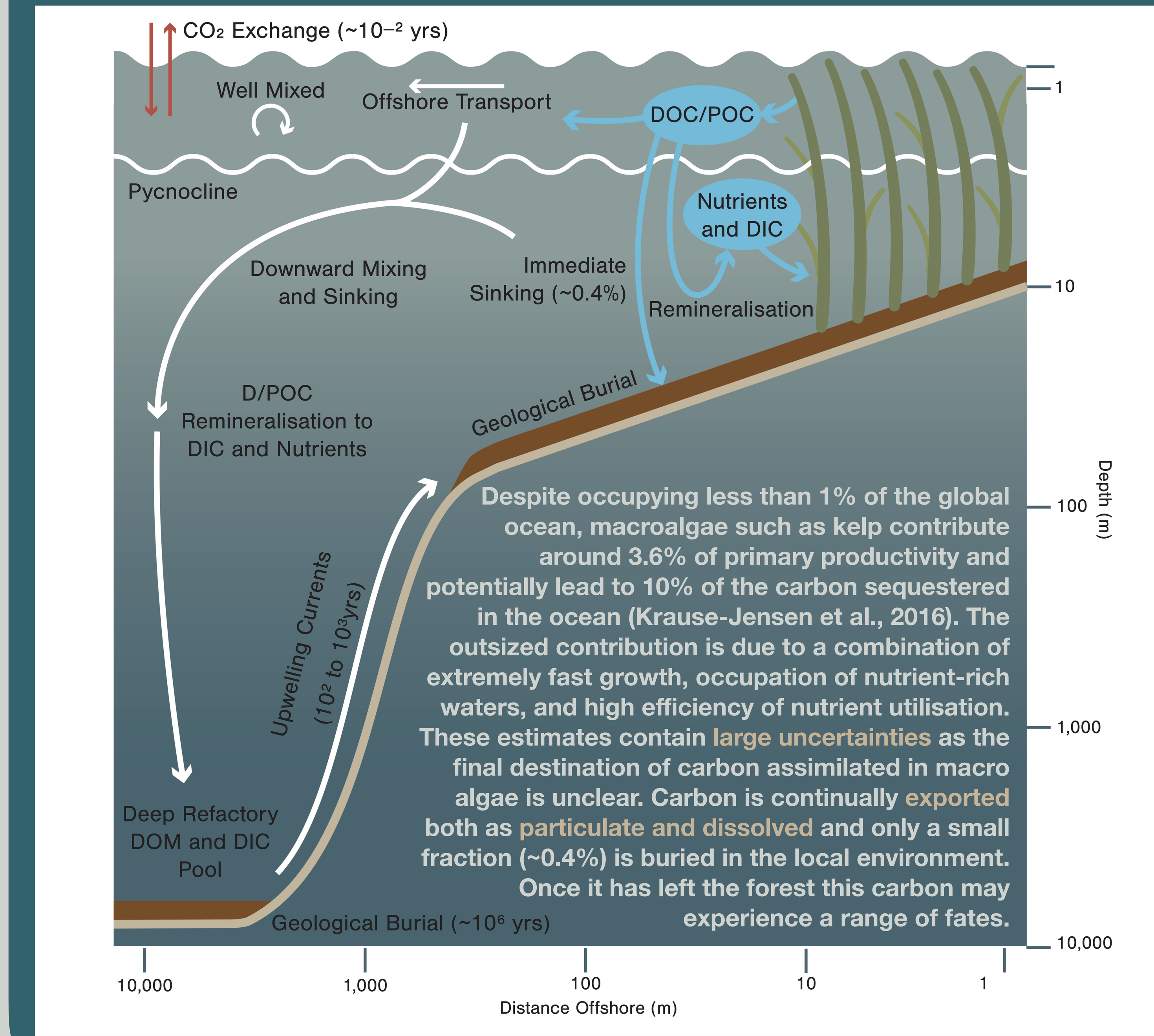
Macroalgae continually export carbon both dissolved in the water and as particulate detritus through erosion and breakage. However, the amount, final destination, and longevity of storage are unclear. As a first step to quantify these, we used modelling to better understand how water mixes with kelp 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.




Despite occupying less than 1% of the global ocean, macroalgae such as kelp contribute around 3.6% of primary productivity and potentially lead to 10% of the carbon sequestered in the ocean (Krause-Jensen et al., 2016). The outsized 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 (~0.4%) is buried in the local environment. Once it has left the forest this carbon may experience a range of fates.

