Currents and turbulence within a kelp forest (Macrocystis pyrifera): Insights from a dynamically scaled laboratory model

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Abstract

The effects of a Macrocystis pyrifera forest on currents and turbulence were investigated in a controlled laboratory setting using a dynamically matched 1/25-scale model. Two kelp configurations with surface canopies and one without a surface canopy were considered. Profiles of mean velocities and turbulence statistics were measured using acoustic Doppler velocimeters. Since flow within the model kelp forest was very heterogeneous, spatially averaged forms of the governing equations were used for the analysis. Stress gradients were small compared with pressure gradient, drag, and acceleration terms of the momentum budget. A good model for kelp drag is therefore required for simulating flow through a kelp forest, while the model for Reynolds and dispersive stresses is less critical. The bulk drag coefficient is highest at the up-current end of a kelp forest and decays with down-current distance as the velocity profile adjusts to the drag profile. Modeling a kelp forest as an array of vertical cylinders underestimates the net drag by a factor of 1.5 to 3 if a substantial surface canopy is present. Turbulence is generated predominantly by small-scale shear in kelp wakes. Vertical mixing of scalars is expected to be significantly smaller than in the surrounding coastal ocean because of the combination of smaller turbulent eddies and reduced currents. The decrease in horizontal transport and vertical mixing within kelp forests may have important implications for nutrient availability to kelp forest organisms and may affect the dispersal or retention of their larvae and spores.

Macrocystis pyrifera (Linnaeus) Agardh (commonly Giant Kelp) forests are important components of temperate coastal ecosystems, providing food and shelter for a diverse array of organisms. Many kelp forest organisms, including M. pyrifera itself, extract nutrients, plankton, or particulates from the water column. The availability of these quantities is determined by mean water motion primarily due to currents and by vertical and lateral mixing due to turbulence and spatial variations in the flow. Most kelp forest organisms release larvae or spores into the water column, and the paths and eventual destinations of these particles are also determined to a large extent by water motion. A good understanding of kelp forest hydrodynamics is therefore required to estimate nutrient availability to different parts of a kelp forest or to predict dispersal distances of reproductive propagules released within a kelp forest.

M. pyrifera forests exert much greater drag on the flow than do kelp-free areas, and, thus, they significantly alter the local flow environment. Field observations indicate that depth-averaged currents within M. pyrifera forests can be reduced by a factor of 1.5 to 5 relative to nearby kelp-free areas (Jackson 1998; Gaylord et al. 2007; Rosman et al. 2007). For a given current direction, the upstream edge of the kelp forest experiences stronger currents, while the downstream edge sees smaller currents. However, as current direction typically switches with tides and winds, the variability in depth-averaged currents is smallest in the center of the forest (Gaylord et al. 2007). While depth-averaged across-shore currents are usually close to zero, vertically sheared (two-layer) across-shore flows driven by wind and internal waves can provide another mechanism for exchange between kelp forests and offshore waters (Jackson 1984; Rosman et al. 2007). The magnitudes of vertically sheared across-shore flows are also damped within kelp forests, although to a lesser degree than are along-shore currents, because kelp forests are typically narrower in the across-shore direction than in the along-shore direction (Jackson 1984; Rosman et al. 2007).

Because variability in depth-averaged and vertically sheared currents decreases with distance into a kelp forest, spore supply to the interior of a M. pyrifera forest is strongly dependent on the local individuals, while spore dispersal distances near the edges of a forest can be much larger (Graham 2003). Similarly, in a time-averaged sense, the kelp near the periphery of a M. pyrifera forest may see a larger nutrient supply than does the kelp in the interior. Within large kelp forests, stipe density tends to be thinner and surface canopy coverage tends to be smaller in low nutrient conditions (Dayton et al. 1992, 1999), and the reproductive output of M. pyrifera is proportional to the availability and uptake of nitrogen (Reed et al. 1996). However, nutrient budgets indicate that nitrate is not depleted sufficiently by upstream kelp to affect uptake rates in the kelp forest interior in medium-sized kelp forests (Fram et al. 2008). The distance over which current speeds decrease is important for determining net fluxes of nutrients and particulates and spore dispersal distances at different positions within a kelp forest.

In order to simulate flow within and around a kelp forest, kelp drag must be modeled. Jackson and Winant...
(1983) estimated drag due to the kelp forest at Point Loma, San Diego (California) by approximating it as an array of vertical cylinders, and they deduced a flow development length of 100 m. During the summer and autumn, however, most of the kelp biomass is in the surface canopy, a dense mass of stipes, blades, and pneumatocysts in the upper 1–2 m of the water column (Jackson 1977; Reed et al. 2008). Therefore, the cylinder model for a kelp forest may not be generally appropriate. Studies of other aquatic vegetation canopies and terrestrial forests have shown that flow structure is strongly dependent on plant morphology (Nepf et al. 1997; Finnigan 2000). The vertical profile of drag in kelp forests—larger drag near the surface and smaller drag in the lower water column—is likely to affect the shape of mean velocity profiles and thus the net drag on the flow.

In addition to affecting horizontal transport by currents, the physical structure of a kelp forest is likely to affect rates of horizontal and vertical mixing. To date, estimates of spore and larval dispersal distances have been based on measured currents and eddy viscosity models developed for the coastal ocean in the absence of vegetation (Gaylord et al. 2002). However, dispersal distances for spores or larvae released within a kelp forest are likely to be strongly affected by characteristics of the local turbulent mixing. Gradient Richardson numbers measured within a kelp forest in Santa Cruz, California, indicated that vertical shear in currents was seldom large enough to overcome the effects of stratification and thereby to generate turbulence through large-scale shear production (Rosman et al. 2007). However, other mechanisms for turbulence generation exist: for example, wake generation behind individual kelp bundles as a result of their interactions with currents and surface waves. Directly measuring currents and turbulence in kelp forests can be difficult: for example, it is not feasible to accurately measure spatially averaged flow properties in a system as heterogeneous as a kelp forest. Additionally, because kelp forests vary enormously in size and structure, it may be difficult to generalize using measurements from a single site. Much can be learned by turning to the laboratory, where simplified representations of a kelp forest can be used to investigate the interaction between a kelp forest and currents under controlled conditions.

