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DEPARTMENT OF ENERGY AND ENVIRONMENT

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ABSTRACT

One of the major environmental consequences of Ocean Thermal Energy Conversion (OTEC) plants may be the artificial upwelling of nutrients to the surface waters of oligotrophic ecosystems. Within a 10 km^2 area, OTEC plants of 1000 MWe total capacity could upwell the same amount of nutrients as occurs naturally off Peru each day. The biological response to possible eutrophication by OTEC plants may not be similar to that within coastal upwelling ecosystems, however. Upwelling in offshore oceanic systems does not lead to increased primary production despite high nutrient content of the euphotic zone. Continuous grazing may not allow phytoplankton blooms to develop in oceanic upwelling systems similar to the proposed OTEC sites. At present this is a hypothesis to be tested before full evaluation of OTEC induced upwelling can be made.

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The potential exists for future commercial development and deployment of Ocean Thermal Energy Conversion (OTEC) plants to generate electricity in the sub-tropical regions of the world ocean. The concept of pumping deep cold water to the warm surface of the sub-tropical ocean, thence using the temperature differential to condense and vaporize a working fluid, in order to turn turbines generating electrical power is not a new idea (d'Arsonval, 1881; Claude, 1930). Over 50 years ago, Georges Claude built a pilot plant in Cuba (Othmer and Roels, 1973), but commercialization did not occur. Continuing societal needs for increasing amounts of energy and for alternatives to consumption of fossil fuel now suggest that OTEC may be a possible power source for populations located in the sub-tropics, i.e. Hawaii, Puerto Rico, and along the Gulf of Mexico. The potential environmental impacts of such power plants in the form of biocides, entrainment, and thermal shock can be somewhat approximated by analogy to results from research conducted on coastal power plants. The effects of artificial upwelling by OTEC plants are relatively unknown, however, because none of the proposed large-scale OTEC structures are operational and little research has been conducted on the consequences of natural upwelling within oligotrophic marine ecosystems.

Small organisms characterize tropical oligotrophic (nutrient poor) ocean environments, where the annual temperature variation is less than 5°C and small food particles are most efficiently removed by small feeders (Sheldon et al, 1973). The large zooplankton are usually omnivores or predators as part of a long food chain which depend on the availability of the smaller zooplankton. These small phyto- and zooplankton and the high temperatures imply short life times, i.e. rapid turnover. Furthermore, most of these organisms cannot store energy as compared to animals from temperate zones, suggesting that food supply has to be virtually continuous for the survival of most tropical zooplankton. The rates of life processes and element cycling (McCarthy and Goldman, 1979) are very rapid compared to vertical loss rates by sinking. This means that the ecosystem is very nearly "closed" and in a steady state of production balanced by consumption, with the small primary production driven by recycling of nitrogen from excretion of zooplankton and fish.

In contrast, coastal ecosystems yield 99% of the global fish catch because of their high primary production and relatively short food chains. Seasonal wind mixing and tidal stirring are able to reach decomposing organic matter on the shelf bottom (<200 m depth), with consequent rapid return of nutrients to the euphotic zone. In contrast, the permanent pycnocline of the deep ocean inhibits fast return of nutrients to the water column, except for seasonal overturn (Menzel and Ryther, 1960; 1961), and tidal mixing is negligible such that the open ocean usually has a daily primary production (0.1-0.5 g C m^{-2} day^{-1}) which is over an order of magnitude less than that (1-10 g C m^{-2} day^{-1}) of shelf waters (Walsh, 1976). In some shelf areas, the annual production is also higher than other coastal regions as a result of additional input of nutrients from upwelling of water induced by favorable winds throughout the year.

Wind events are an important source of habitat variability on the continental shelf in contrast to the open ocean (Walsh, 1976; Beardsley et al., 1976) and are responsible for both the generation of currents and for vertical overturn of the water column by seasonal mixing. Because of the north-south alignment of the North American continent, for example, a southerly wind tends to favor offshore surface flow as a result of the Coriolis force acting upon the wind-accelerated fluid off the east coast of the United States (i.e. to the right in the northern hemisphere) in contrast to the same phenomenon induced by a northerly wind on the west coast. Nutrient rich, cold subsurface water then moves onshore and upwells at the coast to replace the warmer, nutrient impoverished surface water transported offshore by these winds favorable to upwelling (Walsh, 1975). Coastal upwelling is a boundary process and most of the water is upwelled within a zone only 10-20 km from the coast, with offshore secondary cross-shelf flows set up as a function of the shelf width (Walsh, 1977). Most of the major coastal upwelling areas are located on the west coasts of the continents, eg. associated with eastern boundary currents off Oregon-California, Peru-Chile, Northwest Africa and Southwest Africa, with the exception of the monsoon-induced upwelling ecosystem found off the Somali Coast.