## Modelling the kelp-flow interactions

Based on the previously developed models of Utter and Denny, 1996 and Rosman et al., 2013 for *Macrocystis pyrifera* (giant kelp) we model the kelp motion as sections of buoyant springs which experience drag from the water as depicted.

$$\mathbf{F}^D = \frac{1}{2}\rho_W\left(C_{DS}A_S + C_{DB}A_B\right)|\mathbf{u}_{rel}|\mathbf{u}_{rel}$$

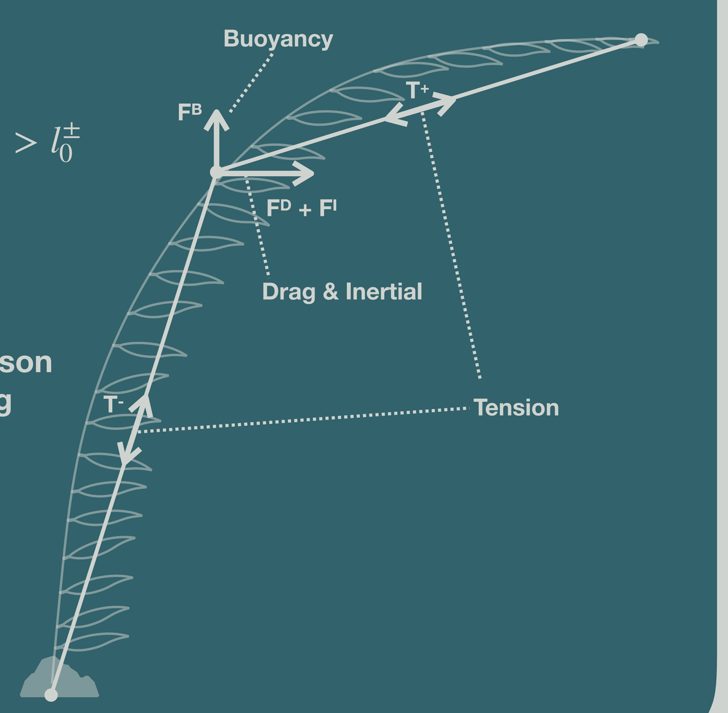
$$\mathbf{T}^{\pm} = \begin{cases} k\left(\frac{|\Delta\mathbf{x}^{\pm}| - l_0^{\pm}}{l_0^{\pm}}\right)^{\alpha} A_C \frac{\Delta\mathbf{x}^{\pm}}{|\Delta\mathbf{x}^{\pm}|} & \text{for } |\Delta\mathbf{x}^{\pm}| > l_0^{\pm} \\ 0 & \text{otherwise} \end{cases}$$

$$\mathbf{F}^I = \rho_w(V_B + V_P)\mathbf{a}$$

We calibrated the drag coefficient by comparison to field observations by Gaylord et al., 2007 using an ensemble Kalman inversion.

The drag force from each kelp was applied locally to decelerate the flow field:

$$\mathbf{a}_u = -\sum_{i \in \text{kelp}}\left[\frac{w_i(x,y,z)}{\rho_w}\mathbf{F}^D{}_i\right]$$

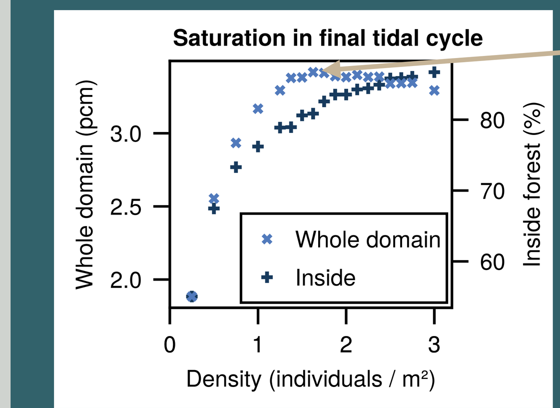



## Limits to nutrient uptake and carbon export

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 model as an idealised circular kelp forest forced by a simple tidal flow. The kelp released a tracer with a saturation form:

