Kelp Forest model development in the Coupled Ocean-Atmosphere-Wave-Sediment-Transport model (COAWST V3.4)

Matheus Fagundes; Fiorenza Micheli; Stephen G. Monismith; Arnoldo Valle-Levinson; C. Brock Woodson

1 Department of Engineering, University of Georgia, Athens, GA, USA
2 Ocean Department, Hopkins Marine Station, Stanford University, Pacific Grove, CA, USA
3 Stanford Center for Ocean Solutions, Pacific Grove, CA, USA
4 Monterey Bay Aquarium Research Institute, Moss Landing, CA, USA
5 Civil and Coastal Engineering Department, University of Florida, Gainesville, FL, USA

Corresponding author:
Matheus Fagundes, mf99274@uga.edu

ABSTRACT

Kelp forests are essential ecosystems in coastal regions around the world. They have large effects on flow structure, biogeochemical processes, and ecological dynamics. However, studies have yet to simulate these ecosystems in either regional ocean or global climate models. Here we describe and validate a model that simulates kelp forests in the water column for the ocean component of the Coupled Ocean-Atmosphere-Wave-Sediment-Transport model (COAWST V3.4) using a simple yet efficient linear regression approach to simulate kelp canopies. An in-situ dataset of 2-1/2 years, with and without kelp forest coverage around Isla Natividad (Baja CA, MX), allowed model validation for the main tidal constituents. We tested different vegetation drag coefficients and compared simulations with our canopy model against the standard vegetation module in COAWST. Results show that while both models simulate the velocities observed in the in situ dataset reasonably well, our model better represents turbulence...
kinetic energy through the water column as observed in laboratory experiments. This new kelp
model can be helpful in ecology, physics, and biogeochemistry studies.
Kelp forest ecosystems occupy almost $7 \times 10^6$ km$^2$ globally, when accounting for polar regions of the world’s coastlines (Duarte, 2017; Macreadie et al., 2019; Wernberg et al., 2019), representing the largest coastal vegetated ecosystem in the world. Kelp lives in nutrient-rich habitats such as Eastern Boundary currents (EBUs) and provides significant global carbon sequestration either through respiration or carbon burial (Mcleod et al., 2011; Britton et al., 2016; Low et al., 2021, Eger et al., 2023). While kelp forests are important for global carbon sequestration (Macreadie et al., 2019), kelp forests also have local biological (Gaylord et al., 2002; Steneck et al., 2003) and physical impacts (Gaylord et al., 2007) that have been observed in situ (Walter et al., 2012; Leary et al., 2017; Monismith et al., 2022) and in laboratory experiments (Rosman et al., 2010; Rosman et al., 2013). Considering that kelp forests have ecological, biogeochemical, and physical importance, comparative efforts to simulate these ecosystems in ocean models have been limited. Up to now, only one study has attempted to include the physical response of flows due to kelp forests into an ocean model, and it did not specifically account for variation in kelp canopy (Wu et al., 2017).

Kelp forests are found worldwide (Delille et al., 2009; Schiel and Foster, 2011; Krause-Jensen et al., 2016) and composed of 5 recognized types based on dominant genus: Ecklonia, Nereocystis, Lessonia, Laminaria, and Macrocystis (Rafaelli & Hawkins, 1999). Along the west coast of North America, the predominant species is the giant kelp *Macrocystis* spp. (Steneck et al., 2002). *Macrocystis* spp. are found generally between 2 to 30 meters in the water column (Jackson & Winant, 1983) forming dense underwater forests (Steneck et al., 2002) (Fig. 3.1). Kelp forests are recognized for their importance as shelter for macroinvertebrates, fish, and mammals (Dayton, 1985; Rafaelli & Hawkins, 1999). Furthermore, kelp forests greatly impact carbon storage or net
primary productivity (NPP). A kelp forest can uptake up to 4-fold more carbon per year than a boreal forest (Reed & Brzezinski, 2009) or phytoplankton production in upwelling zones (Behrenfeld & Falkowski, 1997). Kelp forests account for almost 5% of the total global blue carbon and 1/3 of the total carbon sequestered in coastal regions (Filbee-Dexter & Wernberg, 2020; Eger et al., 2023). Similarly, kelp forests alter currents and mixing in subtidal nearshore environments of temperate and high latitudes (Dayton, 1985; Rafaelli & Hawkins, 1999) and can dampen headland upwelling processes (Valle-Levinson et al., 2022).

Figure 1 - Underwater formation of *M. Pyrifera* (a) and surface canopies at the surface (b). Source: Photos taken by Charles Boch and modified by Matheus Fagundes.