Differences in terminal yield of fish and in offshore nutrient gradients within these eastern boundary currents can be related to both the seasonal variability of upwelling (Walsh, 1976) and effects of bottom topography. Greater intermittency of wind stress and lower potential yield (Walsh, 1972) of these systems are both associated with increasing latitude. The estimated annual primary production also declines with latitude from as much as ca. 1,000 g C m^{-2} yr^{-1} off Peru (15°S) and ca. 600 off Baja California (27°N) to ca. 200 off Oregon (45°N), reflecting differences in the seasonal duration of light and upwelling within those regions. The range in observed daily production at about the same latitude and at the same time of year between the Pacific (ca. 4-6 g C m^{-2} day^{-1} at 27°N) and the Atlantic (ca. 1-2 g C m^{-2} day^{-1} at 22°N) coastal upwelling ecosystems instead reflects shelf width.

As a result of upwelling and/or vertical mixing induced by the equatorial undercurrents, high nutrients ($\sim$10 μg-at NO_3 ℓ^{-1}) are also found in surface water along the equator in the deep Pacific (Walsh, 1976) and the Atlantic (Voituriez and Herbland, 1979) oceans. In fact, the horizontal nutrient gradient from 10 to 0.5 μg-at NO_3 ℓ^{-1}, north of the Pacific equatorial divergence, is at least an order of magnitude wider than that of the coastal upwelling areas. The wide northward extent of the equatorial nutrient gradient appears to be a persistent feature, analogous in origin to a spreading from a line source as far west as 119°W (Love, 1974), 140°W (Sverdrup et al., 1942), and 160°W (Cromwell, 1953; Reid, 1965), despite abundant light and a trans-Pacific trend of lower nutrients within the euphotic zone as one approaches the western boundary (Gueredrat, 1971).

Light and nutrients thus appear to be sufficient for phytoplankton growth in the equatorial divergences but the upwelled nutrients are not removed in these natural upwelling systems of offshore, oligotrophic waters. Notwithstanding suggestions of growth inhibition in this region through lack of available chelators (Barber and Ryther, 1969), the assimilation index (mg C(mg Chl a)$^{-1}$ h^{-1}), an estimate of potential growth of phytoplankton, in the equatorial divergence (Barber and Ryther, 1969) appears similar to that usuually found for organisms in both coastal upwelling systems (Barber et al., 1971; Walsh et al., 1974; Estrada, 1974) and oligotrophic gyres (Thomas, 1970a; Eppley et al., 1973). There is some argument as to whether chelators, eg. EDTA, are required by phytoplankton to 1) detoxify upwelled water by removing trace metals or 2) make available essential trace metals for growth.

However, nitrogen enrichment experiments have been performed on phytoplankton from in situ oligotrophic water in the California Current (Eppley et al., 1971) and near the equatorial divergence (Thomas, 1970b), which both gave about the same maximal algal division rate of 0.7-1.5 doublings day^{-1}, i.e. similar to those of the rich Peru and Baja California upwelling systems (Walsh, 1975; Walsh et al., 1974). Yet, a seasonal input of nitrate to surface waters of the Atlantic equatorial divergence leads to little change in primary production of the euphotic zone (Voituriez and Herbland, 1979). Analysis of variance of integrated primary production with latitude in the EASTROPAC observations (Owen and Zeitzschel, 1970) showed no significant difference in productivity along this zonal gradient of nutrients across the Pacific equatorial divergence as well.

Deep water has also been artificially upwelled from 870 m off St. Croix to provide nutrients for continuous outdoor cultures of diatoms (Malone et al., 1975). In this case, a mixture of EDTA-trace metal-vitamin supplement was added to the upwelled water, no zooplankton were initially present in the growth tanks, and a phytoplankton innoculum was introduced at the beginning of each experiment. Under conditions of presumably little trace metal toxicity, small grazing stress, and a coastal phytoplankton species rather than an oceanic community of microalgae, the nitrate content of the artificially upwelled water was depleted after 1-2 days of phytoplankton growth. These experimental results suggest that artificial upwelling can lead to eutrophication, if the surface community is displaced from the equilibrium conditions of an oligotrophic ecosystem towards the transient conditions of the coastal upwelling ecosystem (Walsh, 1976).