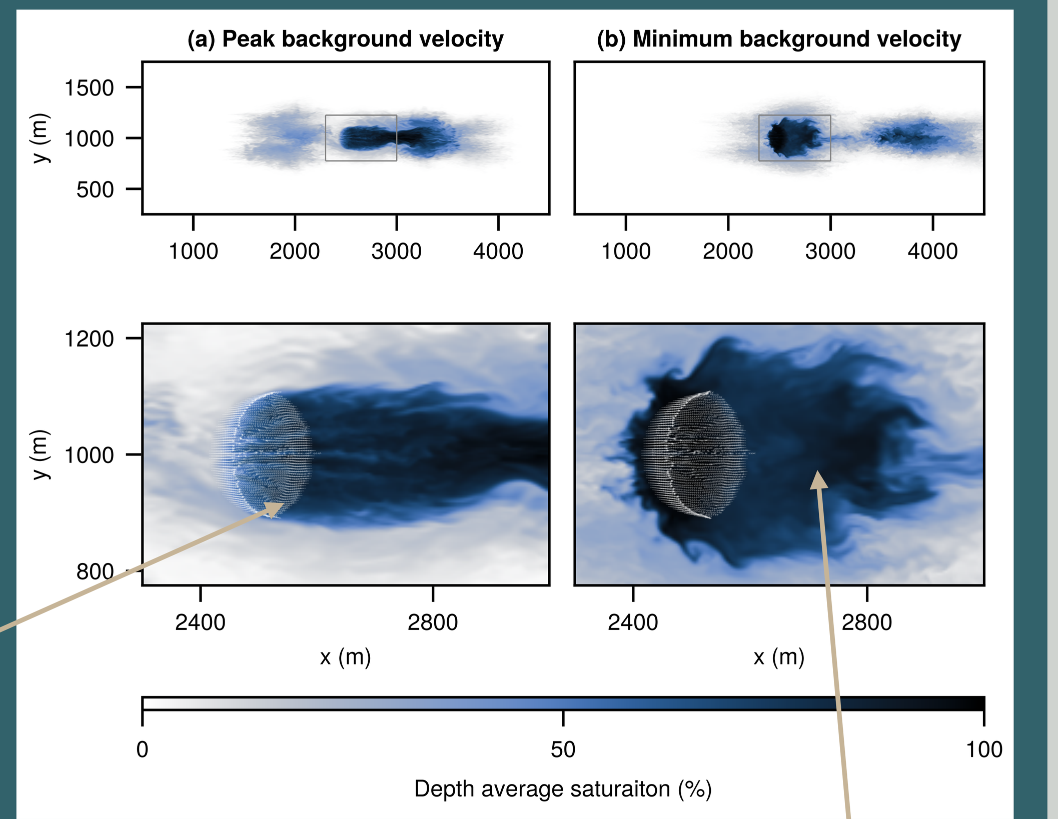
$$F_c = -\frac{\Sigma}{\tau}(C - C_0).$$

Where $\tau$ is the characteristic timescale of release (1 hour), $C_0$ is the saturation value (1), and $\Sigma$ is the scale factor for the kelp density. We then varied the kelp density in the forest to understand how mixing into/out of the forest was limited.




Peak tracer release at ~ 1.5 individuals / m² (coincidentally similar to real life forests)

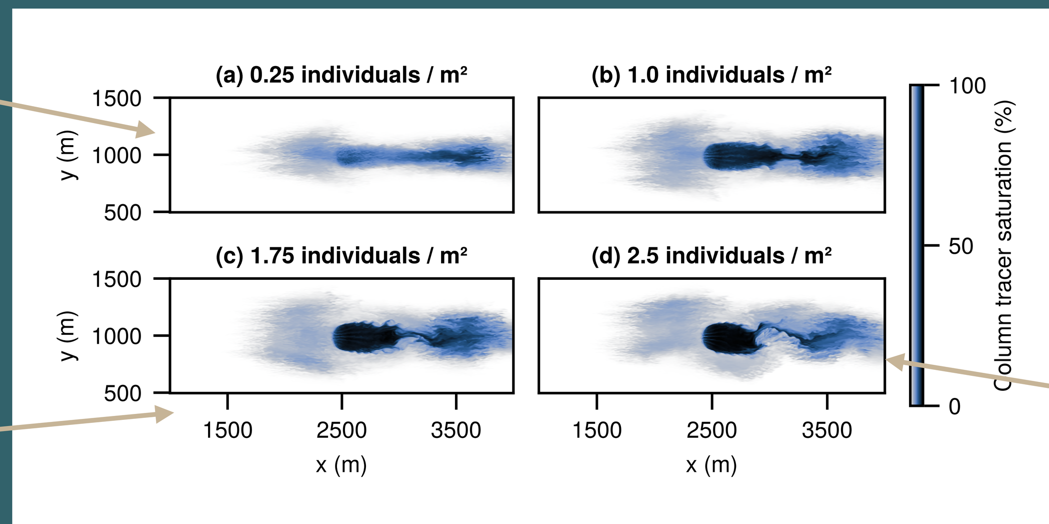
Kelp remain in their "upstream" position when when flow reverses




At different densities the tracer that passes through the forest is mixed with varying amounts of the surrounding water.

