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OCEAN THERMAL ENERGY CONVERSION POWER PLANTS:
MY ROLE IN THE NOAA-NMFS PRELIMINARY FISHERY IMPACTS STUDY

by

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Internship Report

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Finally, my love and gratitude to my wife, Robin, for the faith and support without which this whole crazy undertaking would not have been possible.

And (with thanks to Patricia Tester) a word of encouragement to my colleagues in the MRM program:

Nothing in the world can take the place of persistence.

Talent will not; nothing is more common than unsuccessful men with talent.

Genius will not; unrewarded genius is almost a proverb.

Education will not; the world is full of educated derelicts.

Persistence and determination alone are omnipotent.

- C. Coolidge

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INTRODUCTION

From July, 1982 to August, 1983 I had the privilege of serving an internship as an oceanographer at the National Marine Fisheries Service Beaufort Laboratory. During the period of my appointment I assisted in a preliminary assessment of the potential fishery impacts of ocean thermal energy conversion (OTEC) power plants. This report serves as summary account of that internship.

This report has been divided into a number of parts. It begins with an introduction to ocean thermal energy conversion and OTEC power system technology. These sections are the basis for a discussion of the reasons for concern over the potential environmental impacts of OTEC operations, which is followed by a brief examination of those provisions of the Ocean Thermal Energy Conversion Act of 1980 which were intended to protect marine resources from excessive impacts. This section is, in turn, followed by a description of my role in the study, and a discussion of some of the difficulties that I faced during my internship. The report concludes with a description of the methods used and the difficulties faced in the most frustrating and yet most fascinating part of my duties: the locating of data in the literature.

Three appendices have also been included. The first is a list of the reports produced as part of the study in which I took part. The second is a copy of the characterization of potential OTEC sites in the Caribbean which I drafted and co-edited. This is followed by a short, in-house report on ciguatera fish poisoning which I authored.

AN INTRODUCTION TO OTEC

Ocean thermal energy conversion (OTEC) is a method of producing electricity from the temperature difference between the warm surface waters present in tropical and sub-tropical oceans and the much colder water present in the ocean depths. As such, it can be considered a solar energy technology, with the ocean surface serving as the solar collector.

For an OTEC plant to be economically feasible a temperature difference of approximately 20°C is needed. A temperature difference of this magnitude is available between the surface water and that at a depth of 1000 m at most sites within 20° of the equator (NOAA, 1981; Myers et al., 1985).

Several different location and construction scenarios have been proposed for OTEC plants. A plant could be land-based, mounted on a tower on the continental shelf, moored near the shelf, or be designed as a self-propelled open ocean plantship. A land-based plant would have warm water intake, cold water intake and water discharge pipes extending offshore to the desired depths and conditions. A tower-mounted plant would be built on a platform much like an offshore oil rig. The cold water intake pipe would run down the tower to the bottom, and then continue offshore to the desired depth. A moored plant would consist of a floating platform which would be anchored in water deep enough for the cold water intake pipe to extend down to the desired depth beneath the plant. All of these designs would be connected by cables to the existing electric power grid. Open ocean plantships, on the other hand, would be large ships on which energy intensive industrial processes such as aluminum refining, ammonia production or hydrogen production would be carried out. The energy for these processes would be supplied by an onboard OTEC plant.

OTEC has several of the advantages common to other solar energy technologies. First, there are no fuel costs, which should make the technology more attractive as the price of conventional and nuclear fuels increases. Second, OTEC energy production would appear to be relatively non-polluting. OTEC also has several unique advantages over other methods of electrical power generation. Unlike most solar energy methods, OTEC plants could be used to supply power to the existing electrical grid on a continuous basis. In addition, most OTEC designs would be relatively unobtrusive; tall smokestacks, cooling towers, and large amounts of land would not be needed.

Electricity need not be the only product produced by an OTEC operation. Some designs would also produce fresh water. In addition, the cold water pumped up from the depths is rich in nutrients and could be used in some aquaculture operations. However, the OTEC principle is not without its disadvantages. Some of the characteristics of OTEC technology are cause for concern about potential environmental impacts. To understand the basis for these concerns it is first necessary to look briefly at OTEC power systems.

OTEC POWER SYSTEMS

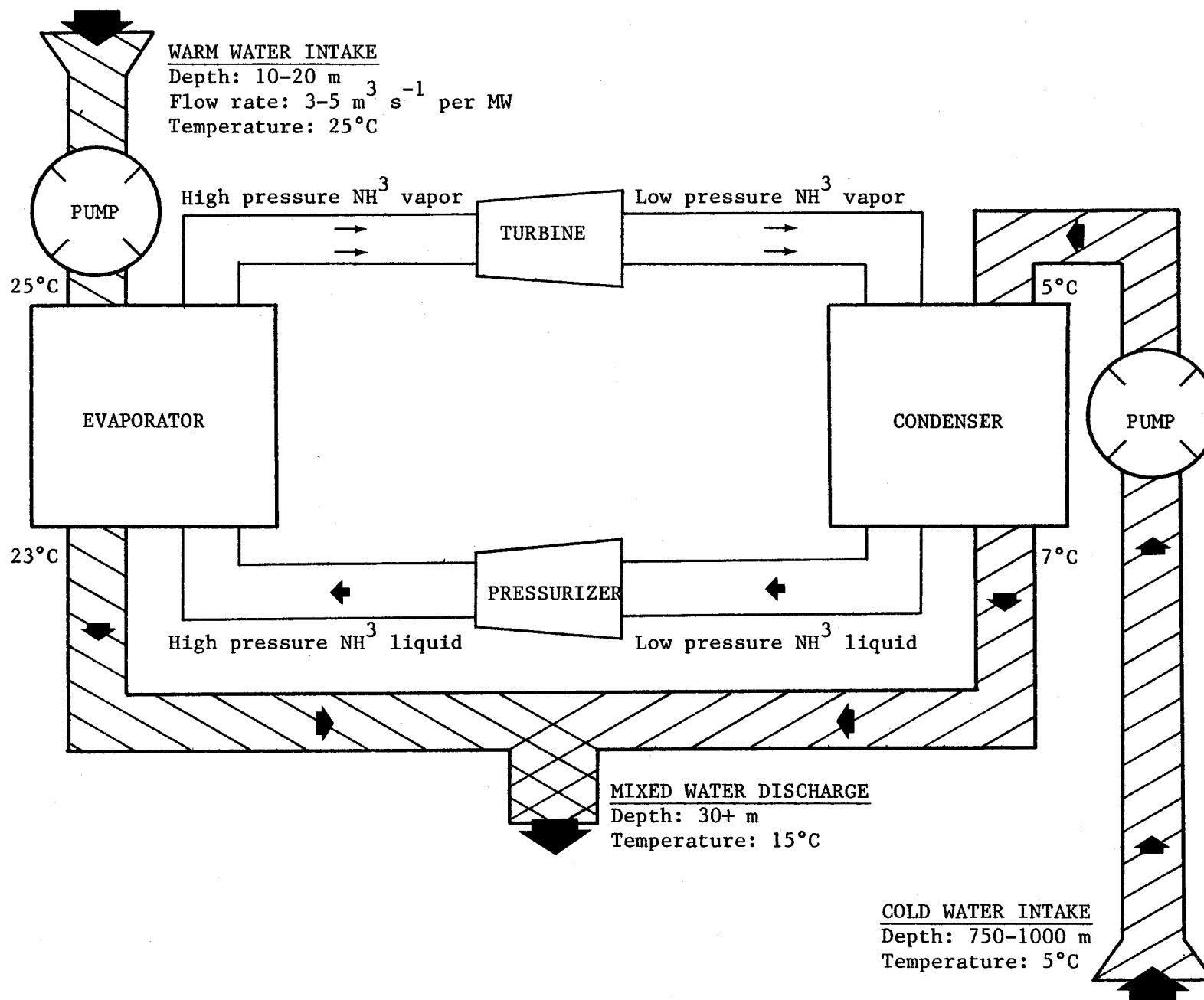
As with any other heat engine, an OTEC power plant requires a heat energy source and a heat sink. In the process of transferring heat energy from the source to the sink, some of the heat energy can be converted to other forms of energy, in this case mechanical and then electrical energy. The warm surface water serves as the heat source, while the much colder water present at great depths serves as the heat sink. Heat energy from the surface water is used to vaporize a working fluid, while the cold water is used to condense that same fluid. Although a number of different power system processes have been proposed, the two systems most likely to be employed in the near future are the closed-cycle and the open-cycle systems.