Previous studies to understand the effect of kelp forests on currents focused on particular regions along the California Current System (CCS; e.g: Jackson, 1984; Monismith et al., 2022), scaled laboratory experiments (e.g: Rosman et al., 2010), or high-resolution simulation of kelp beds (e.g: Wu et al., 2017). While these studies helped better understand flow-vegetation interactions in these complex ecosystems, they did not capture the entire range of effects that kelp forests have on the
biology, biogeochemistry, and currents. In this present study, a high-resolution semi-idealized hydrodynamic model coupled with a vegetation module is used to create and validate a kelp module to allow for studies on the effects of kelp forests, not only on the hydrodynamics, but also the resultant effects on biogeochemical cycling and larval transport.

2 THEORY

The alongshore \( (v) \) momentum term of the Reynolds-Averaged Navier-Stokes (RANS) equations under the Boussinesq approximation (Beudin et al., 2017) can be written as:

\[
\frac{\partial v}{\partial t} + \frac{\partial vu}{\partial x} + \frac{\partial vw}{\partial y} + \frac{\partial vw}{\partial z} + fu = -\frac{1}{\rho_0} \frac{\partial P}{\partial y} - \frac{\partial}{\partial z}(\bar{u}\bar{w}' - \bar{v}) + D_v + F_v \tag{1}
\]

where \( \frac{dv}{dt} \) is the unsteady term, \( \frac{d(uw)}{dx} + \frac{d(vw)}{dy} + \frac{d(vw)}{dz} \) are the advection terms, \( f \) is the Coriolis parameter, \( -\frac{1}{\rho_0} \frac{dP}{dy} \) is the pressure gradient in the \( y \)-direction, \( \rho_0 \) is the reference density of seawater, \( \bar{u}\bar{w}' \) is the vertical flux of horizontal momentum by turbulent velocity fluctuations, \( \nu \) is the molecular viscosity, \( D_v \) is the horizontal diffusive term, and the last term \( (F_v) \) is a forcing term that includes the effects of vegetation on the flow. The spatially averaged vegetation drag force for the alongshore velocity neglecting cross shore velocity can be written as:

\[
F_{d,veg,v} = \frac{1}{2} C_d \rho_d P_d \bar{v} \tag{2}
\]

Where \( P_d \) is plant density (plants \( m^{-2} \)), \( pd \) is the width of kelp (m) or diameter in the case of kelp, and \( C_d \) is the drag coefficient for an individual plant. The code for the vegetation module in COAWST was originally written to represent seagrasses, which do not extend to the water surface, and therefore, no canopy was included. In these situations, the spacing between plants is constant to the surface (Fig. 2a). However, kelp forests can have extensive canopies that cover the last meter or so to the surface (Fig. 1; Traiger et al., 2022). To date, the effects of surface canopies on currents...
have only been studied in laboratory settings (Rosman et al., 2013). However, kelp canopies can be represented using a linear regression to allow individual plants to get closer together and the kelp forest to become denser as the surface is approached (Fig. 2b). The second term important for the development of our approach is plant thickness ($pt$). The $pt$ is inversely proportional to the $pd$ in the second moment of area ($I$) equation ($pd^2 / 12$) for the rectangle shape that was used by Beudin et al., (2017). While not ideal, we decided to keep the same equation for $I$.

![Figure 2 - Schematic of the two simulations in COAWST.](https://doi.org/10.5194/egusphere-2023-2330)

3 METHODS

3.1 Kelp canopy module

To account for kelp canopy, we developed a simple linear regression model that increases $pt$ and $pd$ near the surface as:

$$
\begin{align*}
pt &= pd = 0.3 & \text{if } \text{depth} \leq 12m \\
pt &= pd = 2.3 \times \text{depth} - 27.3 & \text{if } \text{depth} > 12m
\end{align*}
$$

This modification in the vegetation model code captures the increase in kelp spacing ($S$) at the surface between individual kelp plants. For our scenario, this gives $pt$ and $pd$ equal to 2.3 at the surface, forming a virtually solid boundary. The coefficients in (3) can be varied to adjust for the
density, extent of the canopy, or water depth accordingly. The values reported are specific setup
to our model test case.

Two simulations are presented in this paper: The first simulation is running the COAWST
vegetation module with no changes (standard hereafter) (Fig. 2a), and the second is modifying the
code to account for kelp canopy (canopy) (Fig. 2b). The standard simulation assumes that \( pd \) and
\( pt \) are constant from the seafloor to the surface. The canopy simulation assumes a linear increase
in \( pd \) and \( pt \) in the last meter of the water column (Fig. 3.2; Utter & Denny, 1996). The canopy
module (eqn. 3) simulates the effects of kelp stipes and fronds getting close to each other (S) as
they spread out on the surface as they are longer than the water depth (Fig. 2b). The stipes and
fronds are then represented by changing \( pd \) and \( pt \) and, consequently, the effects of kelp forests on
the currents. These differences in \( pd \) and \( pt \) directly affect the bulk drag in the water column,
consequently changing the depth-averaged velocity and turbulence.

