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Effect of a kelp forest on coastal currents

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Abstract—Ocean currents supply a kelp ecosystem with nutrients, planktonic food, and larvae. We have found that these currents in a kelp forest (*Macrocystis pyrifera*) are slower than currents outside. At the Pt. Loma, San Diego, California, site that we studied, current velocities were about a third of those outside. A comparison of frequency spectra shows that semi-diurnal frequencies are preferentially passed by the kelp. This effect of a kelp forest on the currents that nurture it is similar to that of a terrestrial forest on local winds.

INTRODUCTION

TERRESTRIAL plant communities modify the movement of air around and through themselves. Because this modification affects that transfer of momentum, heat, carbon dioxide, and water vapor between the plants and the atmosphere, ecologists and meteorologists have actively studied the phenomenon (MONTEITH, 1973; RAUPACH and THOM, 1981). We report here that similar modifications occur in marine plant communities and speculate on their significance.

The dominant seaweed of the southern California coast is giant kelp, *Macrocystis pyrifera* (NORTH, 1971). It usually grows in water of depth between 2 and 20 m. Plants attach to hard substrata by means of root-like holdfasts. Fronds grow upward to the sea surface from the top of the holdfast, intertwining to form a column between the hard bottom and the sea surface, diverging at the surface to form a canopy. A single mature plant typically contains 40 fronds, the longest of which can be 40 m. The diameter of the frond bundle is 10 to 20 cm; the biomass of a single plant is typically 40 to 60 kg wet weight. The kelp forest off Pt. Loma, San Diego, California, is 7 km long by 1 km wide. Our study area was approximately in the middle of it. Plant densities near our site ranged between 0.02 and 0.14 plants per m² in late 1981 (V. GERARD, personal communication).

Coastal currents result from the interaction of pressure forces, wind shear, and bottom drag (WINANT, 1980; WINANT and BEARDSLEY, 1979). The increased drag of vegetation in river channels can radically slow river currents (SELLIN, 1968); the added drag of a kelp forest should similarly slow ocean currents.

METHODS

We compared currents within the kelp forest at a station 14.0 m deep with those at a sandy, kelp-free area 15.5 m deep, 8.3 km north of the kelp site (all depths are relative to mean lower

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low water—MLLW). Because previous work has shown that depth is the dominant factor determining differences in coastal currents, the kelp-free area acted as a control. We used vector measuring current meters (VMCM) which recorded northward and eastward currents as well as temperature at 4-min intervals (WELLER and DAVIS, 1980). Instruments were in place for 10 days during February 1981. Three meters at each location were spread vertically through the water column in a taut-line mooring. Current measurements at the kelp station were stopped by kelp fouling during the last 3 days of the deployment.

RESULTS

Long-term currents in the kelp stand are low (Fig. 1). Longshore currents averaged over a week are on the order of 1 cm s^{-1} . Water flowing through the 7-km long kelp stand at Pt. Loma will spend more than a week before exiting. This residence time is long compared to characteristic times for nitrate uptake by kelp (4 h) (JACKSON, 1980), phytoplankton doubling (2 days; R. W. EPPLEY, personal communication), and some larval development times (5 days or less; JACKSON and STRATHMAN, 1981). Other processes, including tidal exchange and turbulent diffusion, could decrease water residence times by increasing cross-shore exchange. Tidal excursions can be expected to be fairly small, on the order of 150 m cross-shore.

Longshore r.m.s. (root-mean-square) velocities in the kelp bed were between 0.43 and 0.54 of r.m.s. velocities at the comparable control meter during this deployment; ratios of cross-shore r.m.s. velocities were between 0.30 and 0.44; ratios of temperature standard deviations range between 0.68 and 0.78. A power spectral decomposition of the current records shows that the semi-diurnal tidal component is dampened less than those of other frequencies (Fig. 2). The kelp forest greatly influences the distribution of these three physical properties. Changes in temperature variability are associated with decreased internal wave activity; changes in power spectra are associated with decreased currents.

DISCUSSION

The drag of the kelp can be compared to that of a non-kelp area. Drag at high Reynold's number is given by $D = C_D \rho u^2 dl$, where D is drag per plant, l is plant length (here the depth of the water, 1500 cm), ρ is the density of seawater (about 1.03 g cm^{-3}), d is the diameter of the stipe bundle (about 20 cm), C_D is the drag coefficient (about 0.5 for flow perpendicular to a cylinder), and u is the velocity (BATCHELOR, 1967). At a plant density, σ , of 0.1 plants per m^2 , $\text{drag/area} = 0.15 u^2$ (cgs). A comparable value for non-kelp bottom drag is 10^{-3} to $10^{-2} u^2$ (WINANT and BEARDSLEY, 1979). The drag in a kelp forest is a factor of about 10 greater than that of a non-kelp area. If coastal currents are a balance between pressure gradients and drag, and if pressure gradients are on average the same at different locations, currents in kelp-free areas will be $10^{1/2} \sim 3$ times greater than those in the kelp stand. This difference is comparable to observed velocity differences. (This is an admittedly simplistic view of kelp drag. The change of angle between a plant and the current as high velocity pulls the plant under will change the drag.)