In the closed-cycle system a separate working fluid such as ammonia or Freon is pumped through a heat exchanger. Although heat exchanger design varies, it can be thought of as similar to an automobile radiator, with the working fluid passing through the tubes and the warm surface water being pumped around the tubes. Some of this working fluid evaporates as a result of the heat which is transferred to it. The vapor passes through a turbine, which drives a generator. The vapor continues on to another heat exchanger, around the tubes of which is pumped cold water, and is condensed. The condensed fluid is then pumped back to the vaporizing heat exchanger (Fig.1).

In the open-cycle system the warm water itself serves as the working fluid. This water is pumped into a chamber where, under reduced pressure, it is flash evaporated. The water vapor passes through a turbine and on to a condenser. The condenser can take one of two forms. A heat exchanger such as that in the closed-cycle system can be used; in this instance the condensed working fluid consists of fresh water. Alternatively, the vapor could be condensed with a spray or mist of cold water, thus saving the cost of the heat exchanger.

In both closed-cycle and open-cycle designs the warm water intake is expected to be placed at a depth of about 10 meters (for pilot and small-scale plants) to 20 meters (for larger commercial scale plants) (Ditmars and Myers, 1983). The cold water intake depth will be the result of a tradeoff between obtaining colder water from deeper depths, increasing the temperature difference and thus plant output, and the additional cost of the longer pipe. For most designs this intake will be at a depth of 750 to 1000 meters. Effluent water discharge outlets are expected to be at a depth of 30 m or greater, in order to prevent the discharged water from being drawn back into the warm water inlet (Ditmars and Myers, 1983).

FIGURE 1. Schematic diagram of a closed-cycle OTEC power system.
(Adapted from DOE, 1979.)



The thermal efficiency of a heat engine refers to the ratio of heat energy removed from the heat source to the total amount of heat energy contained by that source. The theoretical maximum amount of energy that can be extracted depends upon the difference in temperature between the heat source and the heat sink. In a conventional or nuclear plant the temperature difference can amount to several hundred degrees. However, due to the much smaller temperature difference of 20-25°C, the maximum thermal efficiency of an OTEC plant is much lower, on the order of 6.0-7.5%. Actual operational efficiency is expected to be less than 2.5% (Myers et al., 1985), compared to the 30% efficiency typical of a coal-fired power plant (Hagen, 1975). Because the thermal efficiency of an OTEC plant is so low (i.e., only a very small amount of energy can be extracted from each cubic meter of water), tremendous amounts of water will be used by a commercial OTEC plant.

Both warm and cold water flow rates are expected to range from 3 to 5 m³ sec⁻¹ per megawatt of electrical capacity (Ditmars and Myers, 1983). To put this into perspective, the total flow through a 100 MW commercial plant would be on the order of 800 m³ sec⁻¹. At the Trojan nuclear power facility on the Columbia River, a 1130 MW capacity facility, total water use is about 1.25 m³ sec⁻¹, while the average flow of the Columbia at that location is about 6300 m³ sec⁻¹ (PGE, 1978; in Garcia et al., 1983).

To handle such a large water flow the heat exchangers of an OTEC plant will have to be very large. Early estimates of total heat exchanger surface area ranged from 7 to 9 m² per kilowatt of electrical capacity (NOAA, 1981). Thus, the total heat exchanger surface area of a 100 MW commercial plant would be on the order of 800,000 m². Because the temperature difference between the heat source and the heat sink is so small, the heat exchangers must be kept much more free of biofouling than the exchangers in a conventional power plant.

ENVIRONMENTAL IMPACTS: THE BASIS FOR CONCERN

The degree to which the heat exchangers in an OTEC power plant must be kept free of biofouling is one basis for concern about biological impacts. Although a number of different methods of control are possible, chlorination of the intake water is the most common. Were large amounts of chlorine found to be necessary to maintain heat exchanger efficiency, the residual chlorine present in the discharge water could affect the biota in the surrounding water.

The tremendous amount of water used by an OTEC plant is the basis for concern over a number of potential effects on the organisms in the surrounding water. Among these are the impingement and entrainment of organisms in the surface waters, the secondary entrainment of organisms in the plume of discharge water, and the changes in near-surface conditions resulting from the release of large amounts of cold, deep ocean water into the near-surface water.

The water intakes of power plants are covered by screens in order to prevent the clogging of pipes in the heat exchangers by debris or organisms. Organisms which are too slow to escape the intake current and too large to pass through the screen itself are caught, or impinged, on the screen. Those organisms which are small enough to pass through the screens are entrained in the flow of water through the plant, where they may be subjected to mechanical injury (abrasion, etc.), pressure and temperature changes, and the chlorination used to control biofouling. Experience from conventional power plant operations has shown that the mortality of impinged and entrained organisms can be quite high. It has been estimated that impingement and entrainment mortality may approach 100% for OTEC operations (Sands, 1980).

As the used warm and cold water is discharged from an OTEC plant a certain amount of the surrounding water will, through turbulent mixing, become part of the discharge plume. Organisms caught in the plume in this manner are said to be secondarily entrained. These organisms could be suddenly subjected to a temperature far lower than that of the surrounding water. They would also be exposed to any residual chlorine present in the discharge water.

The simple act of pumping up large volumes of cold, deep ocean water could also have significant biological effects. This deep water would be much colder and would contain much higher nutrient and trace metal concentrations than the near-surface waters into which it would be released. In effect, an OTEC plant would represent a source of artificial upwelling, and could potentially cause changes in the primary production and species composition of the phytoplankton in the surrounding waters.

OTEC power plants would have some definite advantages over conventional or nuclear power plants. However, as shown above, it is possible that OTEC operations could have severe effects upon the biota in the surrounding waters. In 1980 Congress took steps to promote the development of this renewable energy technology, while at the same time ensuring that appropriate actions to safeguard biological resources would be taken.

THE OTEC ACT OF 1980: ENVIRONMENTAL PROTECTION PROVISIONS

The Ocean Thermal Energy Conversion Act of 1980 (P.L. 96-320, 42 USC 9101-9167) designated NOAA as the lead agency for licensing actions, and established the legal regime within which licensing of OTEC facilities would take place. Included in the Act are several provisions designed to minimize adverse impacts on the marine environment.

Section 101(c)(1) of the Act (42 USC 9111) provides that the Administrator of NOAA may not issue a license where "...he determines that the construction and operation of the ocean thermal energy conversion facility or plantship will not be in the national interest and consistent with national security and other national policy goals and objectives, including energy self-sufficiency and environmental quality;".