3.2 Area of Study

This study focuses on kelp forests surrounding Isla Natividad in the Vizcaino Bay region of Baja
California, MX. Baja California is affected by large scale forcings such as El Niño (Trenberth,
1997) and marine heat waves (Cavanaugh et al., 2010; McPherson et al., 2021). Mesoscale
forcings such as California Current characterized by low salinity, low temperature, high dissolved
oxygen (DO) and California Undercurrent (CU) that is saltier, higher temperature and low in
dissolved oxygen, also play a major role in the physical environment of this region (Mancilla-
Peraza et al., 1993). Seasonally, there is a marked stratification in the upper 20 meters of the water
column, and conditions are influenced by wind-driven upwelling that brings water temperatures
as low as 8°C, salinity (~33.8), and low DO (<5.5 ml/l) to the surface during spring/summer.
During winter, waters can reach 16°C, salinity (~34), and DO around 5ml/l (Mancilla-Peraza et
Isla Natividad, winds, waves (surface and internal), tides, and kelp forests drive the dynamics (Woodson et al., 2018; Valle-Levinson et al., 2022) at relatively small spatial and temporal scales (e.g. < 1 km, < 24 h). For instance, the shape of kelp forests can modify tides and dampen headland upwelling (Valle-Levinson et al., 2022).

Isla Natividad is a 7 km long island south of Isla Cedros in Central Baja California, Mexico (Schlenger et al., 2021) located between 115°15′W-115°6′W and 27°48′N-27°55′12″N (Fig. 3). The island is bounded by Kellet Channel on the north and Dewey Channel on the south (Mancilla-Peraza et al., 1993), and is surrounded year-round by kelp forests (*Macrocystis Pyrifera*) which provide shelter for organisms including abalones (*Haliotis* spp.; Micheli et al., 2012). Isla Natividad has two distinct local ocean regions on each side of the island (Woodson, 2018). On the southeastern side, Morro Prieto can reach mean temperature of 16°C and mean DO of 6 mg/l at 12 m while on the northwestern side, Punta Prieta has waters that are typically 3°C warmer and mean DO of 7.5 mg/l (Boch et al., 2018) at the same depth. Because of the economic and ecological importance of abalone, the fishing cooperative, Buzos Y Pescadores, in Isla Natividad established 2 marine reserves that have been monitored since 2006 (Boch et al., 2018; Micheli et al., 2012). One of the marine reserves is located near Punta Prieta and has oceanographic sensors (CTDs, MiniDOTs, thermistors, and adps) at 7 m and 12 m depth (Boch et al., 2018).
Figure 3 - Map of Isla Natividad indicating regional location and areas covered with kelp. Black circle indicates location of adp data used in this study. Punta Prieta, on the northeastern side of Isla Natividad.

3.3 Forcing

The mooring at Punta Prieta (Fig. 3) was chosen for evaluating the vegetation models in COAWST for four reasons, a) long-term data are available (Woodson, 2018), b) a heat wave in 2015-16 complete removal of kelp (Fig. 4) allowing understanding the environment without kelp (Monismith et al 2022), c) it is within a marine reserve thereby providing a relatively undisturbed habitat (Micheli et al., 2012), and d) flows are generally tidal and alongshore in contrast to flows around Morro Prieto (Boch et al., 2018).

Figure 4 - Averaged kelp biomass around Isla Natividad, MX. Source: Monismith et al., 2022.
In situ current data were collected every 0.5 meter starting from 0.65 meters above the bottom to the surface (~14 m) from 2013-2016 using a 1MHz Nortek Aquadopp (adp; Fig. 3.5). The depth of the adp data used for this simulation was from 2.65-12.65 meters from the bottom to remove errors in the first couple of meters due to sidelobe interference (Lentz et al., 2022). Depth-averaged velocities were calculated after removing errors from bottom and surface (Supplementary Fig. 1). Both E-W and N-S velocities increased in the 2015 period (Supplementary Fig. 1) when there was no kelp biomass observed (Fig. 4) while in 2014, the highest kelp biomass observed for the 2.5-year record, velocities were ~2-fold slower (Monismith et al., 2022).

Currents were rotated into along- and cross-shore axes using Principal Component Analysis (PCA; Campbell & Atchley 1981; Emery & Thompson 2004). The rotated velocities were separated by season (Fig. 5). Based on Fig. 4 and Fig. 5, the cross-shore and alongshore Winter 2015 (henceforth adp15) and Spring 2014 (adp14) velocity records are used for no-kelp and kelp analyses. The adp15 data set was used to validate COAWST without the vegetation module before implementing it for the adp14 dataset (e.g., to estimate drag coefficients in the absence of kelp).
Both, cross-shore and alongshore velocities from adp15 and adp14 were harmonically analyzed using a python version of T-TIDE (Pawlociwicz et al., 2002; Figs. 3.7, 3.8) before being used to force COAWST and to validate the vegetation module, respectively.