In this study, the effects of the surface canopy and kelp spacing on the total drag due to a kelp forest and on vertical mixing within a kelp forest were investigated using a dynamically matched 1/25-scale model with a unidirectional current. We begin with an explanation of the dynamical scaling used, a description of the laboratory flume and model kelp design, and an outline of the experiments performed. This is followed by a description of flow development within the model kelp forest, an analysis of the momentum budget and net drag due to the kelp, and an analysis of the vertical turbulent mixing. The article concludes with a summary and discussion of possible implications for kelp forest ecology.

Methods

Scaling the kelp forest—The small-scale model kelp forest was designed to be dynamically similar to a real kelp forest: the aspect ratios (ratios of length scales) and the ratios of forces acting on the kelp were matched with typical field values (Munson et al. 2002). The external forces acting on a section of kelp under a steady unidirectional current are net buoyancy (the difference between buoyancy and gravity), $F_{B,\text{net}}$, and drag, $F_D$, and the internal forces are tension, shear, and bending moment in the stipe. $M. pyrifera$ stipes have very low bulk modulus of elasticity ($\sim 10^5$ Pa) and a small second moment of area, $I$ (the diameter of the stipe is $<1$ cm), and, thus, they are extremely flexible. Flexing of the stipe therefore results in almost no bending moment; rather, the kelp position adjusts in response to external forces (Wainwright et al. 1976). Thus, the tension and the angle between the kelp stipe and the vertical are determined solely by the relative sizes of the external forces $F_{B,\text{net}}$ and $F_D$. For the model kelp to maintain the correct position in the water column, the ratio

$$\frac{F_{B,\text{net}}}{F_D} \sim \sum_i (\rho_i - \rho_w) g V_i c_d A U^2$$

should be the same in the laboratory as in the field and must be matched for all segments along a kelp frond. The subscript $i$ denotes each kelp component (stipe, pneumatocyst, blade). Water density is denoted $\rho_w$, and the density of kelp component $i$ is $\rho_i$, $g$ is acceleration due to gravity, $V_i$ is the volume of kelp component $i$, $A$ is the frontal area of the kelp segment, $c_d$ is the drag coefficient, and $U$ is current speed. In general, for flows in which gravity and drag are both important, two dimensionless numbers arise: the Froude number, $Fr$, the ratio of inertia to gravity, and the Reynolds number, $Re$, the ratio of inertia to viscous forces (Kundu 1990). Froude number similarity is ensured if the force ratio in Eq. 1 is matched (assuming that the density of the kelp relative to water, the drag coefficient, and the aspect ratios are all the same in the model and the prototype). To ensure that $c_d$ is the same, Reynolds numbers should ideally be matched also. Practically, $c_d$ is reasonably constant with Reynolds number if the wakes behind individual kelps are fully turbulent, a condition that is found to hold for single cylinder wakes when $Re_d$ (based on cylinder diameter) $> 5000$. If kelp stipe bundles are approximated as cylinders, this condition is met in the field where $Re_d$ is of order $10^4$. For our models in the laboratory $Re_d$ is smaller ($Re_d \sim 500$) than is required for a fully turbulent wake. For $Re_d > 200$, the wake behind a cylinder is unstable and irregular, and $c_d$ varies little between $Re_d \sim 500$ and $Re_d \sim 10^4$ (Kundu 1990). We therefore infer, by approximating each kelp stipe bundle as a cylinder, that drag coefficients determined in the laboratory are a reasonable estimate of drag coefficients in the field.

The scaling described above is for a current alone; however, it can be shown that the same small-scale model can be used for experiments with surface waves if the wave period and amplitude are chosen carefully (Rosman 2007).

Model kelp design—Model parameters were selected to be in the middle of the range found in the field (Table 1). The water depth, kelp length, stipe bundle diameter, and
kelp spacing in the model were chosen to be 25 times smaller than typical field values; thus, the aspect ratios were conserved among these quantities. Velocity scales were chosen to be a factor of five times smaller than field values so that the Froude number and the force ratio in Eq. 1 were conserved.

Three M. pyrifera fronds were obtained from 8–10 m in water depth in Monterey Bay and were measured to determine realistic buoyancy and frontal area distributions. Total blade area was estimated as a function of distance along each stipe (Fig. 1a). Kelp density (Fig. 1b) was determined from measurements of the net buoyancy (buoyancy force minus weight) of 2-m kelp sections in seawater and the volume of water displaced by each segment in a graduated container. For practical reasons, the flotation and area measures of about 60 real fronds. The positions of blades and floats along each stipe were selected to match those for the real kelp fronds, but the dimensions of the individual components (blades, pneumatocysts) were not.

The model kelp was constructed from plastic tubing (diameter, 0.004 m; density, 1200 kg m\(^{-3}\)) for stipes, fishing floats (diameter, 0.01 m; density, 500 kg m\(^{-3}\)) for pneumatocysts, and vinyl sheeting (thickness, 0.1 mm; dimensions, 0.025 m × 0.1 m; density, 1200 kg m\(^{-3}\)) for blades (Fig. 2). Each kelp model was composed of three fronds that (each) represented the frontal area and buoyancy of 10 real fronds. The positions of blades and floats along each stipe were selected to match the buoyancy and frontal area distributions measured for the real kelp fronds (Fig. 1). The surface canopy occupied the top 0.10–0.14 m of the water column, becoming denser closer to the surface. This is equivalent to the surface canopy extending 2–3 m below the surface in the field, which is realistic during the summer.

Some experiments were performed for kelp without a surface canopy. The general design of no-canopy kelp was the same as for the with-canopy kelp, except that only the lower 0.4 m of the kelp design was used, and only floats (no blades) were attached to the stipes (Fig. 2c,d).

**Laboratory flume**—A 12.5-m–long and 1.2-m–wide recirculating flume was used for the experiments (Fig. 3). The height of the weir at the downstream end of the flume could be varied along with the pump speed to alter the water depth and flow velocity independently. A current of 0.04 m s\(^{-1}\) and a water depth of 0.41 m were used for all experiments described in this article. For further details about the flume, see Pidgeon (1999).