Section 107 of the Act provides, in part, that

(a) The Administrator shall initiate a program to assess the effects on the environment of ocean thermal energy conversion facilities and plantships. The program shall include baseline studies of locations where ocean thermal energy conversion facilities and plantships are likely to be sited or operated; and research; and monitoring of the effects of ocean thermal energy conversion facilities and plantships in actual operation. The purpose of the program will be to assess the environmental effects of individual ocean thermal energy facilities and plantships, and to assess the magnitude of any cumulative environmental effects of large numbers of ocean thermal energy facilities and plantships.

(b) The program shall be designed to determine, among other things--

(1) any short-term and long-term effects on the environment which may occur as a result of the operation of ocean thermal energy conversion facilities and plantships;

(2) the nature and magnitude of any oceanographic, atmospheric, weather, climate, or biological changes in the environment which may occur as the result of deployment of large numbers of ocean thermal energy conversion facilities and plantships;

(3) the nature and magnitude of any oceanographic, biological or other changes in the environment which may occur as a result of the operation of electric transmission cables and equipment located in the water column or on or in the seabed, including the hazards of accidentally severed cables; and

(4) whether the magnitude of one or more of the cumulative environmental effects of deployment and operation of large numbers of ocean thermal energy conversion facilities and plantships requires that an upper limit be placed on the number or total capacity of such facilities or plantships to be licensed within this Act for simultaneous operation, either overall or within specific geographic areas.

(c) Within 180 days after enactment of this Act, the Administrator shall prepare a plan to carry out the program described in subsections (a) and (b) of this section, including necessary funding levels for the next 5 fiscal years, and submit the plan to Congress.

Section 107(e) of the Act provides that licensing actions are to be considered a major Federal action for the purposes of the National Environmental Policy Act. Thus, NOAA must prepare an environmental impact statement for each licensing action that it undertakes.

In the environmental research plan required by Section 107(c), NOAA identified the prediction of potential impacts on fisheries as a high priority research area in which it believed preliminary studies could be made using information already available (NOAA, 1982, in Myers et al., 1985).

THE BEAUFORT-HONOLULU FISHERY IMPACTS STUDY

In 1983, NOAA's Office of Ocean Minerals and Energy (OME, now the Ocean Minerals and Energy Division of the Office of Ocean and Coastal Resource Management) contracted with the Beaufort, North Carolina, and Honolulu laboratories of the National Marine Fisheries Service for such a preliminary study. Dr. Edward Myers, head of the OTEC Environmental Impact Assessment program within the Office of Ocean Minerals and Energy served as Project Head. Dr. Donald Hoss and Dr. David Peters served as Principal Investigators at the Beaufort laboratory, while Mr. Richard Uchida filled that role at the Honolulu laboratory.

The end goal of this joint study was to produce a final report which would provide a detailed assessment of the potential fishery impacts of proposed OTEC operations and identify high priority research needs. The study was divided into a number of different tasks, with the reports for each of those tasks forming the groundwork for the final report. The tasks were assigned to the two laboratories according to their areas of expertise. Each lab was to prepare a summary of biological and fishery characteristics at potential near-future sites at which OTEC facilities or plantships would be

within U.S. jurisdiction, the Honolulu lab preparing a characterization of Pacific sites and the Beaufort lab preparing one for sites in the Caribbean and the Gulf of Mexico. In addition, because of its experience with fish attraction device buoys, the Honolulu lab was to prepare a report on the potential for fish attraction to OTEC plants. Personnel at the Beaufort lab had already gained considerable experience with the impingement and entrainment effects of conventional power plants, and were to prepare a report on the potential impingement and entrainment impacts of OTEC power plants. Other reports produced during the course of the study include assessments of the potential ecological effects (other than on fisheries), and a preliminary report on potential fishery impacts.

The main project report is currently in the final stages of revision and will be available shortly (E. Myers, personal communication). Full citations for all reports produced in the course of this study are given in Appendix 1.

MY ROLE IN THE FISHERY IMPACTS STUDY

From July 26, 1982 through August 12, 1983, I held the position of Oceanographer at the Beaufort laboratory, assisting in the fishery impacts study. My role in that effort can be broken down into six main tasks:

1. Identify, locate, obtain and evaluate all available oceanographic, biological and fishery data that might be needed in characterizing potential OTEC sites in the Caribbean.
2. Identify, locate, obtain and evaluate other information that might be needed for the tasks assigned to the Beaufort laboratory.
3. Maintain cross-referenced index files of the sources and information obtained above.

4. Draft the characterization of potential OTEC sites in the Caribbean and co-edit the final version of that report (included here as Appendix 2).
5. Summarize the information obtained in (2) in written or tabular form for use by the principal investigators in presentations and in other reports in the study.
6. Assist in the editing of other reports in the study.

My first task was to begin collecting the data needed for the characterization of sites in the Caribbean and the Gulf of Mexico and to begin outlining that report. From the start I was left essentially on my own, trusted to decide what kinds of data would be needed and to locate and obtain them. As I had been following the progress of OTEC technology for several years I had a good knowledge of the mechanisms by which OTEC operations might impact the environment, and therefore of the types of data that would be needed. However, I quickly learned that deciding what data would be needed was often far easier than locating that data.

It soon became apparent that there was little information available in the refereed literature for sites in the Caribbean. This meant that I would have to rely largely on data in the grey literature, which would take longer to locate and obtain. In addition, conditions in the Gulf of Mexico were sufficiently different from those in the Caribbean to warrant separate characterizations for the two areas. Further, OTEC operations in the Gulf were not expected to become economically feasible until well after the first plants in the Caribbean were operational. I presented these facts to Drs. Hoss and Peters, along with a proposed outline for a characterization of potential Caribbean sites. In a September meeting of project participants it was decided that the characterization should be limited to Caribbean sites.

By the middle of October I had expanded my data gathering efforts in several new directions. It had become apparent that the lack of Caribbean data on certain topics (e.g. larval fish distribution and microzooplankton abundance) would require that theory and field data from other locations be used to support the few data from Caribbean sites. I had also begun collecting information on such topics as impingement, entrainment, chlorination effects and trace metal effects on primary production. This information would be used in the preparation of the other reports in the study. During this period I was also investigating the potential effects of artificial upwelling on the phytoplankton, which led to a search for information on the cause and frequency of red tides in the Caribbean. Red tides proved to be infrequent phenomena in the Caribbean, but I found that ciguatera fish poisoning, also caused by a toxic dinoflagellate, was a major problem in some areas, particularly around Puerto Rico and the Virgin Islands. Therefore, the collection of all available information on this phenomenon, and on the dinoflagellate responsible, also went on the list of high priority tasks.

Concurrently with the search for information on topics of the types listed above, I was also searching for information of an ecological nature, including topics such as coral reef ecology and trophic webs in the Caribbean. This information was needed to provide a basis for estimating the magnitude of impacts, particularly indirect impacts.

I began the first draft of the characterization in early November, and the draft was nominally finished in mid-March. In reality, the draft became a working paper, and was constantly in a state of revision. A number of factors made drafting the characterization a slow process. First, the search for additional data continued during this period. Second, material requested earlier from other organizations continued to arrive during this time. In

addition, the principal investigators made a data-gathering trip to Puerto Rico and the Virgin Islands during January, and returned with additional material from the grey literature which I had been unable to obtain. The discovery or arrival of additional data often made it necessary to revise those sections of the characterization already completed. In addition, the principal investigators were not sure which methods they would use to evaluate potential impacts. In order to provide them as many options as possible, I attempted to include all possible information in the characterization.