3.4 Numerical Model Description

The model used in this study was the Coupled Ocean-Atmosphere-Wave-Sediment-Transport model (COAWST V3.4; Warner et al., 2008). The ocean component of COAWST is the Regional Ocean Modeling System (ROMS) (Haidvogel et al., 2008). ROMS is a 3-D, free-surface model that solves the primitive equations using hydrostatic and Boussinesq approximations with topography-following sigma layers (Shchepetkin and McWilliams, 2005; Haidvogel et al., 2008).

For the momentum equations, splines vertical advection and logarithmic bottom friction were selected to keep stability and better represent the environment, respectively. The model used the Mellor-Yamada level 2.5 turbulence closure scheme (MY-2.5). All boundaries (N,S,E,W) allowed along- and cross-shore flows. A periodic boundary condition was applied for free-surface, a Flather
condition for 2D u- and v-momentum, and a Radiation-Nudging condition for 3D u- and v-momentum.

The barotropic time-step was set at 10 s. Bottom roughness ($z_{ob}$) was 0.03 m and surface roughness ($z_{os}$) was 0.4 m with a no-slip condition along the bottom to provide a best fit for the no-kelp simulations to observed velocity profiles. The model had 40 sigma-layers splitting the 13 meters of water column with surface stretching ($\theta_s$) = 1, bottom stretching ($\theta_b$) = 2, and thermocline depth ($T_{cline}$) = 0. The domain was approximately 14 km long by 3 km wide (Fig. 6) with a grid size of 25 meters x 25 meters. The model was initialized at rest with a well-mixed domain where temperature and salinity are 19°C and 34, respectively (Low et al., 2021). The model was forced every 10 min with depth-averaged tidal fits from adp15 (Monismith et al., 2022). Hydrodynamic conditions of the domain were simulated for three months. However, the first 30 days provided dynamic adjustment of the currents. The vegetation module was activated, accounting for the drag due to the kelp forests in the simulations using the standard and canopy modules (Beudin et al., 2017), and the flexibility flag (VEG_FLEX) was turned off for both scenarios. Results are presented for the second month of each simulation.
3.5 Vegetation module parameters

The vegetation module is a standard component in COAWST (Beudin et al., 2017). This module receives \( u \) and \( v \) from ROMS and returns both the drag force \( F_d \) and vertical turbulent mixing (Beudin et al., 2017). The vegetation module requires 4 parameters: plant height (m), plant density (plants/m\(^2\)), plant diameter (m), and plant thickness (m) (Table 1). The other settings are number of vegetation types, Young’s modulus \( (10^7) \), vegetation mass density \( (1000.0) \), additional horizontal viscosity coefficient \( (0.0) \), and drag coefficient for each individual plant \( (0.05-0.6) \).
Table 1 - Vegetation module initial parameters.

<table>
<thead>
<tr>
<th></th>
<th>Plant height (m)</th>
<th>Plant Density (plants/m²)</th>
<th>Plant diameter (m)</th>
<th>Plant thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard</strong></td>
<td>13</td>
<td>0.9*</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Canopy</strong></td>
<td></td>
<td>See equation 3</td>
<td>See equation 3</td>
<td></td>
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*GAYLORD et al., 2007.

3.6 Time-averaged velocity

The output velocity data were used to calculate the time-averaged velocity ($\bar{u}$). To compute $\bar{u}$, alongshore and cross-shore velocities were used to calculate velocity component in the domain, and then, integrated in time:

$$|V| = \sqrt{\bar{u}^2 + \bar{v}^2}$$  \hspace{1cm} (4)

$$\bar{u} = \frac{1}{T} \int_0^T u dt$$ \hspace{1cm} (5)

3.7 Model Skill

A quantitative model skill was presented by Willmott (1981) (eq. 6):

$$WS = 1 - \frac{\sum_{i=1}^{N}(m_i - o_i)^2}{\sum_{i=1}^{N}(|m_i - \bar{o}| + |o_i - \bar{o}|)^2}$$  \hspace{1cm} (6)

where $m$ is the variable modeled being compared against the observed variable ($o$), the index $i$ represents each depth for our case. It takes the sum of difference for each point squared and divides by sum of the absolute variability of the model and observed variable in relation to the mean of the observed variable squared. A Willmott Skill equal to 0 ($WS = 0$), means complete disagreement, and, $WS = 1$ means exact match between simulations and observations. This
verification has been applied in other model simulations (Warner et al., 2005b; Liu et al., 2009).

Before calculating WS, the model was interpolated to the depths of the adp dataset. Time-averaged velocities for the domain with the vegetation module off and the no kelp station (Fig. 6) were the same, and therefore, we used no kelp station for the validation. The kelp station (Fig. 6) was used and compared against adp14 where kelp biomass was the highest (Fig. 4).