The distance over which a longshore current makes the transition to kelp bed flow upon encountering a kelp stand can be estimated by arguing that in this transition region advected momentum balances drag. That is,

$$u \frac{\partial u}{\partial x} = -(C_D d \sigma) u^2.$$

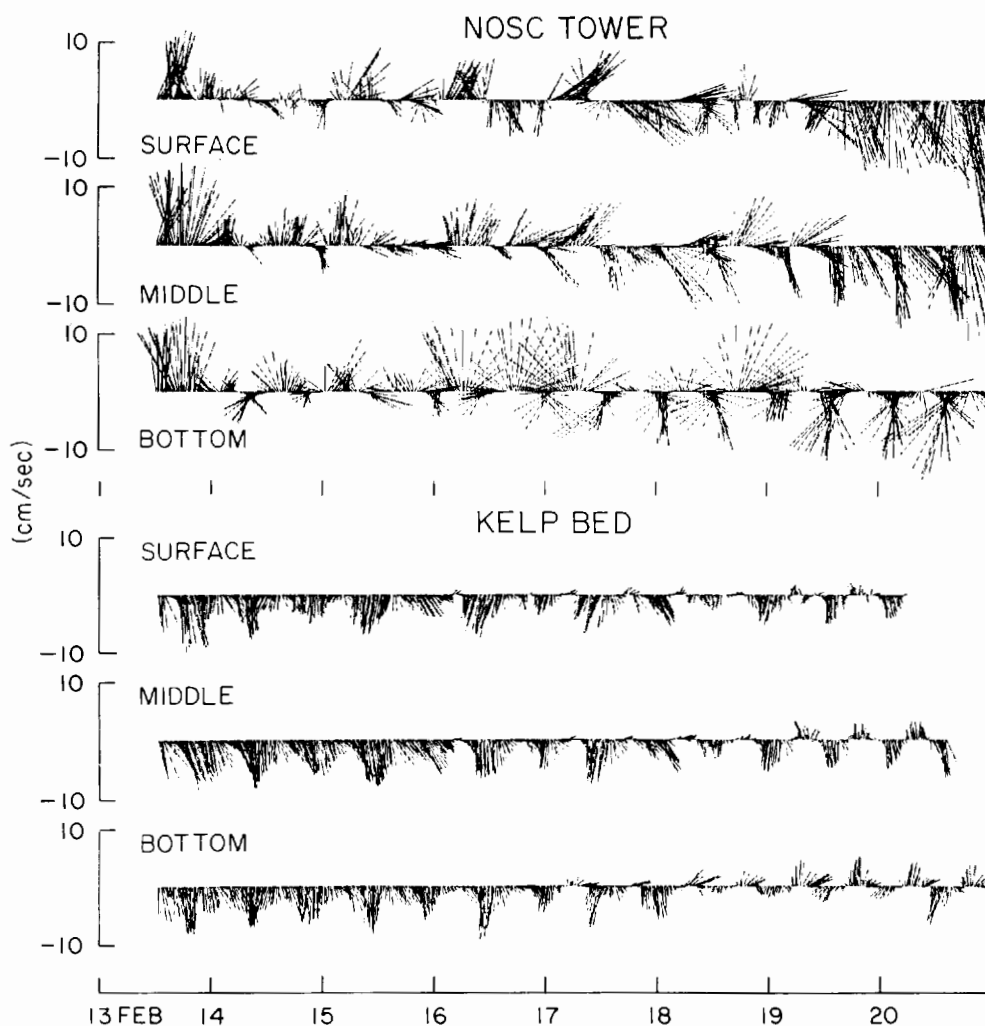


Fig. 1. Currents in a kelp bed and in comparable kelp-free area (NOSC tower). Currents are plotted in the 'broken-stick' style where each line segment is the 20-min average horizontal current vector. The Y -coordinate of the vector represents longshore direction; X -coordinate, the cross-shore. At the NOSC tower depths relative to MLLW were: bottom, 15.5 m; top meter, 4.9 m; middle meter, 8.5 m; bottom meter, 12.2 m. At the kelp station depths were: bottom, 14.0 m; top meter, 4.0 m; middle meter, 7.3 m; bottom meter, 10.7 m. Note the greater vertical coherence in the kelp. The difference in direction of low-frequency flow between the two locations is consistent with the coherence length scales for the southern California shelf. For intermediate frequencies (0.12 to 1.0 cpd) the correlation coefficient at 8 km is only 0.3 (WINANT, 1983). Distance between the two locations here was 8.3 km.

The solution of this equation is $u = u_0 \exp(-(C_D d \sigma)x)$. The scale length for this transition is $(C_D d \sigma)^{-1}$, about 100 m for the Pt. Loma kelp stand.