The period from March through May was spent primarily on three main tasks. First came further revisions to the characterization. Second, during their trip to Puerto Rico and the Virgin Islands the principal investigators learned that ciguatera was of major concern to the authorities there. I therefore made further efforts to locate information on the factors controlling the distribution and abundance of the toxic dinoflagellate responsible for the poisoning, and produced a short report summarizing all the information which I had been able to find on the subject in general (this report is included here as Appendix 3). Third, Dr. Peters and I, over a period of two weeks, edited the 170 page working draft of the characterization down into a draft deliverable report of approximately 105 pages. Fortunately, I had designed the working paper for "cut and paste" editing, which made this process much easier than it would have been otherwise. This deliverable report was presented to Dr. Myers and to Dr. Dean Parsons of the NMFS Office of Habitat Protection at a meeting at the Beaufort lab during mid-May.

The final three months of my appointment were devoted to a number of small tasks. The deliverable draft of the characterization was well received, but a number of small revisions were needed. Most of these were made necessary by the late arrival of still more information from other organizations.

In addition, I continued gathering information on the trophic steps leading to commercial tuna species in the Caribbean. However, the major part of my time during this period was spent in summarizing information for inclusion in the other reports in the study and in assisting in the editing of those reports.

My internship appointment ended on August 12, 1983, the Friday before final draft versions of all reports in the study were due. The reports were presented to local authorities and interested parties in Hawaii, Puerto Rico and the Virgin Islands in meetings held later that year. The second draft of the characterization was accepted without further revision (D. Peters, personal communication). The final summary report for the entire study was written during 1984. I played no role in the writing of this report, although I did review it for Dr. Myers of OME early in 1985. The final version of that report is, as mentioned earlier, in the final stages of revision and should be available shortly.

Comments On The Internship Experience

In general, while I found my internship to be a valuable experience, it was also a frequently frustrating one. This was the first time that I had worked independently on a project of this size. However, my work could not be entirely independent, since the contents of later reports would be, in part, determined by the contents of the characterization. Unfortunately, the principal investigators were often unavailable, particularly during the first half of my appointment. On many occasions this was unavoidable, as one or both were frequently on cruises or facing deadlines on other projects. However, upon completion of a given task I often found that I was unable to go over the completed task with them, and unable to obtain opinions as to what steps should be taken next. Given the fact that this was a broad preliminary

study where project methods, report contents and the like were not (and could not be) fully defined at the outset, where the steps to be taken next often depended on the results of the previous step, I found the lack of input, and the frequent lack of anyone to even bounce ideas off of, to have an adverse effect on my productivity. While I was usually able to determine what steps should be taken next, on many occasions I felt as though I was defining the study, and with my lack of experience did not feel qualified to do so. To use an example mentioned previously, during my writing of the first draft of the characterization the principal investigators were unsure which methods would be used to evaluate impacts. Because of that, and because of the lack of communication resulting from their being unavailable, I was forced to put as much information as possible into that initial draft. I believe that a greater amount of input from the principal investigators would likely have decreased the length of that draft, as well as the amount of time required to prepare it.

Planning, scheduling and implementation of the various phases of the project also left something to be desired. The problems here were caused by a number of factors, many of them being unavoidable since, as mentioned above, the principal investigators had much of their time committed to other projects. In addition, travel money restrictions were responsible for some of the problems. However, some improvements could have been made. As an example, a data-gathering trip to Puerto Rico and the Virgin Islands was not made until January. This was, in part, due to the principal investigators' belief that the method of estimating impacts should be determined before the trip, since that would determine the kinds of data required. However, it turned out that the information available was the limiting factor, and determined the types of analyses that could be done. By the time the trip was made

the initial draft of the characterization was well on its way to completion. The information gathered on that trip necessitated revisions to several parts of the characterization that I had already written. In addition, many sources that I had spent a number of hours or days locating could easily have been acquired on that trip. Therefore, it would have been far better if the trip had been made earlier in the course of the project.

The final factor that made my internship a frustrating experience was the fact that locating the necessary information turned out to be both time consuming and tedious, and was at times an exercise in futility. However, it is in this area that I believe that I gained the most in knowledge and experience.

THE SEARCH FOR INFORMATION

As mentioned previously, I discovered early in my appointment that deciding what data would be needed was frequently far easier than locating and obtaining that data. Fortunately, the Beaufort laboratory is blessed with an excellent librarian in Ms. Ann Hall. Her expertise, tolerance and patient guidance were essential to my success.

The task of locating information in the literature was accomplished by a number of different methods. It was initially expected that queries of the commercial, on-line literature databases, using a keyword-based search strategy, would locate the vast majority of the information required. However, while initial efforts proved moderately successful, it became apparent that even a carefully planned keyword search strategy would not find all of the applicable sources present in the refereed literature. As a result, I soon found myself going through the manuals for the databases I used most frequently, in an effort to make my choices of keywords more efficient. In addition,

I was forced to use alternative search strategies. As an example, if I was able to locate a review paper on a certain topic, a search of the Citation Index database would frequently turn up several more recent papers which had cited the earlier review paper. Alternatively, if I had found several papers on the same topic by one author, a simple search for all recent papers by that author might turn up a paper that had not been located using the normal keyword search strategy. While these different search strategies did turn up additional sources, two facts soon came to light. First, many sources in the grey literature were simply not present on the commercial databases. Second, I was rapidly using up a major portion of the lab's literature search budget. As a result, I increasingly had to turn to other methods of locating relevant data.

One of those other methods consisted simply of going through all available volumes of certain journals. As an example, were I looking primarily for information on the effects of chlorination upon zooplankton, I might go through the indexes for all volumes of Environmental Science and Technology. If the journal was one that might contain information on a number of relevant topics I would go through the table of contents for each volume. This method frequently located papers which should have been located in a query of the commercial databases, but were not. In one instance a search of the commercial databases located two papers on the dinoflagellate responsible for ciguatera fish poisoning that appeared in the Journal of the Japanese Society of Scientific Fisheries. By going through the table of contents of each available volume of that journal I located several more papers on that subject, all of which I would have expected, given the keywords used, to have been located by the database query.

Another method of finding relevant literature consisted simply of utilizing the expertise and personal libraries of laboratory researchers. These researchers were especially helpful in locating material in the grey literature, and were frequently my only means of doing so. Few had their personal collections indexed; my questions occasionally resulted in a statement such as, "You know, it seems like I've got something on that around here somewhere", followed by an hour-long search through boxes of old reprints and reports. However, such inquiries were often quite fruitful. In one instance I obtained an entire set of the fishery statistics reports for Puerto Rico for the years 1973 through 1978. While these reports would have been available directly from the authorities in Puerto Rico, I was able to obtain them several weeks sooner than would have been otherwise possible simply by asking a few questions of staff researchers.

The most tedious searches were those where one specific, crucial piece of information was needed. In one instance the different units used in reporting zooplankton biomass led to a search for conversion factors between displacement volume, wet weight, dry weight and carbon weight. The search involved two queries of the commercial databases and perhaps 20 to 30 hours of looking through journal indexes, questioning staff members, etc. That I was eventually able to locate a paper giving these conversions was more a matter of luck than anything else. In another instance I had to determine if there were any areas in the Caribbean Sea that would lie outside of all potential exclusive economic zone claims, and determine the boundaries of the zone surrounding Puerto Rico and the U.S. Virgin Islands. Locating this information required approximately 20 phone calls, made over the course of 4 or 5 days, which led to an obscure office in the State Department.