3.8 Bulk Drag calculations

Field estimates of kelp forest drag coefficients represent the bulk drag effect of multiple kelp plants. For example, in a 1-D linear momentum balance,

\[ \frac{\partial u}{\partial t} + C_D \frac{U |U|}{h} = -\frac{\partial \eta}{\partial x} \]  (7)

After some manipulation:

\[ C_D^B = -\frac{h(\frac{\partial u}{\partial t} + \frac{\partial \eta}{\partial x})}{U |U|} \]  (8)

Applying the centered difference method for \( \frac{\partial u}{\partial t} \) and \( \frac{\partial \eta}{\partial x} \), yields:

\[ C_D^B = \frac{-\frac{h}{2\Delta t}(u_{j+1}^t - u_{j-1}^t) - \frac{h}{2\Delta x}(\eta_{j+1}^t - \eta_{j-1}^t)}{\bar{u} \bar{|u|}} \]  (9)

The bulk drag coefficient, \( C_D^B \) (eq. 9), is the net coefficient for the entire region of influence, which is not necessarily the drag force on an individual kelp plant, \( C_D^i \). In the COAWST model, the drag coefficient input is for an individual plant, \( C_D^i \). Therefore, to evaluate model input, we changed \( C_D^i \) and used the model to estimate \( C_D^B \). Computing \( C_D^B \) does two things, 1) shows that the drag on an individual kelp plant is not the same as the bulk drag coefficient, and 2) allow us to parameterize the kelp model. In total, there were 12 simulations varying \( C_D^i \) from 0.05 to 0.6. A threshold for
velocities less than 0.05 m/s was imposed in order to get reasonable estimates of $C_D^B$ during calculations.

3.9 Turbulent Kinetic Energy (TKE)

Turbulent kinetic energy (TKE) is generally described by the intensity of the turbulent motion. The nearshore environment is believed to be an important region that dissipates TKE (Carter et al., 2005). Like bottom boundary conditions in a nearshore environment, vegetation also increases TKE (Rosman et al., 2010; Kalra et al., 2017). For example, a laboratory study demonstrated that while kelp increased TKE in the water column when compared to no kelp, the largest turbulence occurred when the kelp had a dense surface canopy (Rosman et al., 2010). TKE was calculated by ROMS and normalized by the total velocity. The TKE calculation was computed only for a cross-section area where kelp forest region was present.

4 RESULTS

Before starting the analysis of the kelp forest model, the model needs to adjust to a stable condition using a spin-up period to remove transient dynamics due to initial startup. For this simulation, we use sea surface elevation as the spin-up variable (Fig. 7). Because the no kelp simulation only has alongshore and cross-shore velocities as forcings, the period needed to stabilize was a little less than a month (Fig. 7-a), when kelp was added the spin-up period increased to closer to a month (Fig. 7-b). The amplitude of the sea surface height (SSH) stayed at 0.02 m and 0.001 m for no kelp and vegetation module on, respectively. There was no difference in SSH amplitude and time for the system to stabilize for both simulations standard and canopy. When the vegetation module is added, SSH amplitude decreases, representing up to 40% reduction in amplitude.
For the remaining analysis, the model was interpolated to the points of the adp dataset. The no kelp model showed good agreement with adp15 (Fig. 8). Validation of the time-averaged currents was only possible up to 10.15 m from the bottom due to invalid values measured by the adp15 instrument. The model overestimated the velocity over the first 4 m, underestimated it up to 9 m, and overestimated for the remainder of the data available. The absolute maximum difference was 0.008 m/s between model velocity and those observed at 6 m. The skill for the time-averaged velocity in the no kelp model run compared to adp15 was 98.8%. A high WS indicates a good agreement with the variability of the observed dataset.
Figure 8 - Time-averaged profile comparison between adp data and model run without vegetation model. The gray region shows the 95% CI and mostly represents variation in velocity due to tides. Y-axis is above the bottom.

For both configurations with kelp, modeled time-averaged velocities decreased with increased $C_{d,\text{veg}}$ as expected (Fig. 9). The standard configuration showed a slightly higher time-averaged velocity than canopy throughout all case scenarios. This difference was more pronounced in the last 4 m to the surface. $C_{d,\text{veg}}$ was a way to change the fit of the velocities in the kelp simulation. Changes of 0.05 for $C_{d,\text{veg}}$ were considered a safe and fast approach to fit the best scenario while not having to simulate too many scenarios. The best fit scenarios were $C_{d,\text{veg}} = 0.35$ (Fig. 9-g) and $C_{d,\text{veg}} = 0.4$ (Fig. 9-h) for the canopy and standard models, respectively. At $C_{d,\text{veg}} = 0.35$, the standard model provided a better fit between 7-9 m than the canopy but overestimated everywhere else compared to the new model. This was different for the $C_{d,\text{veg}} = 0.4$ scenario. While the canopy model showed a slightly better fit in the first 5 meters from the bottom, the overall best fit was modeled using the standard approach. The higher value for the standard module also represents the effect of not applying the effects of the kelp canopy over the entire water column.
Figure 9 - Time-averaged profiles comparison between adp data and for standard and canopy. The gray region shows the 95% CI for the effects of the tides. Y-axis is above the bottom.