There thus appears to be an anomaly of natural offshore ecosystems with relatively high nutrients, high light, perhaps no intrinsic differences in potential growth among the dominant phytoplankton, and yet with evidently low phytoplankton utilization of the nutrients within oceanic upwelling areas, i.e. wider observed horizontal nutrient gradients, despite the presumably lower physical input of nutrients in these upwelling areas compared to the coastal systems (Walsh, 1976). Differential importance of herbivory in these ecosystems may explain the contrast in horizontal nutrient gradients among the types of pelagic systems, for the loss rate of a phytoplankton population may also set its growth rate.

The central biotic provinces of the oceans have been characterized as high diversity systems (Timonin, 1971) with little temporal variability of the low zooplankton standing crop of small organisms (McGowan, 1974), while the eastern boundary currents appear to have zooplankton populations of low diversity, high standing crop, large size and high variability (Longhurst, 1967; Wickett, 1967). The phytoplankton-herbivore interactions may thus be quantitatively different in the nearshore coastal upwelling areas from that of the gyres and offshore divergences, with perhaps more cropping of phytoplankton by herbivores offshore. The relative short term constancy, or seasonal predictability, of the slowly varying physical forcing functions within the offshore habitats may thus have allowed the herbivores to evolve evolutionary strategies such as seasonal migration in high latitudes to anticipate phytoplankton blooms (McAllister et al., 1960, Voronina, 1972) and speciation in low latitudes to biologically expand the number of niches in a relatively stable physical habitat with a wide diversity of herbivores to graze all size classes of phytoplankton (Sheldon et al., 1973).

The high nitrate contents of the open North Pacific ocean (Anderson and Munson, 1972) and the outer Bering Sea shelf (Coachman and Walsh, 1980) are attributed to efficient grazing by copepods with an ontogenetic migration that occurs before the bloom in contrast to shelf grazers whose cohorts develop after the spring bloom. Similarly in oceanic waters off Peru, the studies of the EASTROPAC program (Love and Allen, 1971-1975) indicate that: (1) within August surface waters there are as much as 18 to 20 μg-at NO_3 ℓ^{-1} as far as 170 km offshore; (2) there are still 14 to 16 μg-at NO_3 ℓ^{-1} in November at the same distance offshore, and (3) only 2 to 4 μg-at NO_3 ℓ^{-1} within this offshore area in February. Such a seasonal increase in the nutrient content of offshore Peruvian waters presents an apparent paradox because of the lack of utilization of these nutrients by phytoplankton similar to the gradient of unused nutrients across the equatorial and Antarctic divergences (Walsh, 1976).

During August 1976, chlorophyll concentrations less than 1 μg chl a ℓ^{-1} were found offshore where as much as 7 to 8 μg-at NO_3 ℓ^{-1} were encountered. The occurrence of patches of blue water and high nutrient concentrations off Peru has been attributed to heavy grazing pressure (Strickland, Eppley and DeMendiola, 1969; Ryther, Menzel, Hulburt, Lorenzen and Corwin, 1971). Based on measurements of zooplankton excretion and biomass (Walsh et al., 1979) the estimated ingestion flux of all size classes of zooplankton amounted to 0.60 g C m^{-2} day^{-1}, or 69% of the August 1976 offshore primary production (0.87 g C m^{-2} day^{-1}), in contrast to an ingestion flux of 1.05 g C m^{-2} day^{-1}, or 32% of the nearshore Peru production (3.22 g C m^{-2} day^{-1}).

One commercial Ocean Thermal Energy Conversion (OTEC) plant of 400 MWe capacity, about half that of the Three Mile Island nuclear plant, might have a sea water flow-through of $\sim 2.8 \times 10^8$

m^3 day^{-1} (Lockheed, 1975). Assuming an equal mixture of cold water from 1000 m and warm water from 0-30 m, nutrient rich source water (~30 mg-at NO_3 m^{-3}) would be artificially upwelled at a rate of ~1.4 x 10^8 m^3 day^{-1} or ~.14 km^3 day^{-1}. If this nitrate flux of 4.2 x 10^9 mg-at NO_3 day^{-1} were discharged by the OTEC plant over a 11 km^2 area of all of the upper 200 m of an ocean ecosystem, a daily nitrogen addition of ~2 μg-at NO_3 ℓ^{-1} day^{-1} would occur. The mean nitrate concentration of the upper 200 m of oligotrophic ocean water is now about 2 μg-at NO_3 ℓ^{-1} (Walsh, 1974). At the same time, the surface temperature of the water in the 11 km^2 around the OTEC plant would be lowered by ~1.28°C (Bathen, 1975).

