

Reports

Solar Ultraviolet Radiation and Coral Reef Epifauna

Abstract. Many "shade-loving" reef organisms show adverse effects when irradiated with full natural sunlight but not if radiation shorter than 400 nanometers is screened out. Shortwave solar radiation appears to be an important physical factor controlling the biology of shallow tropical benthic marine communities.

Ultraviolet radiation (UV) is harmful to many forms of life (1). The amount of UV reaching the surface of the ocean increases with decreasing latitude (2). Failure to recognize the significance of this factor on low-latitude coral reef ecosystems probably is due to difficulties in measurement and the widespread misconception that water readily absorbs short wavelength radiation. Actually, UV penetrates clear ocean water nearly as well as visible light (3). Absorption of UV is caused by dissolved and particulate organic material which is deficient in the exceptionally clear water characteristic of tropical oceans.

Shallow coral reefs typically have a depauperate epifauna (4), although photosynthetic coelenterates are well represented. The reefs of Kaneohe Bay, Hawaii, conform to this pattern, except where shaded by large piers or wharves. For example, the subtidal area under the Lilipuna Dock of the Hawaii Institute of Marine Biology is covered by tunicates, sponges, bryozoans, barnacles, oysters, and other sessile organisms that normally dominate only the deeper portions (below 5 m) of the bay. The unshaded area immediately adjacent to the pier is nearly identical with respect to substratum, water motion, depth, temperature, and water chemistry; but it is devoid of such epifauna. Midday light under the pier is only 2 percent of that measured in the adjacent unshaded area. The contrast in community structure seems to be caused by differences in incident radiation. Also, many tropical marine species die if cultured in our laboratory under full sunlight, even when all other conditions are optimal. Solar UV could be the detrimental factor involved. Simple pilot experiments designed to test this hypothesis were carried out.

The experiments were conducted in a long fiber glass aquarium (180 cm long by

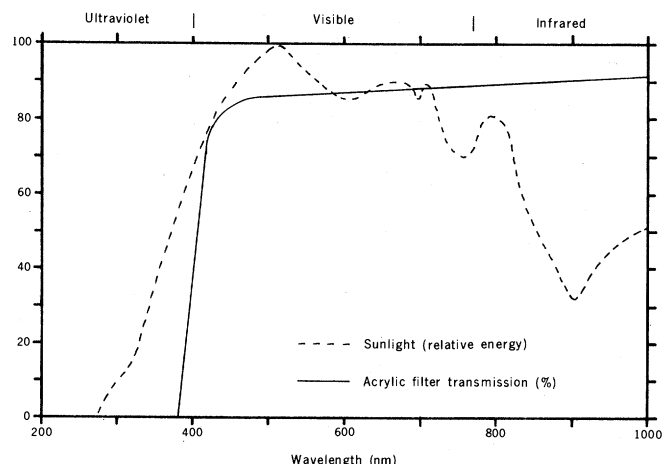
55 cm wide by 30 cm high) located in full sunlight and supplied with sediment-free seawater at a rate of 20 liter min^{-1} . The aquarium was vigorously aerated at both ends to ensure a high concentration of dissolved oxygen, adequate water motion, and thorough mixing. Temperature in the aquarium ranged between 25.5° and 26.5°C during the experimental period. One end of the aquarium was shielded from UV with 6-mm-thick transparent acrylic plastic sheet. This material was opaque to UV radiation but transmitted 90 percent of the energy at longer wavelengths (Fig. 1). The other half of the aquarium was covered with neutral density fiber glass mesh screening that transmitted 90 percent of incident energy at all wavelengths. Therefore conditions at both ends of the aquarium were nearly identical, except for lack of short wavelength radiation in the control portion. Twenty representatives of common epifaunal and cryptic species were transferred from shaded field environments. Ten were placed under the UV screen and ten under the neutral density screen. Test animals were positioned at 20 cm beneath the water surface. Obser-

vations of moribundity and mortality were made at 24-hour intervals. The initial experiments were conducted between 22 May and 10 June 1979. Daily solar energy was measured with an integrating Eppley pyrheliometer. Mean solar input was 479 $\text{cal cm}^{-2} \text{ day}^{-1}$ (range, 212 to 590; standard deviation, ± 95).