Table 2 shows WS calculated for the best $C_{d,\text{veg}}$ of each configuration. The water column was divided into upper and lower regions for this assessment to understand the impact of the code modification but also assess over the entire water column to check the overall fit. The division at 5 m was done because the in-situ data only extends to 10 m. Over the entire water column WS was similar. Between the two regions, both simulations had greatest skill in the first 5 m which is observable in Fig. 9g-h. The standard model was slightly better near the bottom. The largest difference was observed in the upper 5 m, where canopy model had the most skill (WS = 0.767). This difference is due to a slightly better fit between 5-6 m and between 8-9 m, where the velocity still feels the canopy acting on the surface velocities.
Table 2 - WS for the two best vegetation drag for both standard and canopy models.

<table>
<thead>
<tr>
<th></th>
<th>top*</th>
<th>down**</th>
<th>total***</th>
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<tbody>
<tr>
<td>Standard</td>
<td>0.721</td>
<td>0.972</td>
<td>0.983</td>
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<tr>
<td>Canopy</td>
<td>0.767</td>
<td>0.967</td>
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* Calculated using values where depth is greater than 5. ** Calculated using values where depth is less or equal 5. *** Calculated for all the water column.

WS scores separated by 0.01 m/s bins are shown in Fig. 10. Both canopy and standard simulate similar along- and cross-shore velocities when compared against in situ datasets. WS values range from 0.25-0.93 for alongshore velocities (Fig. 10a) and 0.19-0.47 for cross-shore velocities (Fig. 10b). As expected, alongshore WS showed better comparison than cross-shore. One possible reason is that cross-shore velocities at the Punta Prieta site are also affected by internal waves and tides, while surface tides dominate alongshore velocities. As a result, alongshore velocities compare better with observations at higher velocities than velocities closer to zero where there can be more uncertainty in both the model and measured velocities. Cross-shore velocities are best simulated between 0.04 and 0.05 m/s.
Figure 10 - WS for alongshore (a) and crosshore (b) for canopy and standard simulations split by 0.01 m/s bins.

Median bulk drag ($C_D^B$) increased as vegetation drag ($C_{d,veg}$) increased for both simulations (Table 3). The variability also increases as $C_{d,veg}$ becomes large. The $C_D^B$ calculated for canopy is slightly larger for all $C_{d,veg}$ used. $C_D^B$ for the best simulations were the same 0.084 and had the same variability ±0.072. These values are within the values for dense kelp forests ($C_D^B = 0.18$) and sparse kelp forests ($C_D^B = 0.07$) in a laboratory study (Rosman et al., 2010). The values were also in agreement with Monismith et al., (2022) for the adp15 data used for this simulation ($C_D^B ~ 0.04$).
Table 3 - Median bulk drag coefficient and 95% CI calculated from equation 7 for standard and canopy.

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<th></th>
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<tr>
<td>Cd_{veg}</td>
<td>0.05 ± 0.016</td>
<td>0.08 ± 0.028</td>
<td>0.10 ± 0.037</td>
<td>0.17 ± 0.045</td>
<td>0.30 ± 0.052</td>
<td>0.57 ± 0.059</td>
<td>0.86 ± 0.065</td>
<td>1.00 ± 0.072</td>
<td>0.87 ± 0.078</td>
<td>0.90 ± 0.084</td>
<td>0.92 ± 0.090</td>
<td>0.95 ± 0.093</td>
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<td><strong>Canopy</strong></td>
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<td>Cd_{veg}</td>
<td>0.06 ± 0.018</td>
<td>0.06 ± 0.030</td>
<td>0.06 ± 0.040</td>
<td>0.10 ± 0.048</td>
<td>0.19 ± 0.056</td>
<td>0.32 ± 0.063</td>
<td>0.54 ± 0.070</td>
<td>0.77 ± 0.085</td>
<td>0.91 ± 0.091</td>
<td>0.94 ± 0.094</td>
<td>0.96 ± 0.094</td>
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The estimates of bulk drag ($C_d^B$) improves as Reynolds number (Re) increases (Fig. 11). Depth-averaged velocity was binned from 0.01 m/s to 0.09 m/s with 0.01m/s intervals. $C_d^B$ also has a Re dependency as expected. The medians for the two models are not statistically different. The $C_d^B$ estimations are higher and less precise for smaller Re values (e.g: $10^{5.5}$ to $10^{5.8}$), and as the depth-averaged velocity increases bulk drag estimates are closer to what has been observed in the literature (Rosman *et al.*, 2010; Monismith *et al.*, 2022).

While the time-averaged profiles and bulk drag estimation are similar between both models, the difference in the mean velocity and its variability observed from the last two meters to the surface is quite different (Fig. 12). Overall, the largest differences are on the edges of the kelp forest region.

The *standard* model had higher velocity and variability than *canopy* model in the last 2 m near the surface (Fig. 12a-b), resulting from the addition of kelp canopy in the latter model. *Canopy* had slightly higher velocity just below the kelp canopy especially on the edges (Fig. 12a). This decrease in time-averaged velocity at the surface and an increase at the bottom has been previously observed in laboratory for dense kelp with canopy (Rosman *et al.*, 2010; Rosman *et al.*, 2013).
Figure 11 - Bulk drag versus Reynolds number for depth-averaged velocities at each 0.01m/s interval for both canopy and standard.