**Kelp configurations**—Experiments were performed with two model kelp configurations with surface canopies (dense kelp spacing, \(S = 15 \text{ cm}\); sparse spacing, \(S = 25 \text{ cm}\)), one configuration without a surface canopy (\(S = 15 \text{ cm}\)), and without kelp. The model kelps were arranged in lines in the across-flume direction, but they were staggered in the direction of flow (Fig. 2). The along-channel kelp forest length was 2 m for dense kelp configurations and 3.2 m for sparse kelp configurations. This is equivalent to real kelp forests extending 50–80 m, the length of the flume and the number of kelp that could realistically be constructed limited the extent of the model kelp forest. The length of the small-scale kelp forest was found to be sufficient for studying flow development and turbulence.

**Measurements**—Velocities were measured using an acoustic Doppler velocimeter (Vectrino Plus) mounted on a traverse that allowed accurate vertical and horizontal positioning. Each vertical profile consisted of 12–15 measurement points in the unobstructed part of the water column. Velocities were recorded at 25 Hz for 10 min at each measurement point. Velocity profiles were measured immediately upstream of the leading kelp forest edge and at four to six different positions along the length of the model kelp forest. At each along-channel measurement position, five (sparse) or six (dense and no canopy) velocity profiles were measured at equal (0.025-m) intervals across the flume between adjacent kelp to determine spatial means and spatial variances in time-averaged velocities and turbulence statistics.

Uncertainty in spatially averaged flow statistics arose primarily because the flow was spatially variable, and it was only practical to average measurements at a small number of positions across the flume. The uncertainty in spatially

### Table 1. Ranges of parameters expected in the field and those chosen for laboratory model. Numbers in parentheses are field values that correspond to the laboratory values used.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Field</th>
<th>Laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current, (U) m s(^{-1})</td>
<td>0–0.3(0.2)</td>
<td>0.04</td>
</tr>
<tr>
<td>Water depth, (H) m</td>
<td>7–15(10)</td>
<td>0.4</td>
</tr>
<tr>
<td>Stipe bundle diameter, (d) m</td>
<td>0.2–0.3(0.3)</td>
<td>0.012</td>
</tr>
<tr>
<td>Kelp spacing, (S) m</td>
<td>3–10(4–6)</td>
<td>0.15–0.25</td>
</tr>
<tr>
<td>Kelp length, (L) m</td>
<td>5–20(15)</td>
<td>0.6</td>
</tr>
</tbody>
</table>

### Fig. 1. (a) Blade area and (b) density distributions along the length of three real kelp fronds and the small-scale model. Distance from frond base is denoted \(\lambda\). \(L\) is total frond length, and \(z\) is blade area per unit stipe length. \(z\) was non-dimensionalized by dividing by the stipe bundle diameter, \(d\), which was taken to be 0.3 m for real stipe bundles and 0.012 m for models.
averaged quantities was taken to be twice the standard error in the spatial-mean, which is approximately equivalent to the 95% confidence interval. Uncertainties in higher order quantities, such as terms of the momentum budget, were computed using general principals for propagation of uncertainty in nonlinear functions (Taylor 1997).

Results

General observations—For configurations with surface canopies, the upper water column velocity decreased with along-channel distance, resulting in a downward velocity component in the upper part of the water column (Fig. 4). At the downstream end of the model kelp forest, streamwise gradients in velocity were markedly diminished, and vertical velocities were close to zero (Fig. 4f,l). Henceforth, we use the term fully developed for the uniform flow near the downstream end of the model kelp forest. The slight increase in along-channel velocity in the lower water column within the kelp array is likely an artifact of the one-dimensional laboratory situation in which the total flow rate must be conserved. There was also a marked increase in the spatial variability of the flow when water entered the kelp arrays.

For the configuration without a surface canopy, spatially averaged velocity and Reynolds stress profiles did not differ
significantly from those without kelp, although the spatial standard deviation was much greater (Fig. 5). For the dense and sparse configurations, Reynolds stresses were negative in the shear layer beneath the surface canopy (Fig. 5j,n), indicating a layer in which low-momentum fluid in and near the surface canopy was transported downward by turbulence. In some ways, this is similar to the shear layer that forms above submerged vegetation canopies (Ghisalberti and Nepf 2002); however, in the model kelp forest, obstacles occupied the full water column and drag varied continuously in the vertical. There was no inflection point in the velocity profile, and no shear instabilities were observed. The turbulent kinetic energy (tke) within the kelp arrays was much larger and more spatially variable than without kelp. The average tke was slightly greater for configurations with a surface canopy than for those without a surface canopy, and it was slightly greater for the dense than for the sparse kelp arrangement, possibly as a result of the greater density of wake-forming obstructions.

**Momentum budget**—To interpret the observations and develop a predictive capability that allows laboratory results to be extended to the field, we can consider the momentum budget. Flow within vegetation canopies like kelp forests is spatially variable as a result of flow deviations around individual plants. To analyze the net effect of a vegetation canopy on the flow it is useful to average the governing equations, which are usually valid at a point, over a volume that is large compared with random spatial variations but small compared with gradients in the larger scale flow (Raupach and Shaw 1982). For flow within a kelp forest, as for most vegetation canopies, the most appropriate averaging volume is a box that is much thinner in the vertical than the horizontal; thus, averages are computed over many kelp individuals, but gradients in the vertical are resolved.