Response of the representative "shade-loving" species was dramatic (Table 1). The most sensitive sponges, bryozoans, and tunicates were killed by 1 to 2 days of UV exposure. Damage to more resistant species was observed within the first few days. In some cases the dead tissues appeared to protect the living underlying tissues. Eventually the necrotic tissues were sloughed off, exposing underlying tissues to further UV damage. The bryozoan (*Schizoporella unicornis*) showed a limited ability to tolerate UV irradiation. This species inhabits shallower and more exposed locations than its extremely sensitive counterparts. In all cases, the control specimens remained in good condition.

Many of the epifaunal species occurring in deep water or under shaded piers or ledges live as cryptofauna in environments exposed to high solar radiation. The underside of rubble on reef flats is usually covered by such organisms. Flat rocks were transferred from the reef into the aquarium and placed in an overturned position to expose the cryptofauna to the experimental sunlight regimes. The numerous species of sponges, encrusting bryozoans, and tunicates died rapidly. Approximately 80 percent of the coverage was eliminated by UV within 3 days; no changes were observed on overturned material maintained in the control portion of the aquarium. The black encrusting sponge *Chondrosia chucalla* was the only common cryptic species that withstood the UV treatment. It is an atypical sponge that

Fig. 1. Spectral transmission curve for the acrylic filter material (solid line) as measured with a Beckman DBG spectrophotometer. A typical relative spectral energy curve for sunlight (5) is included (broken line).



completely lacks protective spicules. This species is exceptional because it appears to be limited by fish predation. This sponge can extend growth onto exposed areas when predation is absent.

The photoadaptive capacity of the highly sensitive sponge *Mycale cecilia* was tested to ascertain whether UV-sensitive marine organisms adapt to gradually increasing levels of solar radiation. Ten rocks completely covered by *M. cecilia* were maintained in darkness as a control while ten others were exposed to gradually increasing levels of solar radiation. Attenuation of solar radiation was regulated with neutral density mesh screening. During the first 5-day period, the sponges were held in darkness followed by a 5-day period at 5 percent of ambient sunlight, then 5 days at 18 percent, 5 days at 50 percent, 5 days at 75 percent, and finally full sunlight. When the light was increased to 50 percent, the sponges became slightly discolored and showed minor areas of tissue death. These changes accelerated when the light was increased to 75 percent of ambient sunlight. By day 3 of treatment four of the ten colonies were severely damaged and the remainder showed conspicuous tissue loss. At the end of 5 days, all ten were damaged with only about half of the original tissue remaining on the upper surfaces of the rocks. Light was increased to the 100 percent

level, and the ten dark-held control sponges were added to the full sunlight aquarium. The sponge tissue on the dark-held controls was still healthy and intact. Both the acclimated and non-acclimated sponges died back rapidly when exposed to full solar radiation. Little living tissue remained on the upper surfaces of the rocks after 2 days of exposure. Acclimation appeared to have no effect. Sponge tissue encrusting the undersides of all 20 rocks was shielded from solar radiation and showed no adverse effects. This provided an additional control on the experiment. These results are in agreement with the laboratory observation that shade-loving organisms will never extend growth into high light even if substratum is suitable and competitors and predators are excluded. In nature, these organisms live under rocks or in deep low light environments and cannot be found in high light areas no matter what other conditions are prevalent.

Avoidance, then, appears to be an important UV defense mechanism for many coral reef organisms. Cryptic, infaunal, and deep living species are shielded from UV. Animals living in shells or tubes also are protected, although the newly settled life stages of these organisms might be extremely vulnerable. High substratum surface relief is known to enhance recruitment and development of tropical epifauna (6). The

cryptic areas might provide UV protection for larvae in addition to providing a refuge from predation.

Certain species are adapted to deal with high levels of UV exposure. For example, the solitary tunicate *Ascidia interrupta* contains a dense black pigment that probably acts as a UV absorber (7). This species is common in high light environments where the translucent counterpart *Ciona intestinalis* does not occur. The UV-tolerant equivalent of the encrusting sponge *Mycale cecilia* in Kaneohe Bay is *Tedania ignis*. Superficially both are identical. The branching sponge *Callyspongia diffusa* replaces *Zygomycalc parishi* on shallow (less than 3 m) reefs in Kaneohe Bay and thrives in shallow aquariums in full sunlight. *Callyspongia diffusa* contains a rich violet pigment that probably reflects harmful UV. It is excluded from habitats occupied by the UV-intolerant sponge *Z. parishi*. One might suspect that the metabolic burden of maintaining enzyme systems required for UV protection would reduce growth and reproductive potential. This in turn could place the organisms at a competitive disadvantage in crowded shaded habitats. A selective advantage of UV tolerance might be the avoidance of competition for space.