Comments On The Problem Of Locating Information

I am firmly convinced that many preliminary studies of the type in which I was involved can be made using existing literature. The major block to effective use of this data is simply locating it. To quote John D. Costlow, director of the Duke University Marine Laboratory, "There is a sea of knowledge out there, and we're swimming in it" (address at the Estuarine Sanctuary Workshop, Nov. 13-16, 1984, as reported in Ocean Science News, November 15, 1985). The research and resource management communities have not yet developed mechanisms to cope with the vast amount of information presently available, particularly that in the grey literature. This appears to be true at the levels of the individual, the laboratory or office, and the agency or company. At the Beaufort laboratory researchers frequently did not have any index system for the reprints and reports in their personal collection. While the Beaufort laboratory maintained a list of all publications and contributions made by laboratory staff, the list did not include any in-house reports, and the other NMFS labs in the region did not maintain such lists at all. Such problems also existed at the regional headquarters; administrative heads there were, on several occasions, unable to locate reports that their office was supposedly responsible for. And, of course, the amount of information in the grey literature, in intra-agency and in-house reports, is growing rapidly. If redundancy and repetition of research is to be avoided, if the vast amount of information already present is ever to be efficiently utilized in resource management decisions, methods of keeping track of this data and making it generally available must be developed.

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APPENDIX 1:

**LIST OF THE REPORTS PRODUCED AS PART OF THE BEAUFORT-HONOLULU
OTEC FISHERY IMPACTS STUDY.**

APPENDIX 1

REPORTS PRODUCED AS PART OF THE OTEC FISHERIES IMPACT STUDY

- Ditmars, J.D., and E.P. Myers. 1983. Preliminary estimates of the range of operating conditions expected for initial OTEC deployments. Argonne National Laboratory, Energy and Environmental Systems Division, Argonne, Illinois. 6 p.
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- Seki, M.P. 1983. Summary of pertinent information on the attraction effects of artificial structures placed in tropical and subtropical waters. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Southwest Fisheries Center Honolulu Laboratory, Honolulu, Hawaii. 28 p.

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APPENDIX 2: THE MAJOR INTERNSHIP PRODUCT-

**STUDY OF THE POTENTIAL IMPACT TO FISHERIES OF OTEC OPERATIONS:
SUMMARY REPORT OF PERTINENT BIOLOGICAL INFORMATION FROM THE CARIBBEAN**

STUDY OF THE POTENTIAL IMPACT TO FISHERIES
OF OTEC OPERATIONS

Task 2a

Summary Report of Pertinent Biological
Information from the Caribbean

Donald E. Hoss

David S. Peters

Robert E. Rose

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INTRODUCTION

The purpose of this report is to synthesize existing information on the biological and fishery characteristics of potential OTEC operating sites in the Caribbean Sea, in order that the potential for significant impacts on the fisheries at these sites can be evaluated. The impacts could be indirect, such as changes in the abundance or composition of phytoplankton or zooplankton food organisms, or direct, such as the entrainment or impingement of larval or juvenile fish.

Potential OTEC Sites in the Caribbean Sea

The basic operational requirement for an OTEC plant is an adequate temperature difference between the surface and deeper water. An annual minimum difference of 20°C is considered necessary (Sands 1980). Once this basic requirement is met, tradeoffs between increased performance (resulting from a greater temperature difference) and increased costs (resulting from a longer cold water pipe and/or longer underwater cables) become important. In general, the cold water source should be available as close as possible to the site of power use or distribution.

PLANTSHIP SITES

The temperature difference at oceanic sites in the Caribbean is more than adequate for OTEC operations. However, all areas in the Caribbean lie within existing or potential Exclusive Economic Zone claims of some country (W. Hazlep, Dept. of State, Office of the Geographer, Washington,

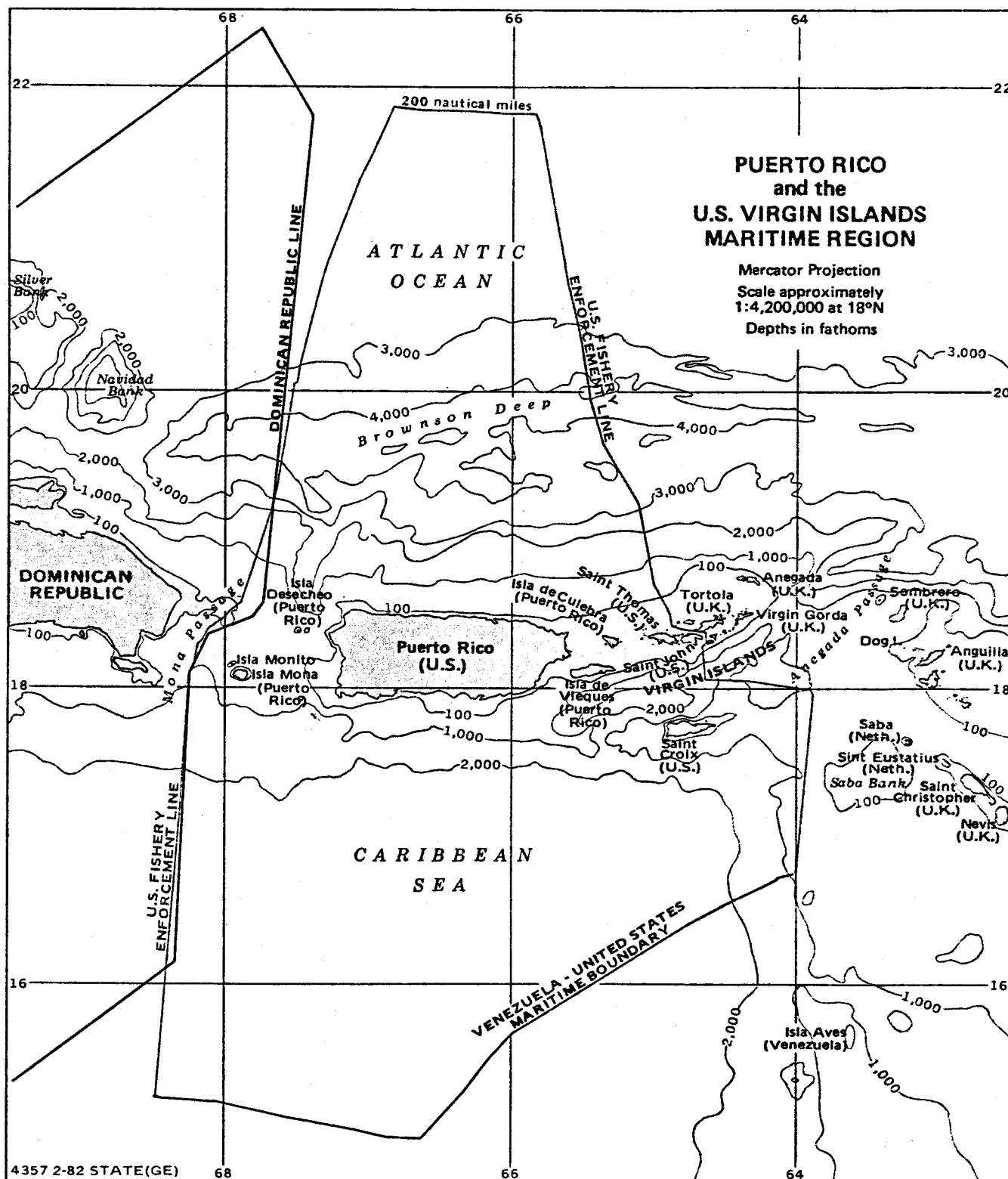
D.C., personal communication). Therefore, plantship operations by American corporations may be limited to the Fishery Conservation Zone surrounding Puerto Rico and the U.S. Virgin Islands (Fig. 1).