The spatially averaged momentum equation in the along-channel direction within the model kelp forest is

\[
\frac{\partial \langle u \rangle}{\partial t} + \frac{\partial \langle u u \rangle}{\partial x} + \frac{\partial \langle w \rangle}{\partial z} = -\frac{1}{\rho} \frac{\partial \langle p \rangle}{\partial x} + \frac{1}{\rho \gamma} \frac{\partial \langle \tau_{xz} \rangle}{\partial z} - f_{Fx} - f_{Vx} \tag{2}
\]

\[
\tau_{xz} = -\rho \langle uu'w' \rangle - \rho \langle u'u'w' \rangle + \mu \frac{\partial \langle u \rangle}{\partial z}
\]

\[
f_{Fx} = \frac{1}{\rho \gamma} \int_A p n_x \, dA
\]

\[
f_{Vx} = -\frac{\mu}{\rho \gamma} \int_A \left( \frac{\partial \langle u \rangle}{\partial x} n_x + \frac{\partial \langle u \rangle}{\partial y} n_y + \frac{\partial \langle u \rangle}{\partial z} n_z \right) \, dA
\]

where \(x, y, \text{ and } z\) are orthogonal coordinates (\(z\) is vertical and \(x\) is...
positive in the direction of mean flow); $u$, $v$, and $w$ are the velocities in directions $x$, $y$, and $z$, respectively; and the unit normal to the solid surface has components $n_x$, $n_y$, and $n_z$. The fluid density is $\rho$, $\mu$ is molecular viscosity, and $p$ is pressure. The porosity, $\gamma$, is the ratio of fluid volume to total volume, and $A$ is the total area of solid surface within the averaging volume. Over-bars indicate time averages in the Reynolds-averaged sense, and angular brackets indicate spatial averages. Single primes indicate deviations from the time average (e.g., $u' = u - \bar{u}$), and double primes indicate deviations from the spatial average (e.g., $\bar{u}' = \langle \bar{u} \rangle - \bar{u}$). The shear stress, $\tau_{xz}$ (denoting stress in the $x$-direction exerted by fluid above and below a given point), is the sum of the viscous stress, the Reynolds stress, and the dispersive stress. The dispersive stress is the spatial analogue of the Reynolds stress. While the Reynolds stress represents the transport of momentum due to the time-averaged effect of turbulent fluctuations, the dispersive stress represents the transport of momentum due to the spatially averaged effects of persistent spatial variations in the flow. The form drag ($f_{Fx}$) and viscous drag ($f_{Vx}$) terms arise from integrating the pressure gradient and viscous stress terms of the Navier–Stokes equations around solid obstacles.

The steady form ($\partial (\bar{u}/t) = 0$) of Eq. 2 was used for the analysis. Advection accelerations and shear stress gradients were computed from spline fits to spatially averaged velocity and Reynolds stress measurements. Viscous stresses were assumed to be negligible compared with turbulent stresses. The dispersive stress gradient was omitted (assumed to be zero) because of the large
uncertainty in this term. Dispersive stresses were the same size as, or smaller than, Reynolds stresses for all kelp configurations, and stress gradients made a very small contribution to the momentum budget. As the porosity within the model kelp forest was very close to unity (γ = 0.975–0.998), γ = 1 was used in the calculations.

A quadratic drag parameterization was used for the drag term. For $Re_x > 100$, form drag due to solid obstacles is usually assumed to be much larger than viscous drag, and net drag is parameterized using a quadratic drag law (Nepf 1999), thus:

$$f_{Dx} \approx f_{Fx} = \frac{1}{2} c_{d} a \langle u^2 \rangle$$

(3)

where $f_{Dx}$ and $f_{Fx}$ are the total drag and form drag per unit along-channel length, respectively; $a$ is the frontal area of solid objects per unit fluid volume; and $c_{d}$ is the drag coefficient that relates the form drag on an obstacle at height $z$ to the fluid velocity and obstacle frontal area at that height. The net drag due to an array of sparsely spaced objects in which the individual wakes do not interact can be expressed as a simple sum of the drag due to the individual elements. As objects become more closely spaced, wakes begin to interact and flow sheltering occurs, reducing the average drag imposed per unit frontal area. For arrays of cylinders, flow sheltering becomes significant when $ad > 0.01$, where $d$ is the cylinder diameter (Nepf 1999).

Equation 3, with $c_{d} = 1$, was used to compute the drag at a reference level above the bottom boundary layer and below the surface canopy ($z_{ref} = H = 0.25$), where the assumption that the kelp stipe bundles behave like vertical cylinders with non-interacting wakes is best. The along-channel pressure gradient was then calculated from the simplified momentum budget at height $z_{ref}$ using the equation

$$\begin{align*}
\left[ \frac{1}{\rho} \frac{\partial \langle p \rangle}{\partial x} \right]_{z_{ref}} &= \left[ \frac{\partial \langle u \rangle}{\partial x} \right]_{z_{ref}} + \frac{\partial \langle w \rangle}{\partial z} \frac{\partial \langle u \rangle}{\partial z} - \langle w \rangle \frac{\partial \langle u \rangle}{\partial z} \left. \right|_{z_{ref}} \\
&+ \frac{\partial \langle u w \rangle}{\partial z} - \frac{1}{2} c_{d} a \langle u^2 \rangle \left. \right|_{z_{ref}}
\end{align*}$$

(4)

From the vertical momentum budget, the variation of the horizontal pressure gradient over the water depth was found to be less than 10% of the depth-averaged pressure gradient term; therefore, the along-channel pressure gradient was assumed to be uniform in the vertical, and the drag profile in the flow development regions was computed as

$$f_{D} = \frac{1}{\rho} \frac{\partial \langle p \rangle}{\partial x} \left. \right|_{z_{ref}} - \langle w \rangle \frac{\partial \langle u \rangle}{\partial z} - \frac{\partial \langle w \rangle}{\partial z} \frac{\partial \langle u \rangle}{\partial z} + \frac{1}{\rho} \frac{\partial \langle u w \rangle}{\partial z}$$

(5)

Where the flow was fully developed, the advective terms in Eqs. 4 and 5 were omitted from pressure gradient and drag calculations.

For fully developed flow the along-channel pressure gradient is balanced by the shear stress gradient and the drag due to the model kelp. The drag is much larger than the stress gradient; thus, the drag term is almost uniform with depth (Fig. 6d–f). The stress gradient term is more significant for the sparse configuration than for the dense configuration because the drag term is several times smaller; however, it is still small compared with other terms in the momentum budget.