At the lowest densities very little turbulent mixing occurs, limiting the tracer release to water which directly passes through the forest

At intermediate densities mixing is enhanced by shear instabilities at the edge of the wake




Flow begins to reverse early in the slowed wake region

At the highest densities a von Kármán vortex street develops, further enhancing mixing

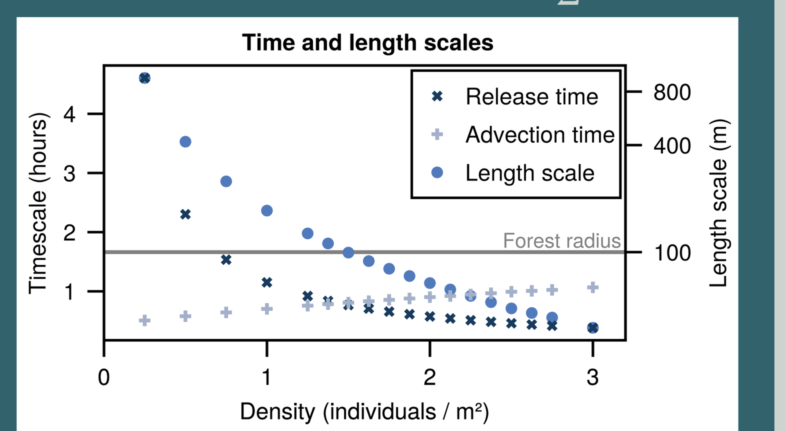
To diagnose the factors dominating the peak tracer release at about 1.5 individuals / m², we took the volume averaged tracer evolution equation,

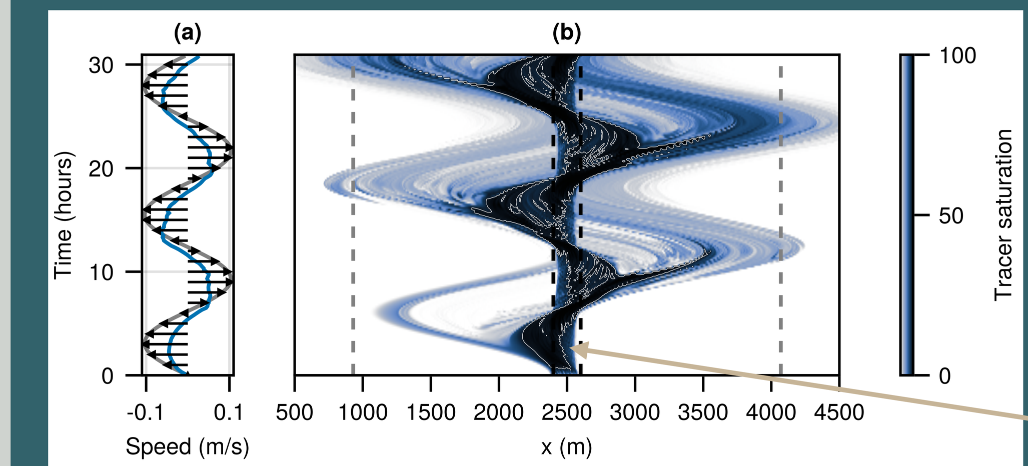
$$\frac{1}{V}\int\frac{\partial C}{\partial t}dV = \frac{\partial\overline{C}}{\partial t} = -\frac{1}{V}\int\mathbf{u}\cdot\nabla C dV + \frac{\Sigma}{\tau}(C_0 - \overline{C}),$$

and defined the release and advection timescales: $\tau_r = -\frac{\tau}{\Sigma}\ln 0.1$ and $\tau_{adv} = \frac{r_f}{|\overline{u}|}$, as well as defining the length scale characteristic of the distance a fluid parcel would travel before becoming more than 90% saturated, $l \equiv |\overline{u}|\tau_r = -|\overline{u}|\frac{\tau}{\Sigma}\ln 0.1$.