This possibility was investigated. Branches of the UV-sensitive sponge *Z. parishi* were tied to plastic plates in contact with branches of the UV-tolerant sponge *C. diffusa* and subjected to the experimental light regimes. Each clone combination was done in duplicate to allow a paired comparison test. One of each pairing was placed in the full UV portion of the aquarium while the second was placed in the section shielded from UV radiation. Ten parabioses were placed in each treatment. Thin sheets of *Z. parishi* tissue rapidly grew over the adjacent *C. diffusa* branches in the treatment lacking UV. *Callyspongia diffusa* is a weak competitor and did not overgrow the *Z. parishi* in either treatment. After 7 days the maximum extension of *Z. parishi* tissue over the *C. diffusa* branch was measured for each of the ten pairings exposed to UV and the ten control pairings. The median *Z. parishi* overgrowth in the ten parabioses exposed to UV was only 1 mm (range, 0 to 2 mm) compared to a median of 7 mm (range, 0 to 10 mm) for the treatment shielded from UV. The observed difference is significant ($P < .01$) by the nonparametric Wilcoxon paired-sample test (8). The *Z. parishi* showed tissue damage on all surfaces exposed to UV but formed new growth into areas of shade caused by adjacent *C. diffusa* branches. The *C. dif-*

Table 1. Response of representative epifaunal species to natural solar ultraviolet irradiation.

Exposure (days)	Response
<i>Mycale cecilia</i> (encrusting sponge)	
1	Discoloration and slight necrosis in all ten specimens.
2	All ten dead, no apparent changes in ten control sponges.
<i>Zygomycalc parishi</i> (branching sponge)	
1	Discoloration (bleaching) of exposed upper surfaces.
2	Loss of tissue on upper surface of all ten sponges; spongin skeleton exposed.
4	All ten UV-irradiated sponges extensively damaged; some living tissue remains deep in spongin network where it is shielded from UV. Controls undamaged. Some living tissue persisted within spongin skeleton for several weeks.
<i>Ciona intestinalis</i> (large translucent solitary tunicate)	
3	First visible damage, three UV-irradiated tunicates sloughing dead tissues from exposed surfaces.
4	One tunicate dead; nine heavily damaged.
6	Four dead; remainder in very poor condition.
9	Six dead; four dying.
13	Ten dead; ten controls in good condition but have developed slight pigmentation.
<i>Didemnum candidum</i> (white colonial tunicate)	
1	Exposed portions of UV-irradiated colonies dying.
2	Five colonies dead, five damaged.
4	All ten colonies dead; controls in good condition.
<i>Schizoporella unicornis</i> (black branching bryozoan)	
4	Polypides on exposed surfaces contracted; loss of coloration; many areas deteriorating.
8	Surfaces exposed to UV are dead.
14	All ten UV-irradiated colonies are damaged but living polypides remain in cryptic areas of colony. All controls in good condition.

fusa was not visibly effected by conditions in either treatment. Overgrowth by *Z. parishii* continued in the treatment without UV and smothered the *C. dif-fusa* within 2 months. *Callyspongia dif-fusa* in the treatment with UV remained healthy.

Photosynthetic reef organisms require light and cannot avoid the associated harmful UV. Corals and other marine photosynthetic plant-animal associations can produce pigments that selectively absorb, reflect, or harmlessly fluoresce UV radiation (9). The ability of these animals to shield their contained algae from UV could be important in the success of symbioses on shallow reefs. Certain species of benthic algae are known to contain UV-absorbing substances (10), but the overall impact of UV on reef productivity and calcification is unknown.

The dramatic effects observed in this preliminary investigation demonstrate that UV can be an important physical factor on coral reefs. Ultraviolet radiation levels covary with other depth-related environmental parameters. Consequently, effects of UV appear to have been confused with effects of water motion, sedimentation, abrasion, desiccation at low tide, algal competition, predation, or other factors.