At the upstream end of the kelp forest where the flow is developing, vertical velocities and along-channel velocity gradients are non-zero for configurations with surface canopies; thus, the advective acceleration terms are also important (Fig. 6b,c). Velocities are relatively uniform over the water depth; therefore, the drag is much greater in the upper water column, where the kelp frontal area is large, than in the lower water column. This vertical difference in drag results in the water being accelerated (negative advective accelerations) in the upper water column and accelerated in the lower water column.

The flow adjustment distance can be estimated by scaling the terms of the momentum budget. If the flow is steady, advective terms are expressed in conservative form, shear stress gradients are neglected, and a quadratic approximation is used for the drag terms, Eq. 2 reduces to

$$\frac{\partial \langle u \rangle}{\partial x} + \frac{\partial \langle w \rangle}{\partial z} \frac{\partial \langle u \rangle}{\partial z} = - \frac{1}{\rho} \frac{\partial \langle \gamma (p) \rangle}{\partial x} - \frac{1}{2} c_{d} a \langle u^2 \rangle$$

(6)

Terms on the left-hand side scale as $U^2 L_{x}^{-1}$, where $U$ is a scale for the along-channel velocity and $L_{x}$ is a length scale for flow development. Terms on the right-hand side scale as $c_{d} a U^2$. By equating scales for the left-hand and right-hand sides, it can be shown that $L_{x} \sim (c_{d} a)^{-1}$. Thus, the flow will develop over a shorter distance for dense canopies (large $a$) than for sparse canopies (small $a$).

**Estimates of drag**—As described in the previous section, the drag force is an important term in the momentum budget within kelp forests. A good estimate of the drag term is therefore required to make predictions about currents within kelp forests or to simulate them numerically. Profiles of $f_{D}$ from the momentum budget for developing and fully developed flow (Eq. 5) were used to compute two independent estimates of $c_{d} a$ (Fig. 7). The two $c_{d} a$ estimates agreed within uncertainty limits, except within the surface canopy for the dense configuration, indicating that a quadratic drag law is probably not appropriate within dense surface canopies.

The net effect of a kelp forest on depth-integrated currents can be represented by the depth-integrated drag, which is typically modeled using a bulk drag coefficient, $C_{D,\text{bulk}}$. Assuming quadratic drag parameterizations are appropriate both for the drag at each height $z$ and for the depth-integrated drag, $C_{D, \text{bulk}}$ is defined

$$C_{D, \text{bulk}} = \frac{\int_{0}^{H} f_{D} \gamma dz}{\int_{0}^{H} \langle u \rangle \gamma dz} = \frac{1}{U} \frac{\int_{0}^{H} c_{d} a \langle u^2 \rangle \gamma dz}{\int_{0}^{H} \langle u \rangle \gamma dz}$$

(7)

where $U = H_{\text{eff}} / \int_{0}^{H} \langle u \rangle \gamma dz$ is the depth-averaged velocity, $H_{\text{eff}} = \int_{0}^{H} \gamma dz$ is the effective water depth (volume of water per unit plan area), and $H$ is the total water column height.

Bulk drag coefficients were computed from Eq. 7 using measured velocity profiles and the average of the $c_{d} a$ profiles deduced for developing and fully-developed flow. For the kelp configuration without a surface canopy,
CD, bulk does not change along the length of the kelp forest because the velocity profile does not adjust significantly (Fig. 8). For configurations with surface canopies, CD, bulk is largest at the upstream end of the kelp forest, decreases with along-channel distance, and reaches a minimum for fully developed flow.

At the upstream end of the kelp forest, the velocity is nearly uniform over the water depth $\langle u \rangle \approx U$; thus, the expression for the bulk drag coefficient in Eq. 7 reduces to

$$C_{D,\text{bulk}} \approx \frac{1}{2} \int c_d a_d \, dz$$  \hspace{1cm} (8)

The bulk drag coefficient for fully developed flow can be estimated by assuming a pressure-drag momentum balance, both at each height in the water column and for the depth-integrated flow, and by assuming that the pressure gradient is uniform in the vertical. The result is

$$C_{D,\text{bulk}} \approx \frac{H_{\text{eff}}}{\left( \frac{1}{H_{\text{eff}}} \int_0^H 2(c_d a_d)^{-1/2} \, dz \right)^2}$$  \hspace{1cm} (9)

As the velocity profile adjusts, $C_{D,\text{bulk}}$ decays from Eq. 8 to Eq. 9. The distance over which $C_{D,\text{bulk}}$ decreases corresponds to the distance over which the velocity profile develops and hence scales with $(c_d a_d)^{-1}$, which is propor-

![Fig. 6. Terms of the along-channel momentum budget for developing and fully developed flow, non-dimensionalized by dividing by $U^2 H$. Accelerations and stress gradients were computed from spline fits to velocity and Reynolds stress profiles. Pressure and drag terms were calculated from the momentum budget. Horizontal bars indicate 95% uncertainty limits for each term.](image)

![Fig. 7. Drag coefficients calculated from the momentum budget for developing and fully developed flow. Drag coefficients are plotted as $c_d a_d$ and are normalized by multiplying by the stipe bundle diameter, $d$. Horizontal bars indicate 95% uncertainty limits.](image)
tional to $S^2d^{-1}$. For our dense and sparse kelp configurations the flow development length is about $0.3 \times S^2d^{-1}$ (Fig. 8).

Previously, drag coefficients for kelp forests have been estimated by approximating the kelp as cylinders with the same diameter as stipe bundles (Jackson and Winant 1983). In this case, Eqs. 8 and 9 both reduce to

$$C_{D,\text{bulk}} = \frac{1}{2} \frac{c_d d H_{\text{eff}}}{S^2}$$

This approach gives $C_{D,\text{bulk}} = 0.11$ for the dense and no-canopy configurations and $C_{D,\text{bulk}} = 0.038$ for the sparse configuration. For configurations with surface canopies, these $C_{D,\text{bulk}}$ estimates are three times too small for developing flow and 1.5 times too small for fully developed flow (see Fig. 8). Approximating a kelp forest as a cylinder array therefore results in underestimation of the net drag if a surface canopy is present; however, the additional drag due to the canopy is partially mitigated by adjustment of the velocity profile to the drag profile.