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, reducing the total tracer released.

The maximum total tracer occurs when the release and advection timescales intersect. This density also corresponds to the point when the saturation length scale becomes smaller than the forest extent, suggesting that the fluid becomes saturated before it travels through the kelp forest.



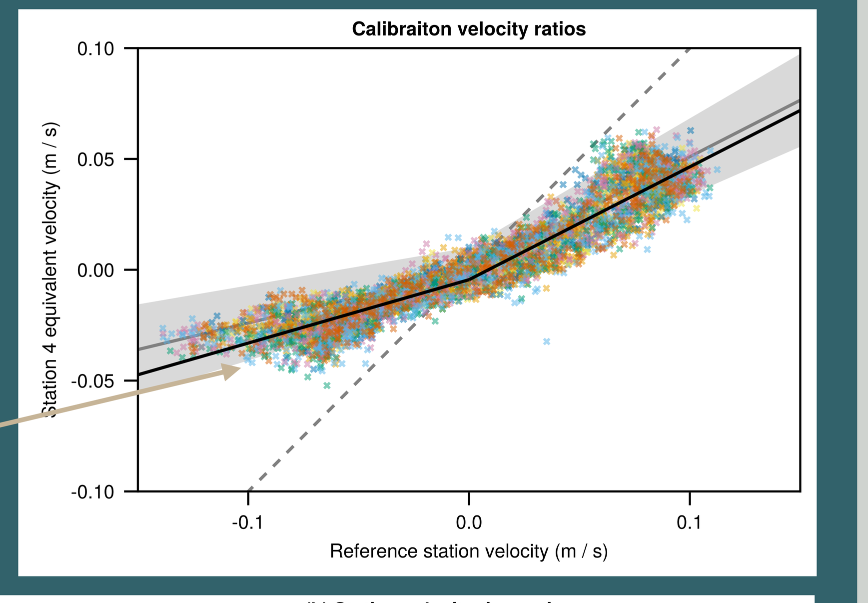

The drag induced by the kelp also reduces the distance that the tracer is transported away from the forest as the areas of high saturation only travel ~500m while a small amount of tracer entrained in the exterior flow travels to the background tidal excursion distance (~1500m). Also, at this density (peak release) it can be seen that the tracer saturates around halfway through the forest in each tidal cycle.

The kelp density at which tracer export/uptake 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 kelp forests is important to their potential 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 of use when considering kelp farms.

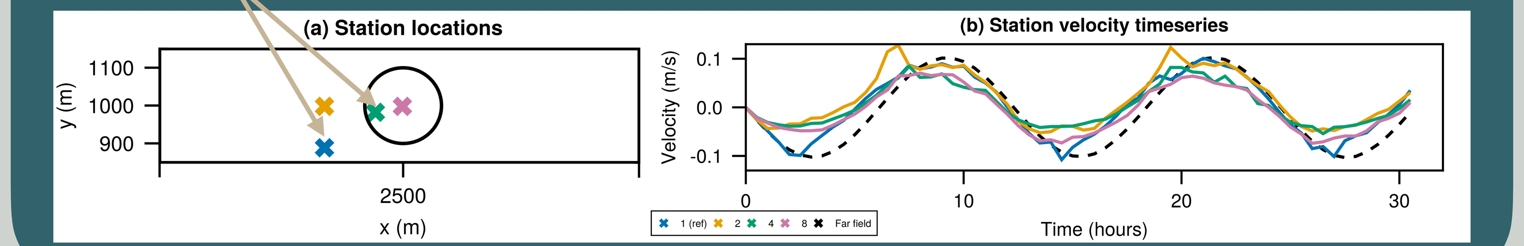
To better understand the carbon drawdown potential of kelp forests, our next step is to couple the growth of kelp with the surrounding biogeochemistry. This will allow us to understand how these flow processes influence nutrient concentrations and primary production.

## Constraining uncertain physical parameters

A key unconstrained parameter in our model of the kelp motion was the drag coefficient of the blades. In order to constrain this, we conducted an ensemble Kalman inversion (Dunbar et al., 2022) where we generated an ensemble of synthetic observations of velocity inside and outside of the forest to compare to observations in Mohawk reef (California) from Gaylord et al., 2007.