Figure 12 - Mean (a) and standard deviation (b) of velocities difference between standard and canopy. Alongshore slice at 1500m.
Absolute time-averaged cross-shore (Fig. 13a) and alongshore (Fig. 13b) velocities for the canopy simulation illustrate the ducting of flow around patches of kelp (Valle-Levinson et al. 2022). Velocities in the kelp were disregarded, and where kelps are present in the model are shown in brown. There is an increase in mean time-averaged cross-shore speed along the outer and inner edges of the kelp forest (Fig. 13a). The highest absolute cross-shore velocities are located between kelp forests at 6.8 and 7.4 km. Flow acceleration along the edges of kelp forests has been previously observed (Jackson & Winant, 1983; Jackson, 1998; Graham, 2003). In addition, the flow channeling between kelp gaps has been described recently for the same region (Valle-Levinson et al., 2022). The absolute time-averaged alongshore speeds decrease to almost zero between 1 and 1.5 km (Fig. 13b). The giant patch in front of this section is the cause of these velocities being almost null. The alongshore section shows flow channeling between 1.5 and 2 km. Flow channeling is stronger closer to the 2 km region and for depths between 8.5 m and the surface. Velocities are higher on the outer edge (approximately at 2.2 km) where there is no large patch that inhibits flows in that area. As a result, our model could also be applied to understand the effects on nutrient uptake (Gaylor et al., 2007), larvae dispersal (Graham, 2003), and connectivity among beds (Gaylord et al., 2006). In addition, Valle-Levinson et al., (2022) hypothesized that these regions could provide localized sites of fertilization and safe spaces for various species.
Profiles of normalized TKE (hereafter TKE) for standard, canopy, and canopy with 50% coverage (instead of 100%) at the surface (canopy50) further illustrate the effects of kelp canopy on flows (Fig. 14). TKE was relatively the same from 0.5 m up to 7 m above the bottom for both the standard and canopy models. The standard profile is close to a linear function as expected for free surface flows. Similar mean TKE profiles were observed for no kelp and no canopy scenarios in a laboratory experiment (Rosman et al., 2010). The canopy simulation showed a TKE peak 2-fold higher than Rosman et al. (2010) while canopy50 showed values similar to this laboratory study for a dense canopy scenario. We believe this is because of the spacing at the surface in the canopy scenario acting as almost a solid boundary at the surface generating more friction, and therefore, more TKE. While the profiles in the Rosman et al. (2010) do not show the bump observed in the simulations, we observed that the peaks, for both sparse and dense with kelp fronds, are always deeper than the actual kelp fronds located at the surface which is also observed in both simulations canopy and canopy50. TKE then decreases within the canopy.
5 DISCUSSIONS

The Coupled Ocean-Atmosphere-Wave-Sediment transport (COAWST) modeling system has been successfully applied to characterize wave-flow-seagrass interactions (Beudin et al., 2017). The new module described in this paper, expands COAWST capability to simulate flow-vegetation interactions for canopied vegetation, specifically kelp forests. This module not only simulates the time-averaged tidal-driven currents in the presence of kelp forests but also the wake (turbulent kinetic energy) generated by kelp fronds as observed in laboratory experiments (Rosman et al., 2010).

The influence of kelp forests on currents have been modeled previously (Wu et al., 2017; Frieder et al., 2022). However, these models did not explicitly account for the presence of a canopy or were run offline and thus did not provide feedback to the regional model. In this study, we implemented changes in flow and turbulence caused by kelp forests in a regional ocean model that
provide feedback on the flows themselves. This was possible because of the vegetation module
developed by Beudin et al., (2016) and our modified approach to simulate kelp canopy. In a
previous study, the effects on currents by the drag generated due to kelp forests was only
implemented at the bottom of the domain (Wu et al., 2017). Like this study, they also observed
damping in the tidal velocity for regions where kelp beds were present. The most recent study
documenting kelp forest simulation (Frieder et al., 2022) not only added the changes in the flows
in the water column but also simulated growth and death of kelp forests, making their model more
robust than the one present here for simulating kelp effects over longer time frames. However, the
shortcoming of their model was that they used an offline Large Eddy Simulation (LES) forced by
model outputs, and therefore, no direct feedback in the regional ocean model. While we understand
our kelp forest simulation uses a static kelp forest domain and does not show a more realistic kelp
forest seasonal cycle, it does represent well the domain when kelp density is zero and when kelp
density is high (0.9 plants/m$^2$). This module can be expanded to be used to understand the two way
interaction between kelp forests, currents, and biogeochemistry, for example, and could be
modified to vary parameters through time to account for growth and decay of kelp forests over
seasonal and interannual cycles.