Experiments analogous to those discussed in this report have been carried out with very similar results. When rubble is overturned on reef shallows the crypto fauna is quickly destroyed (4). This was believed to result solely from predation and sedimentation. Sponges grow more rapidly in situ when shielded by transparent acrylic plastic, but again the effect was attributed to reduced sedimentation rather than reduced UV dosage (11). Hawaii (21°N) is near the extreme northern latitudinal limit of reef development. The effects noted in these experiments probably are much more severe on reefs closer to the equator where incident UV is greater. Intensity of UV diminishes with increasing depth, but subtle UV effects can be expected in the deeper portions of the photic zone. Thus UV is a niche dimension that must be carefully evaluated in future research.

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Fallout Plutonium in an Alkaline, Saline Lake

Abstract. *Plutonium isotopes, derived from global fallout following atmospheric testing of nuclear weapons, have been measured in the water and sediments of a natural alkaline, saline lake. The activities of fallout plutonium in the water column are about two orders of magnitude greater than in most freshwater lakes, where these nuclides are found predominantly in the sediments.*

Measurements of radionuclides can provide valuable information about many types of chemical, biological, and physical processes in aqueous systems. Such information is useful in helping us to understand the behavior of unperturbed natural waters and in predicting the fate of materials which may reach ground and surface waters as a result of man's activities. Plutonium is relatively reactive in natural waters, and in most lakes, rivers, estuaries, and coastal ocean waters fallout plutonium is found predominantly in association with particles. The most frequently observed value of the apparent distribution coefficient, K_d (1), for fallout plutonium in lakes, rivers, estuaries, and coastal waters is $\sim 10^5$ (2), and in a water body such as Lake Michigan about 97 percent of the total activity is found in the sediments.

We have analyzed samples of water and sediment from Mono Lake, a natural closed-basin (3) alkaline, saline lake in California, for fallout plutonium isotopes. The concentrations in the water

column are about two orders of magnitude greater than usually observed for surface waters and the K_d between sediments and water is $\sim 10^3$, about two orders of magnitude lower than generally found for surface waters. Our original purpose in measuring the present distribution of fallout plutonium in Mono Lake was to explore the possibility that CO_3^{2-} complexing could be an important factor governing the amount of plutonium in the aqueous phase of natural water systems, as appears to be the case for uranium (4). The evidence reported here tends to support such a hypothesis but is not sufficient to prove the importance of CO_3^{2-} complexing of plutonium. Other factors such as the oxidation state of plutonium (5) are probably also quite important in controlling the effective solubility of plutonium in natural waters. Laboratory experiments carried out with sediments from a pond contaminated with wastes from the Rocky Flats Plant in Colorado indicate increased mobility of plutonium at high pH, but the solution properties regulating the release were not established (6). On the basis of our data for Mono Lake and data from other studies, some of which are referred to above, it seems reasonable to suggest that plutonium can be substantially more mobile in natural waters than was generally accepted only a few years ago. This finding has important implications for management policies related to plutonium in surface waters and in the evaluation of alternatives for radionuclide waste isolation (7). There is a clear need to improve the general understanding of the factors that control the mobility of plutonium and other radionuclides in natural water systems.

Mono Lake is located in a closed structural depression at the base of the

Table 1. Fallout plutonium activity in Mono Lake water. All activities reported are for whole water samples. The activities of $^{239, 240}\text{Pu}$ published for Lake Michigan (~ 0.5 pCi/m³), Lake Ontario (~ 0.3 pCi/m³), Hudson River estuary (~ 0.3 pCi/m³), and New York Bight (~ 0.7 pCi/m³) are much lower (2).

Volume (liters)	$^{239, 240}\text{Pu}$ (pCi/m ³)	^{238}Pu (pCi/m ³)
80	19.5 ± 0.7	0.9 ± 0.1
80	19.0 ± 0.7	0.7 ± 0.1
160	19.1 ± 0.8	0.8 ± 0.1
240	22.9 ± 1.6	1.3 ± 0.3
240*	$\geq (16.4 \pm 0.8)$	$\geq (0.5 \pm 0.9)$
240*	$\geq (11.1 \pm 0.7)$	$\geq (0.5 \pm 0.1)$

*Data reported represent minimum values only for these samples.