ISLAND SITES

Excellent conditions for OTEC operations exist at Puerto Rico and at St. Croix in the U.S. Virgin Islands. The temperature difference in this area is always at least 20° and can reach 23.9°C (Goldman et al. 1979; Ocean Data Systems, Inc. 1977 and Munier et al. 1978, as reported in Sullivan et al. 1981). Depths of 1000 m are found within 3 km of Punta Tuna, on the southeast coast of Puerto Rico (Fig. 2). A benchmark site for the gathering of baseline environmental data has been established at approximately $17^{\circ}57'\text{N}$, $65^{\circ}52'\text{W}$, about 4 km off Punta Tuna. However, several other sites in Puerto Rico are also being investigated (Goldman et al. 1979). Depths of 1000 m are also available within 3 km of the northwest coast of St. Croix (Fig. 2). St. John and St. Thomas, however, lie on the Virgin Islands Shelf and depths of 1000 m are not available within 9 km of St. John and 15 km of St. Thomas (Wilde et al. 1981).

Both Puerto Rico and St. Croix would benefit greatly from OTEC power generation. Puerto Rico has sufficient power generating capacity for present and near-future needs, but 98% of its electrical power is generated from imported petroleum. All of the electrical power on St. Croix is generated from imported petroleum and capacity is insufficient to meet local demand, severely limiting economic growth on the island (Sullivan et al. 1981). In addition, St. Croix suffers from a chronic shortage of fresh water, which is produced as a by-product of some open-cycle OTEC power systems.

FIGURE 1. The Fishery Conservation Zone surrounding Puerto Rico and the U.S. Virgin Islands. (U.S. Department of State, 1982.)



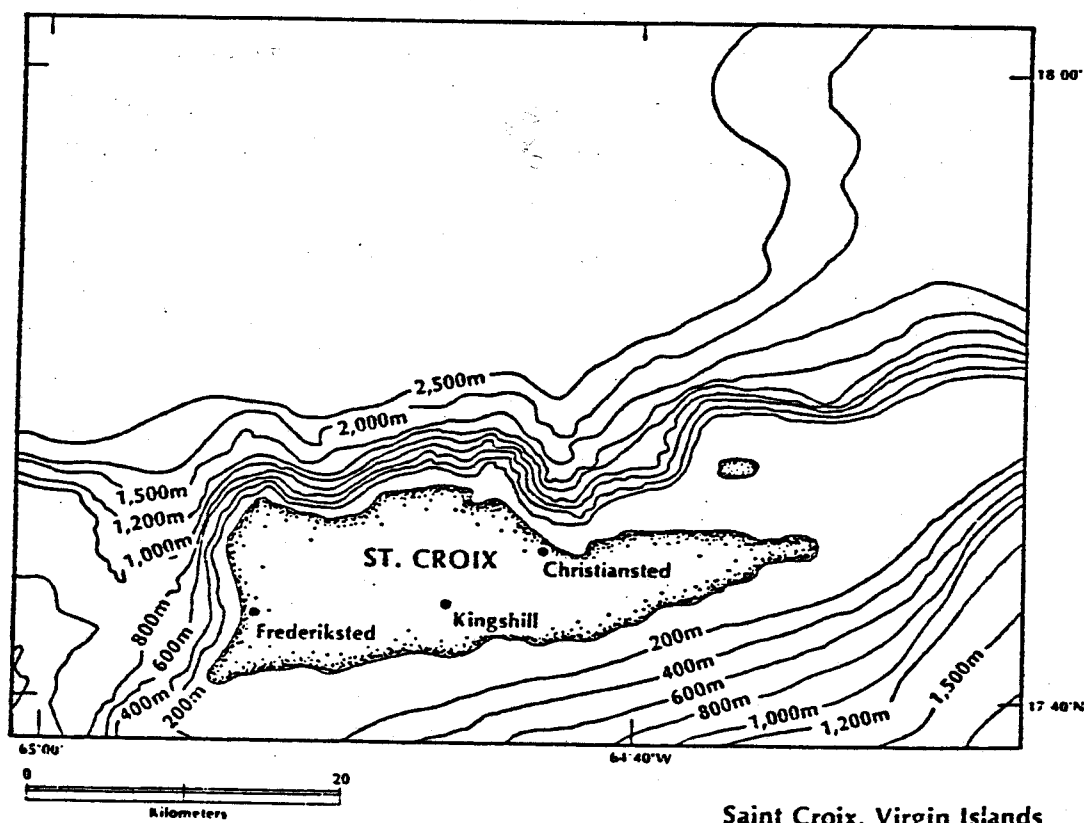
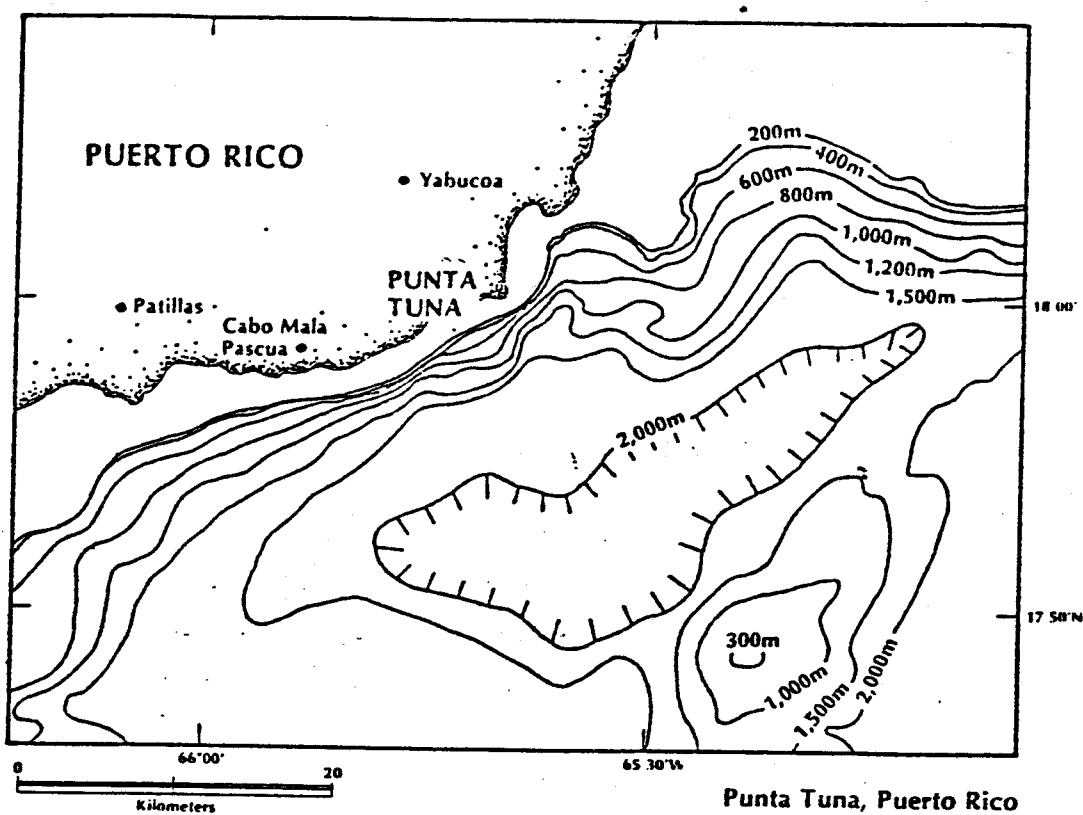


FIGURE 2. Bathymetry near potential OTEC sites at Punta Tuna, Puerto Rico and St. Croix, U.S. Virgin Islands. (From Sullivan et al., 1981.)