In contrast, within a baroclinic radius of deformation, ~11 km off Peru, the nearshore upwelled input of nitrate into a 20 m surface Ekman layer can be estimated by the equation, $\frac{\partial NO_3}{\partial t} = \frac{w(\partial NO_3)}{\partial z}$ where w is the upwelling velocity (10 m day^{-1}), (∂NO_3) is the nitrate gradient between 15 and 25 m (5 μg-at NO_3 ℓ^{-1}), and ∂ z is 10 m (Walsh, 1975). This nitrate input of ~5 μg-at NO_3 ℓ^{-1} day^{-1} is associated with a surface temperature (~16°C) at the Peru coast which is about 3°C less than offshore waters (~19°C). Thus, the nutrient input and surface temperature decline from 2.5 OTEC plants within a 11 km^2 area might be equivalent to that of a similar area off Peru, the world's most productive coastal upwelling region (Walsh, 1974). However, the nearshore Peru upwelling zone consists of ~1 x 10^4 km^2 and 2,500 OTEC plants of 400 MWe capacity would be required to support a similar pelagic clupeid fishery; furthermore, the OTEC plants may enrich offshore ecosystems not coastal areas.

The nutrient input of the OTEC plants may be confined, however, to depths of 150-200 m, i.e. below the permanent pycnocline. For the OTEC plants to be efficient, the temperature gradient between surface and deep water has to be utilized at a maximum. This implies that recirculation of mixed water (surface and deep water) i.e. reentering of mixed discharge back into plant intake, must not be allowed, since a decrease of 1°C in the thermal gradient would result in a loss of the net power output of the OTEC plant by about 10%. Thus, a plant designed for a thermal gradient of 20°C would lose as much as 20-25% of its net power output if the thermal gradient were to be lowered to 18°C (Allender et al., 1978). For this reason, current OTEC research is emphasizing plants with combined discharge at a depth of about 150 to 200 m, and this design will be used for OTEC-1 and subsequent test platforms.

The temperature-salinity characteristics of surface and deep seawater of the tropical oceans are such that the discharge of mixed seawater is likely to remain at the depth of discharge, between 150 and 200 m. This is shown by sigma-t values estimated from the vertical distribution of temperature and salinity (Defant, 1961) for areas of the Gulf of Mexico and the Caribbean Sea. The combined surface-deep water output would remain around the depth of density equalization, below 150 m for the Gulf of Mexico and below 200 m for the Caribbean Sea. Allender et al. (1968) estimated this depth to be 216 m for the area south of Puerto Rico.

Since the depth of the mixed layer for a typical tropical ocean is less than 100 m, OTEC nutrient enrichment to most of the euphotic zone would then be limited by vertical diffusion (about 10^{-4} m^2/s), i.e. certainly much less than what is estimated above. This implies that OTEC plants, rather than being a source of upwelling, might act as a source of downwelling by sinking below the euphotic zone significant fractions of the surface zooplankton community, thereby decreasing the ambient grazing stress of the offshore oligotrophic ecosystems. If all of the OTEC nutrient supply is not being used (because of quasi-continuous grazing pressure), introduction of a time lag (i.e. removal of the grazers) might result in increased nutrient utilization, higher primary productivity, and perhaps higher terminal yield of ambient fish populations. There has been much discussion of the fragility of tropical terrestrial ecosystems in response to human perturbations (Ferri, 1974), however. It is possible that tropical oceanic ecosystems, with their relatively low nutrient input and low frequency of variability, may not have the resilience (Holling, 1973) to respond to such perturbations of the plankton communities, for these organisms are not usually subject to the same high frequency fluctuations as those of the eastern boundary currents.

A comparative analysis of marine ecosystems in coastal and offshore divergences, suggests that natural experiments have already been performed, on an evolutionary scale, along gradients of the factors controlling nutrient utilization in the sea. The importance of any one factor such as nutrient limitation or herbivory depends on the spatial and temporal scales of habitat variability characterizing the ecosystem. Further evaluation of OTEC environmental consequences will thus have to await information on the rate processes of the plankton communities at prospective sites. Appropriate time series now need to be taken with respect to the life cycle of the important organisms of the oligotrophic ecosystem.

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