Turbulence characteristics—The characteristics of turbulence, along with velocity profiles, determine the mixing and transport of scalars such as nutrients, larvae, and spores. In an array of solid obstacles such as the model kelp forest, turbulence can be produced by shear production at a scale larger than the averaging volume ($P_s$) or in individual wakes behind obstacles within the averaging volume ($P_w$). The expressions for $P_s$ and $P_w$ are

$$P_s = -\langle u_i' u_j' \rangle \frac{\partial \langle u_i \rangle}{\partial x_j}$$

and

$$P_w = \langle u_i' u_j' \rangle \frac{\partial \langle u_i \rangle}{\partial x_j}$$

Because direct computation of wake production requires knowledge of the velocity at every point, $P_w$ is often estimated from the work done by the drag force per unit time (Nepf 1999), thus:

$$P_w = f_{D,x} \langle \dot{u} \rangle$$

Shear production (from Eq. 11) was at least an order of magnitude smaller than wake production (from Eq. 13) for all of the kelp configurations investigated, indicating that tke was primarily generated in kelp wakes.

To investigate the effects of wake-generated turbulence on the mixing of momentum and scalars it is instructive to compute characteristic turbulent length scales. The mixing length is a scale for the distance over which momentum is mixed by turbulence. If flow is in the $x$-direction and the only non-zero mean shear is $\partial \langle u \rangle / \partial z$, the mixing length is defined as (Pope 2000)

$$\ell_m = \frac{\langle u' w' \rangle^{1/2}}{\langle \partial \langle u \rangle / \partial z \rangle}$$

Computing a mixing length from Eq. 14 was problematic where $\partial \langle u \rangle / \partial z$ was small. The mixing length is often reasonably well approximated by the integral length scale, a scale for the size of the large eddies or the distance over which turbulent fluctuations are correlated (Pope 2000). We were unable to compute integral length scales directly because this requires simultaneous velocity measurements at many positions. Instead, the correlation time scale at the measurement position was computed from

$$\ell_t = \frac{1}{w' \langle w_{ij} w_{ij} \rangle} \int_0^{\infty} \langle u' \rangle \, dt$$

where $w'$ is the turbulent vertical velocity fluctuation, $\langle w_{ij} w_{ij} \rangle$ is the autocorrelation function at time lag $\eta$, and $\eta_0$ is the time lag at which the autocorrelation function approaches zero or ceases to fall off with increasing lag. The correlation time scale was then converted to a length scale by assuming that turbulent eddies were advected past the measurement position at speed $\bar{u}$ (Taylor’s frozen turbulence hypothesis):

$$\ell_z = \bar{u} \ell_t$$

Integral length scales agreed well with mixing lengths throughout most of the water column for the sparse and dense kelp configurations (Fig. 9). Without kelp, as well as upstream of the model kelp forest, turbulent length scales increased with distance from the water surface and from the bottom, reaching a maximum size of about $l/lH = 0.2$ ($l/l = 7$) in the middle of the water column (Fig. 9a). Integral length scales agree reasonably well with the theoretical mixing length profile for open channel flow (Nezu and Rodi 1986); the deviation from the theoretical curve indicates that the log-layer may not quite be fully developed in the laboratory flume. Within the model kelp forest, turbulent length scales were much smaller and were comparable to the wake scale ($l/l = 1$).

Velocity fluctuations with small spatial scales are smoothed to some extent because of the Vectrino sample volume size (6 mm wide $\times$ 5.5 mm tall). Comparison of
power spectra from Vectrino and Laser Doppler Anemometry (LDA) measurements (not shown) indicated that velocity fluctuations at scales smaller than 1 cm were damped to some extent by the Vectrino. However, Lagrangian integral length scales computed from Vectrino measurements within the kelp arrays closely matched those from LDA measurements.

Turbulent length scales decayed with distance into the kelp forest from the upstream edge toward a value that was approximately equal to the stipe bundle diameter (Fig. 10). Turbulent length scales decreased most rapidly in the surface canopy ($z/H \approx 0.8$), where obstacles were most densely spaced and turbulent eddies were broken up most rapidly. The decrease in turbulent length scale occurred over a longer distance in the lower water column ($z/H \approx 0.2$), where obstacles were more sparsely spaced. In the lower water column, turbulent length scales decreased more rapidly for the dense configuration than for the sparse configuration as a result of the greater density of wake-forming obstacles.

Although turbulent kinetic energy was greater within the kelp forest than it was upstream (Fig. 5), the largest turbulent eddies were much smaller and thus presumably less effective at mixing. Mixing of momentum by turbulence can be quantified using the turbulent eddy viscosity, $v_t$. For the model kelp forest where flow is in the $x$-direction and $\partial \langle u \rangle / \partial z$ is the dominant component of shear, an eddy viscosity can be computed from

$$v_t = -\frac{\langle uu' \rangle}{\partial \langle u \rangle / \partial z}$$  \hspace{1cm} (17)

From scaling, $v_t$ can also be estimated as (Pope 2000)

$$v_t \propto k^{1/2} \ell_m$$  \hspace{1cm} (18)

where $k$ is the turbulent kinetic energy and $\ell_m$ is the mixing length. Eddy viscosities were computed from the measurements using Eqs. 17 and 18; the integral length scale was used for the length scale. Although strictly speaking the integral lengths scales computed using Eqs. 15 and 16 are stream-wise eddy dimensions, they agree closely with mixing length throughout much of the water column, and they are better behaved than mixing lengths (Eq. 14) where velocity gradients are small.

Using the direct approach (Eq. 17) to compute $v_t$ was problematic in those parts of the water column where the velocity gradient was small. By comparing $v_t$ estimated from Eq. 18 with the theoretical profile for open channel
flow, the constant of proportionality was deduced to be 0.4. Scaling estimates of $n_t$ (Eq. 18) agreed quite well with values computed directly (Eq. 17) in the upper water column for the sparse and dense configurations, where the mean shear was large. Eddy viscosities within the model kelp forest were about 60–70% of those upstream, and they were more uniform over the water depth (Fig. 11). These results indicate that under the same mean shear, vertical mixing due to turbulence in a kelp forest would be weaker than in the surrounding coastal ocean, primarily because the turbulent eddies are smaller.