There is little doubt that other island sites are possible, as surface water temperatures are consistently high throughout the region. The factor limiting development of other sites will most likely be the availability of deep, cold water reasonably close to shore. Sites which are not economically feasible at the present time will become feasible as OTEC technology progresses and fossil and nuclear fuels become more costly. Therefore, while we will provide information for the Punta Tuna and St. Croix sites whenever possible, this report is not intended to be site-specific, nor is that possible with the data currently available. Much of the data presented in the characterization of island sites comes from studies made off Jamaica and Barbados. This is done out of both necessity and a desire that this report be applicable to sites that become feasible in the future as well as the sites currently proposed.

CHARACTERISTICS OF THE PHYTOPLANKTON

Hydrographic Features of the Caribbean--Sources of Nutrient Enrichment

The Caribbean Sea has long been recognized as an area of low organic productivity. Steeman Nielsen and Jensen (1957) stated that data from the "Galathea" Expedition showed that the rate of primary production in the tropical and subtropical parts of the ocean was strictly dependent upon the local hydrography, and that the production levels found in the Caribbean were typical of "Areas without a pronounced admixture of nutrient-rich water from below. Some admixture -- although of minor importance -- may occur, however, through turbulence." They went on to note that the carbon

fixation rate in such areas was typically 100 to 200 mg C m⁻² day⁻¹, and that the majority of the tropical and subtropical regions of the oceans have similar productivities.

Variation in the generally low productivity in the Caribbean Sea may be associated with nutrients from: (1) the enrichment of surface waters during passage through the Windward Islands chain or over the shallow Antilles Banks, (2) the eddies present in the wake of the Windward Islands, (3) the geostrophic tilt of the pycnocline and the related upwelling along the coasts of Colombia and Venezuela, and (4) upwelling at the periphery of large anticyclonic eddies of low salinity water from the runoff of the Amazon River.

As water enters the Caribbean through the passages between the Windward Islands or over the Antilles Banks, deeper (Antarctic Intermediate) water with its high nutrient content is forced toward the surface (Wood 1971). Nutrient enrichment around islands also is increased by eddies formed in the wake of currents passing around the islands. These eddies, which have been identified at St. Vincent, St. Lucia, Grenada and between Barbados and Martinique (Brucks 1971; Leming 1971; Emery 1972) bring deeper nutrient-rich water toward the surface. The force of the trade winds on the surface waters drives a northward Ekman transport of water in the top 100 m, creating a wedge of low density water in the northern Caribbean and resulting in periodic upwellings of nutrient-rich water along the coasts of Colombia and Venezuela (Gordon 1967).

The importance of the outflow of the Amazon River as a source of nutrient enrichment is still uncertain. While the flow of the Amazon is quite large (12 times that of the Mississippi) the nitrate and phosphate

content of Amazon water is quite low. However, upwelling at the periphery of large (400-600 km diameter) anticyclonic eddies of low salinity Amazon water may be a significant source of enrichment (Ryther et al. 1967). The discharge of the Amazon varies seasonally and, while the degree of enrichment from these eddies appears to be relatively low, some studies have found evidence of seasonal variations in phytoplankton and zooplankton abundance and composition (Kidd and Sander 1979; Yoshioka et al. 1983). However, the degree of enrichment may vary from year to year, as other studies (Steven 1971; Sander and Steven 1973) have failed to identify such seasonal variations.

Since all of the sources of nutrient enrichment mentioned above are located along the southern coastal boundary or among the more southerly of the Lesser Antilles, it appears that primary production should be greatest in the southeastern Caribbean. Advection of nutrients from the southeast to the west and northwest by the Caribbean Current would be expected to result in a gradient of decreasing production to the northwest. Potential OTEC sites near Puerto Rico and St. Croix may be particularly low in primary and secondary production due to the thick wedge of low density surface water present and a possible lack of advection of nutrients from the sources of enrichment.

Characteristics of the Phytoplankton at Oceanic Sites

ABUNDANCE

Estimates of absolute abundance of phytoplankton in oceanic regions of the Caribbean vary considerably due, at least in part, to methodologies used. Some studies employ techniques which include counts of smaller and

more fragile cells not included by others, making inter-study comparisons difficult. There are trends, however, which are in general agreement with regional hydrographic characteristics.

Wood (1971) found that the phytoplankton was usually less abundant near the surface (generally 20,000 to 30,000 cells per liter) than at lower depths. The depth of maximum phytoplankton concentration was generally at or near the bottom of the mixed layer, i.e., between 50 and 100 m.

Transects running from north to south across the Caribbean show that phytoplankton numbers are greatest near shore with lower values in mid-Caribbean. Hulburt (1966) reported concentrations in the upper 25 m of 2,500 to 3,700 cells/l near the Virgin Islands, decreasing to about 1,000 cells/l in the mid-Caribbean and increasing to more than 500,000 cells/l in an upwelling area off Venezuela. Another transect running south from Hispaniola showed the same pattern, i.e., the lowest density being in the mid-Caribbean.

Cell counts also appear to decline as one moves west across the Caribbean. Marshall and Solder (1982) found that the mean surface concentration at four stations south of Puerto Rico was 13,400 cells/l while for seven stations south of Hispaniola the mean was about 2,000 cells/l. Further west the average declined to about 1,100 cells/l. Counts from a single transect from east to west across the area (Wood 1971) showed a general decline in abundance at the depth of the subsurface abundance maximum.

STANDING CROP--CHLOROPHYLL a CONCENTRATIONS

The trends of chlorophyll a concentration (Table 1) are in close agreement with trends in cell counts and the hydrographic conditions

TABLE 1. Surface chlorophyll a concentrations (mg m^{-3}) at oceanic sites in the Caribbean.

Location	Value or mean	Range	Source
Barbados	0.156	---	Sander and Steven 1973
Lesser Antilles (upcurrent)	0.11	0.05 - 0.27	Hargraves et al. 1970
Lesser Antilles (downcurrent)	0.38	0.05 - 0.98	Hargraves et al. 1970
St. Croix	0.107	---	Knauer and Flegal 1981
South of Puerto Rico	0.116	0.054-0.155	Marshall and Solder 1982
South of Hispaniola	0.078	0.030-0.068	Marshall and Solder 1982
Western Caribbean	0.042	0.030-0.068	Marshall and Solder 1982
Western Caribbean	0.055	0.029-0.079	Malone 1971

discussed above. The increase in concentration as water passes the Lesser Antilles is presumably due to the sources of nutrient enrichment in that area. As the water moves further west nutrients are depleted and standing crop declines. The vertical distribution of chlorophyll a has subsurface maxima with concentrations which may be two or three times surface values. The integrated value in the water column is about 15 to 30 mg Chl a m⁻² (Hargraves et al. 1970; Malone 1971; Knauer and Flegal 1981).

PRIMARY PRODUCTION--¹⁴C FIXATION RATES

Primary production measurements from the Caribbean (Table 2) are typical of relatively oligotrophic tropical waters. The value found by Steeman Nielsen and Jensen (1957) off northern Puerto Rico, which is technically in the southern Sargasso Sea and not in the Caribbean proper, is extremely low and is more typical of mid-ocean gyres than of the Caribbean in general. Evidence of isolated production rates higher than most shown in Table 2 is available from other studies.