Ratios between synthetic observations at these locations



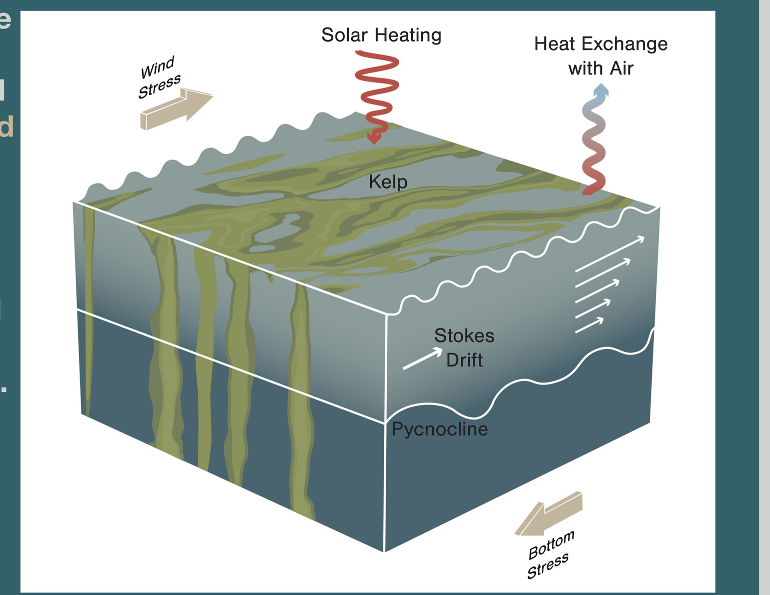

## More realistic mixing processes

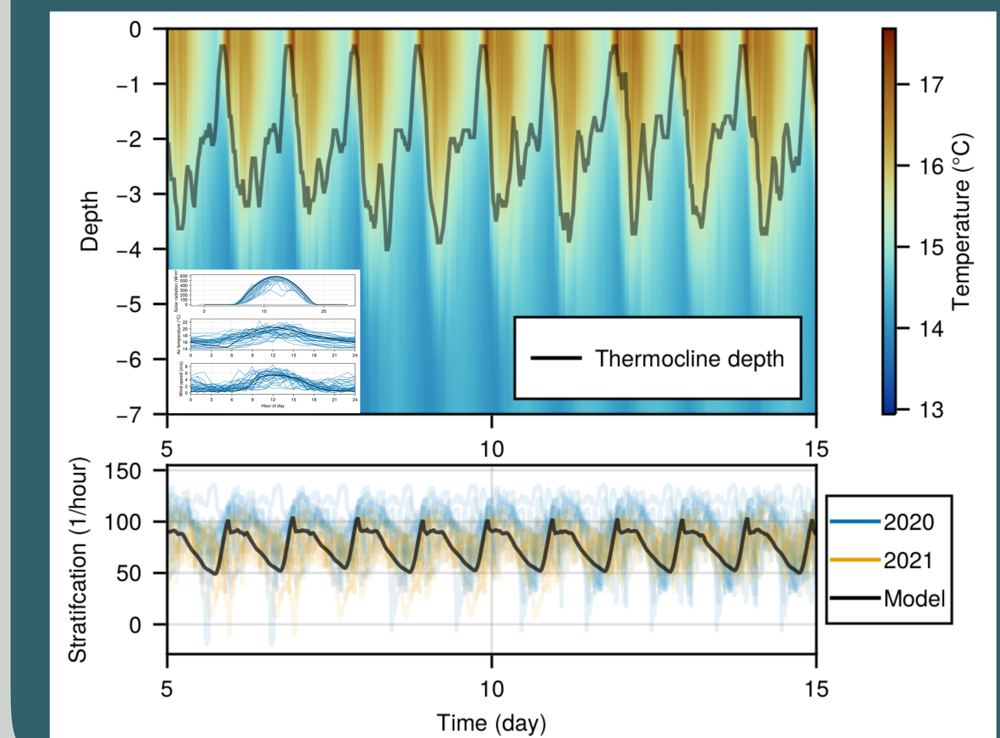
Our next step to quantify the carbon sequestration potential of kelp forests is to improve the realism of the mixing inside the forest and to add biogeochemical interactions.

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

Kelp forests *may* increase this stratification by slowing the surface water and reducing the mixed layer depth, and by attenuating more of the solar radiation and trapping more heat near the surface.

Stratification may to have an important affect 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 this effect in my future work coupling kelp with the biogeochemistry, we have configures 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 Mohawk reef in California (Santa Barbara Coastal LTER, 2024) which showed good agreement with mean temperature and diurnal stratification cycles (as shown to the left).

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