Discussion

Main findings of this study—Our results indicate that the surface canopy must be included in drag coefficient estimates for kelp forests; a simple cylinder model is not appropriate if a substantial surface canopy is present. If a surface canopy is present, the bulk drag coefficient appropriate for modeling depth-integrated drag decreases with distance into the kelp forest, as the shape of the velocity profile adjusts to the drag profile. Near the upstream kelp forest edge, the bulk drag coefficient can be three times that for an array of cylinders with the same spacing and diameter as kelp stipe bundles. However, for fully developed flow, $C_{D,\text{bulk}}$ is only 60% greater than for an equivalent cylinder array. Errors in bulk drag coefficients translate to errors in currents computed from numerical models and, consequently, into errors in estimated fluxes of important commodities such as nutrients, larvae, and spores at different points in a kelp forest.

Stress gradients form only a small contribution to the momentum budget; therefore, a good model for turbulent and dispersive stresses is not critical for computing currents within kelp forests. However, turbulence and spatial variability cannot be neglected when estimating transport rates of scalars. Laboratory results indicate that turbulence within kelp forests is generated predominantly in wakes, and therefore the mixing length, a measure of the distance over which scalars and momentum are mixed by turbulent eddies, can be approximated by the diameter of a stipe bundle. The largest scales of turbulent motion within a kelp forest are therefore much smaller than in the surrounding shallow coastal ocean, where eddy sizes are limited only by the water depth and stratification. The reduced eddy size translates to eddy viscosities that can be 30–40% less than without kelp. Thus, standard eddy viscosity profiles for the coastal ocean are likely to somewhat overestimate vertical mixing rates in kelp forests.

The flow modifications we observed in the laboratory varied with kelp spacing and the presence or absence of a surface canopy. These variations in kelp forest structure were designed to reflect those that occur in nature between different seasons and years; thus, substantial variation in bulk drag coefficients and turbulent eddy viscosities is expected among real kelp forests.

Application to a real kelp forest—In the laboratory, the model kelp forest covered the full width of the flume; hence, the flow was one-dimensional and water was forced through the kelp forest at a constant rate. In the coastal ocean, water is able to deviate laterally around high drag regions; thus, flow rate decreases with distance into kelp forests. Two different types of flow development therefore occur in real kelp forests: adjustment of the velocity profile shape to the vertical distribution of drag and decrease in depth-averaged currents due to lateral flow deviation around the kelp forest. The former type of flow development was investigated in this study and the latter was considered by Jackson and Winant (1983). Here we discuss the implications of our results for each type of flow development.

Our results indicate that the shape of the along-shore velocity profile adjusts to the vertical drag profile over a distance of about 0.3 $S^2d^{-1}$, where $S$ and $d$ are the mean kelp spacing and stipe bundle diameter, respectively. For real kelp forests equivalent to our dense ($S \sim 3.75$ m; $d \sim$...
because of symmetry. Assuming a constant along-shore that gradients in the \( y \)-direction have been neglected because of symmetry. A constant along-shore surface slope \( (\frac{\partial \eta}{\partial x} = -\zeta) \) and a constant \( C_{D,\text{bulk}} \), the solution is

\[ U = \left[ U_0^2 \exp\left( -\frac{2 C_{D,\text{bulk}}}{H} x \right) \right]^{1/2} \]

This solution differs from that proposed by Jackson and Winant (1983) because we retained the horizontal pressure gradient term in the momentum balance, as this term is usually important in shallow water. The behavior of Eq. 20 is shown in Fig. 12 for several values of \( C_{D,\text{bulk}} \). In contrast to the Jackson and Winant (1983) curve, Eq. 20 decays to a constant non-zero value in the kelp forest interior and thus provides a better fit to the data of Gaylord et al. (2007).

The data of Gaylord et al. (2007) correspond most closely with \( C_{D,\text{bulk}} = 0.08 \); however, values for \( U_0 \) (0.2 m s\(^{-1}\)), \( \zeta \) (1 \times 10\(^{-6}\)), and \( H \) (10 m) were assumed to compute these curves.

Flow adjustment occurs in a distance of about \( 3HC_{D,\text{bulk}}^{-1} \) (Fig. 12). For kelp forests with similar physical structures to our dense \( (H = 10 \text{ m}; C_{D,\text{bulk}} = 0.18) \), no canopy \( (C_{D,\text{bulk}} = 0.11) \), and sparse \( (C_{D,\text{bulk}} = 0.07) \), configurations, flow development distances would be about 170 m, 270 m, and 340 m, respectively. These flow development distances are similar to those of several hundred meters observed by Jackson (1998) and those of about 200 m observed by Gaylord et al. (2007). The decrease in currents that occurs as a result of lateral deviation around a kelp forest occurs over a much longer distance than does the adjustment of the velocity profile, and, hence, the two processes can be considered independently.

The discussion above is relevant only to depth-averaged currents, which are oriented primarily in the along-shore direction. However, vertically sheared across-shore currents are a significant exchange mechanism between a kelp forest and offshore (Jackson 1984; Rosman et al. 2007). Across-shore velocity profiles are expected to adjust to kelp drag profiles over a similar distance to alongshore velocities (of order \( S^2 d^{-1} \)), resulting in decreased exchange by this mechanism in the kelp forest interior. However, baroclinic pressure gradients (due to across-shore temperature gradients) and vertical stratification are important for the dynamics of across-shore flows and were not considered in this study.

Because flow is not able to deviate around the model kelp forest in the laboratory flume, currents within the model kelp forest are quite large (equivalent to 20 cm s\(^{-1}\) in a real kelp forest). Thus, the ratio of drag to buoyancy is large, and model kelp may have submerged somewhat more than in a real kelp forest. In a real kelp forest, the shear associated with the surface canopy may be limited to a thinner layer near the surface than was observed in this study, and bulk drag coefficients may be somewhat smaller as a result.