We estimated the barotropic currents as the average of the three meters at each site, kelp stand, and kelp-free NOSC tower area. We defined baroclinic currents as the difference between this vertical average and the actual current at the meter. Currents at the two locations had different patterns. Low-frequency longshore modes were the only barotropic

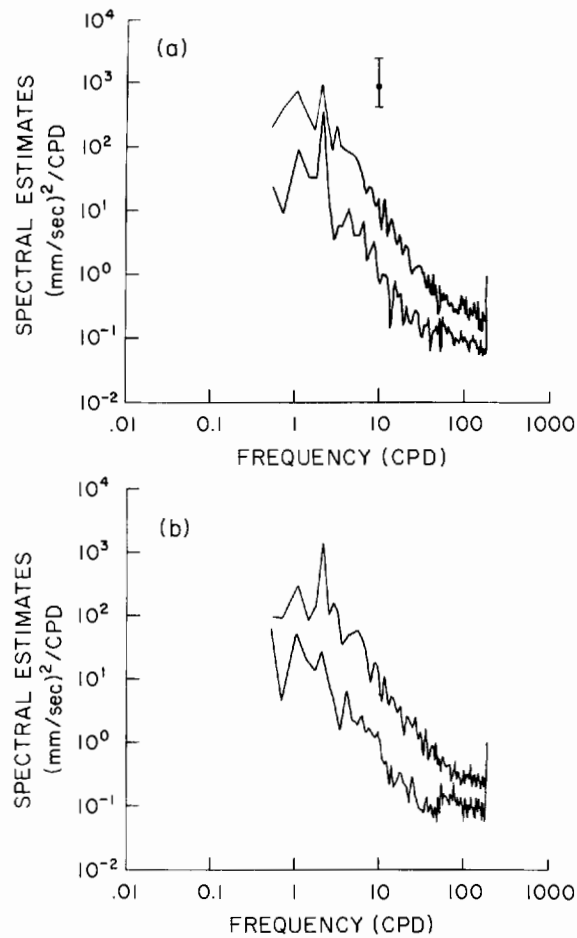


Fig. 2. Power spectra for longshore (a) and cross-shore (b) currents of top meters in kelp and in non-kelp control (NOSC tower). Time series were linear detrended and cosine tapered. Resulting spectra have been band averaged. Error bar in (a) represents the 95% confidence limits on the random error for semi-diurnal peak; bias error caused by averaging over the peak is not included (BENDAT and PIERSOL, 1971). Upper line in either figure is the spectrum for NOSC tower; lower line is for the kelp station.

motions more energetic than baroclinic at the NOSC tower; baroclinic modes dominated. In the kelp, however, the only baroclinic modes that were more energetic than the barotropic were those cross-shore motions with frequency higher than 3 d^{-1} . These motions are in the internal wave band. Thus, currents in the kelp bed are fairly uniform vertically, having less shear than currents outside the bed.

The picture that emerges of kelp bed flow from our study is of fairly stagnant water in the interior, with net water flow parallel to shore 1 to 3 km a day or less. Semi-diurnal motions slosh water back and forth between 0.5 to 1 km every 12 h. Water motion is strongest on the edges. Most of an energetic longshore current upon encountering a kelp stand will flow around it, moving to the outside. Water entering the kelp will slow to kelp bed velocities within 100 m. On the outside edge of the kelp stand there will be some exchange of waters, facilitated

by both barotropic and internal wave motions. Internal waves, with frequencies of 3 d^{-1} and velocities of 1 cm s^{-1} will move water inward for half a cycle ($1/6$ of a day) a distance of 150 m. Barotropic motions could move it further.

Changes that a kelp forest makes on coastal currents have profound effects on the kelp ecosystem because the bed is intimately connected with its surrounding waters. The sea is the source of nutrients for plants, planktonic food for fishes and filter feeders, and planktonic larvae for a range of animals inhabiting the forest; the sea is the sink for internally-spawned larvae and storm-detached plants. Water flowing alongshore over a sandy bottom will, upon meeting a kelp forest, flow around it or slow down and flow through it. Although we do not know the exact flow field, kelp plants on the outside edge should be in faster flowing water than those on the interior. Interior areas will see water that has already had time to interact with the kelp ecosystem. Larger forest size and higher plant density increase the time before water reaches the interior plant from outside. Nutrient uptake, fish feeding on zooplankton, and larval settlement can be expected, and occasionally have been observed to be, greater near the kelp forest perimeter (JACKSON, 1977; BRAY, 1981; BERNSTEIN and JUNG, 1979; TEGNER and DAYTON, 1981). Slower water velocities can also decrease the intensity of boundary layer phenomena, such as nutrient transport to an individual kelp blade (WHEELER, 1980).

Decreased exchange between ocean and kelp ecosystems could also make the kelp ecosystem self-sufficient. Slower currents would allow an increased chance for planktonic larvae to develop wholly within the ecosystem, nutrients to recycle internally, and plankton populations to exist solely within. The low net longshore currents in the Pt. Loma kelp forest during a different deployment gave a calculated residence time as long as 7 days.

CONCLUSION

The kelp forest physical regime is important, as is that of a terrestrial forest, because it controls the movement of ecologically important, water-borne substances into the kelp bed and determines their movement within. Differences between the terrestrial and the marine include differences in driving mechanisms and in ecological interactions. Both systems affect their physical regimes.

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