The module presented here shows good agreement for the time-averaged velocity at Punta Prieta
for the 2015 period when kelp was absent (Monismith et al., 2022). The differences observed
mainly in the middle of the water column between our model and the in situ dataset could have
been because the simulation was only forced with the two main tidal constituents for the domain
and did not include wind and wave effects on currents (Monismith et al., 2022). However, while
the largest difference between model and in situ dataset occurs in the middle of the water column,
we believe this difference could be due to two possible issues: a) model settings, for example, the
sigma layers being coarser in the middle of the water column, or b) not having a solid coast on the south boundary representing the island which could change the cross-shore velocities in the water column (Russell & Vennell, 2017). The upper 2 m of the water column cannot be compared due to adp instrument capabilities pointed out by Monismith et al., (2022). This upper 2 m is strongly influenced by winds and waves that increase the velocity (see Fig. 7 in Monismith et al., 2022) and for our case we did not consider these two other processes.

When kelp is present, time-averaged velocity profiles show a rapid decrease in the last meter to the surface. Neither the standard nor canopy modules captured the change in the last 2 m of the water column observed in the in situ datasets. When kelp is present at the Punta Prieta site, the velocities are wave-induced (Monismith et al., 2022). This forcing is not imposed in the domain. Consequently, both models simulate similar patterns up to 10 meters by changing the vegetation drag by only 0.05. However, even if measurements for the last two meters are unreliable, we observe that the in situ data tends to slow down in the canopy region. The canopy region is formed due to the spread out of kelp fronds in the upper 2 m (Jackson, 1984), resulting in a dense region with larger drag than the rest of the kelp environment (Rosman et al., 2010), almost like a semi-wall. Although, our canopy approach does not account for changes in kelp orientation with currents, it shows better results in the canopy region than the standard module (Fig. 12h).

The nearshore environment is believed to be a region that dissipates TKE (Carter et al., 2005). Like bottom boundary conditions in a nearshore environment, vegetation increases TKE (Rosman et al., 2010; Kalra et al., 2017). For example, kelp forests significantly affect the various physical, chemistry, and biological processes due to the turbulence near the canopy region (Rosman et al., 2010). To our knowledge, this is the first time a hydrodynamic model was able to model TKE in the water column caused by canopies.
The density of *M. pyrifera* plants varies significantly throughout the year (Monismith et al., 2022). Reed et al., (2009) found that the lowest densities were during the end of winter season while the highest were during summer. The same authors found that the spacing between canopies decrease to its minimum during fall and increase during winter. For our simulations, we found that plant density ~ 0.9 plants m$^{-2}$ (Gaylord et al., 2007; Reed et al., 2009) and canopy50 produced the best scenario for summer periods, and therefore, the best fit to TKE estimates. Consequently, a study to develop a time-varying change in canopy spacing is needed to understand the impact of fronds for seasonal and yearly variability in kelp domains. Nonetheless, this new module opens opportunities to study how TKE affects nutrient availability (Rosman et al., 2010), oxygen dynamics (Murie & Bourdeau, 2020), and larval transport (Pakhomov et al., 2022) in kelp forest regions.

6 CONCLUSIONS

The *canopy* method presented in this paper to simulate kelp forests including the canopy is a new and relatively simple way to represent kelp forests in COAWST. The module modifies the plant thickness and plant diameter to decrease spacing in the last meter of the water column to mimic the effects of the kelp canopy. The revised module slightly improved fits to velocity and greatly improved fits to TKE depth profiles over the default vegetation module provided in COAWST. Although both the canopy and standard modules produced comparable time-averaged velocity profiles compared to the *in-situ* data, the presence of the kelp canopy resulted in a marked enhancement of turbulence near the surface. Such an improvement could considerably influence air-sea fluxes, biogeochemical processes, and the distribution of larvae within the kelp forest. This model provides improved opportunities to study the impacts of kelp forests around flows and can
further be used to understand larvae dispersal and biogeochemistry in a kelp environment using hydrodynamic models.

**Code availability**

The modified code for the *canopy* module and the codes to generate the data and figures are available at [https://doi.org/10.5281/zenodo.10160564](https://doi.org/10.5281/zenodo.10160564) (Fagundes and Woodson, 2023). The COAWST V3.4 source code is available from [https://github.com/CSOMIO/COAWST](https://github.com/CSOMIO/COAWST) (last access: Nov, 27th, 2023)

**Author contributions**

C.B.W. designed the study. M.F. conducted model runs. M.F. and C.B.W. analyzed the data. F.M, S.G.M, A.V.L contributed significantly with constructive feedback to the science and internal discussions of the manuscript.

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**Competing interests**

The contact author has declared that none of the authors has any competing interests.

**Acknowledgments**

The gratefully acknowledge support by NSF grants.

**Financial support**

This research has been supported by National Science Foundation (grant nos. OCE-1416837, OCE-1737090, OCE 1736830, DISES 2108566, and RISE-2108566)

**References**