Both wake production and shear production scale with velocity cubed and the inverse of length, thus the ratio of \( P_s \) to \( P_w \) is not a function of the flow speed or length scale. \( P_s/P_w \) should be similar in the laboratory model and in a real kelp forest. Hence, the laboratory results suggest that wake production is the main turbulence production mechanism in a kelp forest, and the size of the largest eddies scales with the stipe bundle diameter. Eddy viscosities in Fig. 11 should be generally applicable because they are non-dimensionalized by the local current and the stipe bundle diameter. For example, if currents are a factor of 3 smaller within a kelp forest than outside (Rosman et al. 2007), our results indicate that the eddy viscosity is four to five times smaller within the kelp forest and more uniform over the water depth. As stratification limits vertical mixing, eddy viscosities from this study may overestimate vertical mixing if the water column is stratified.
We have investigated appropriate models for drag and turbulent mixing in kelp forests when the current is constant and unidirectional. Kelp forest geometry and coastal ocean hydrodynamics were simplified in our laboratory model in order to make the physics tractable. In real kelp forests there is a wide range of kelp sizes, individuals are irregularly spaced, and bottom topography can be rough and heterogeneous. Hydrodynamics in real kelp forests are further complicated by time-varying currents, vertically sheared across-shore flows, surface waves, and stratification (Utter and Denny 1996; Jackson 1998; Rosman et al. 2007). Waves may increase turbulent mixing while stratification inhibits vertical mixing. The implications of these other processes may be investigated in future, carefully designed studies of kelp forest hydrodynamics.

**Implications for biology**—The fluxes of nutrients, plankton, and particulates to kelp forest organisms are determined by currents and by vertical and lateral mixing due to turbulence and spatial variations in the flow. Because both currents and vertical mixing are reduced within kelp forests, *M. pyrifera* could potentially limit nutrient fluxes to itself and other kelp forest organisms and may restrict the transport of larvae or spores.

The surface canopy contains a large fraction of the biomass in kelp forests and is responsible for the majority of *M. pyrifera* nitrogen uptake (Jackson 1977; Fram et al. 2008; Reed et al. 2008). Nutrient concentrations within kelp forests are often larger in the lower water column than in the upper water column as a result of upwelling of deeper nutrient-rich water from offshore and depletion by nutrient uptake in the surface canopy. Additionally, our results indicate that currents through the surface canopy may be as small as 30% of those lower in the water column, and exchange between the upper and lower water columns may be limited within kelp forests because turbulent eddies are small. Vertical mixing would be further limited if the water column were stratified. Nutrient fluxes available to kelp in the surface canopy could therefore be much smaller than would be predicted using depth-averaged velocities and nutrient concentrations. Kelps are capable of some translocation of nutrients, however, providing an alternative mechanism for moving nutrients from the lower water column to the more nutrient-depleted upper water column.

In the absence of translocation of nutrients, the distance over which uptake in the surface canopy affects lower water column concentrations can be estimated from scaling arguments as \( L_v \sim UH^2K_z^{-1} \). Our results indicate that the eddy viscosity can be estimated as \( \nu_l \sim 0.1 Ud \) (see Fig. 11). If we assume that momentum and scalars are mixed in a similar way by turbulence, then \( \nu_l \) is a reasonable estimate for \( K_z \). For water depth \( H = 10 \text{ m} \) and stipe bundle diameter \( d = 0.3 \text{ m} \), nutrient uptake in the surface canopy would affect supply to the benthos over a distance of order 3000 m. As vertical mixing is inhibited by stratification and may potentially be increased by waves, \( L_v \) would be greater if the water column was stratified and may be smaller in wavy conditions. The primary method by which mature kelp with surface canopies limit the growth of juvenile and understory kelp is shading of light. Our results suggest that the surface canopy would have minimal effect on nutrient concentrations seen by understory kelp in most kelp forests.

The structure of *M. pyrifera* forests typically varies seasonally. In the spring, there is often no surface canopy; thus, bulk drag coefficients should be relatively small, allowing for relatively high flow rates and large nutrient fluxes, which could translate into high growth rates. As the season progresses and the canopy fills in, demand for nutrients increases, and at the same time the flux of nutrients decreases because currents are reduced as a result of increased drag. This negative feedback could potentially limit the growth rate of mature kelp. Additionally, mature kelp, through their large drag, could limit the flux of water and thus the nutrient supply to the kelp forest as a whole by causing water to deviate laterally around the kelp forest.

Kelp forests can also affect food supply to benthic invertebrates by reducing the length scale of turbulent eddies and decreasing currents, thereby reducing turbulent diffusivities. This decrease in turbulent mixing is expected to lead to smaller fluxes to the bed of neutral particles like phytoplankton but faster downward flux of dense particles like many zooplankton, organic detritus, and sediment (Denny and Shibata 1989; McNair et al. 1997). Higher sedimentation rates could be detrimental to benthic organisms, while higher deposition of organic material and plankton could be beneficial.

Most kelp forest organisms release larvae or spores into the water column, and the paths and final destinations of these particles are determined to a large extent by water motion. Stochastic diffusion models have been used to estimate dispersal distances of larvae and spores in streams and in the coastal ocean (Denny and Shibata 1989; McNair and Newbold 2001; Gaylord et al. 2002). Turbulent eddy diffusivity profiles are required as an input for this type of model. In the future, dispersal distances for larvae and spores released within a kelp forest could be modeled using the turbulent diffusivity profiles developed in this study.

In conclusion, our laboratory experiments have shown that a good model for drag is essential for correctly modeling currents within and around kelp forests and that the surface canopy must be included in drag estimates. In order to estimate nutrient and particulate fluxes to organisms or dispersal distances for larvae and spores, a model for vertical mixing is also required. Models for vertical mixing traditionally used in the coastal ocean are not applicable to kelp forests because turbulent eddies are much smaller. The expressions for drag and eddy viscosity developed in this study are expected to be an improvement over the parameters used in previous studies, although substantial variation is expected among real kelp forests.

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