The majority of photosynthesis occurs in small cells. At 36 oceanic stations, Steeman Nielsen and Jensen (1957) found that the cells which passed through a No. 25 (64 μ m) mesh screen were responsible for an average of 94% of the primary production. Malone (1971) found that the nanoplankton (less than 22 μ m) accounted for an average of 87% of the standing crop (as measured by chlorophyll a concentration) and 92% of the primary production (as measured with standard ¹⁴C methods) in the Caribbean region. Similar measurements made at oceanic stations off the west coast of Mexico and Central America and in Peru Current waters gave essentially the same results.

TABLE 2. Primary production at oceanic sites in the Caribbean.

Location	Production (g C m ⁻² day ⁻¹)		Surface productivity (mg C m ⁻³ hr ⁻¹)		Source
	Value or mean	Range	Value or mean	Range	
Barbados 13°15'N, 59°43'W	0.288	0.037-1.283	0.44	---	Steven 1971 Sander and Steven 1973
St. Croix 17°44'N, 65°00'W	---	---	0.28	---	Knauer and Flegal 1981
Off northern Puerto Rico	0.056	---	0.072 ¹	---	Steeman Nielsen and Jensen 1957
Mid-Caribbean 15°00'N, 71°06'W	0.190	---	0.306 ¹	---	Steeman Nielsen and Jensen 1957
Mid-Caribbean 11°52'N, 77°41'W	0.140	---	0.126 ¹	---	Steeman Nielsen and Jensen 1957
Jamaica 17°52'N, 76°43'W	0.18	0.08-0.52	---	---	Beers et al. 1968
Western Caribbean (several locations)	---	---	0.33	0.12-0.62	Malone 1971

¹ Steeman Nielsen and Jensen's published values for productivity (in mg C m⁻³ hr⁻¹) represented the rate at the depth of maximum photosynthesis. They stated (p. 102) that the rate of photosynthesis at the surface is about 60% of this maximum. The values given above are 60% of their published values.

The importance of the picoplankton (less than 2.0 μm) has only recently been recognized and no data are available from the Caribbean. However, Platt et al. (1983) found that these small forms are capable of supplying 60% of the total primary production in an open-ocean system. As is the case with nanoplankton, the picoplankters appear to increase in numbers with distance from shore (Reid 1983). Unfortunately, the extent to which picoplankton production is included in the primary production estimates in Table 2 is not clear.

The primary production rates for the Caribbean reported in Table 2 were derived from standard ^{14}C techniques and as such are useful in making general comparisons, but they should not be considered measures of actual production. It is clear that standard ^{14}C methods do not give an accurate measure of primary production, since decreases in the chlorophyll a concentration and changes in the taxonomic composition of the phytoplankton are known to occur in standard size incubation bottles (cf. Venrick et al. 1977; Gieskes et al. 1979). In addition, Sheldon and Sutcliffe (1978) noted that if grazers are not excluded from the incubation bottles then the incubation period must be kept short compared to the turnover time of the phytoplankton. Since they have measured generation times of 3 hours in subtropical microplankton, it is possible that during the standard incubations of 6 or more hours the phytoplankton population will have turned over at least once. In that situation there would exist a state of quasi-equilibrium between the ^{14}C in the phytoplankton and that in the water, and the measurement obtained would relate more to standing stock than to production.

Much higher estimates of primary production have been produced using newer methods. These estimates, about 10 times those previously reported, have been derived from: (1) the increase of particulate ATP during short incubations (Sheldon and Sutcliffe 1978), (2) analysis of the diurnal rhythm of oxygen concentration (Tijssen 1979), (3) daily variations in the particulate organic carbon content of the water column (Postma and Rommets 1979), and (4) ^{14}C uptake in larger (3800 ml) incubation bottles (Gieskes et al. 1979). The ecological implication of primary production occurring at rates higher than previously believed is not clear.

COMPENSATION DEPTH

Estimates of compensation depth derived from measurements with photometers and secchi discs at various Caribbean locations all indicate values near 100 meters (Steeman Nielsen and Jensen 1957; Beers et al. 1968; Hargraves et al. 1970; Hernandez-Avila et al. 1979).

TAXONOMIC COMPOSITION

The composition of the phytoplankton community in the Caribbean has not been adequately described. The species are generally the same as those in the North Equatorial Current (Wood 1971), and are represented primarily by diatoms and sizeable populations of coccolithophorids, dinoflagellates and blue-green algae (Margalef 1971). Bjornberg (1971) noted that tropical oceanic waters contain a higher percentage of nanoplankton than do temperate or neritic waters. The smaller cells, with less volume per unit of surface area, stand a better chance of being able to absorb the amount of limiting nutrients necessary for survival, growth and reproduction.

Data on nano and picoplankton are few, in part because of collecting and counting problems. Most data are on net plankton. Samples of the larger (i.e. net) plankton collected between Puerto Rico and Trinidad with a 76 μm mesh net have been described by Hargraves et al. (1970). While those samples contained many species of diatoms and dinoflagellates (Table 3), individuals of species with widespread distributions were, in general, more abundant in the samples than those of localized taxa. Particularly abundant were Bacteriastrum hyalinum, Chaetoceros coarctatum, Hemiaulus hauckii and Oscillatoria (Trichodesmium) thiebautii.

Marshall and Solder (1982) used sampling and counting techniques appropriate for nanoplankton and thus present a more extensive and considerably different species list. They identified 245 different taxa (Table 2, Marshall and Solder 1982) and showed regional differences in distribution of the taxa. The major features included the dominance of diatoms in the eastern Caribbean; 73 of the 88 diatom species found were present in this area and they accounted for over 90% of the cells. The relative abundance of phytoflagellates (consisting mainly of dinoflagellates and coccolithophores) increased greatly at stations further west, where they accounted for more than half of the cells. One hundred thirteen of the 143 species identified from those orders were present in the mid-Caribbean. No surveys designed to show species composition of picoplankton have been completed in the Caribbean.

Oscillatoria (Trichodesmium), a genus of blue-green algae or cyanobacteria, is particularly abundant in the Caribbean and warrants special mention. The dominance it displays at some locations was described by Carpenter and Price (1977), who reported a mean abundance of over 2×10^9 cells m^{-2} . They found that the maximum concentration of Oscillatoria was present at a depth of 15 m (mean value 75×10^6 cells m^{-3}) and that the genus

TABLE 3. Phytoplankton species found at 6 or more of 17 stations in the Lesser Antilles regions. (From data of Hargraves et al. 1970.)

Species	Number of stations where recorded
Bacillariophyceae	
<i>Asterolampra marylandica</i>	11
<i>Bacteriastrium hyalinum</i>	13
<i>Chaetoceros coarctatum</i>	16
<i>Chaetoceros didymum</i>	8
<i>Chaetoceros lorenzianum</i>	13
<i>Chaetoceros peruvianum</i>	6
<i>Chaetoceros</i> cf. <i>seychellarum</i>	6
<i>Chaetoceros</i> sp.	8
<i>Cocconeis scutellum</i>	9
<i>Coscinodiscus centralis</i>	7
<i>Coscinodiscus excentricus</i>	7
<i>Coscinodiscus nitidus</i>	8
<i>Hemiaulus hauckii</i>	13
<i>Nitzschia bica pitata</i>	6
<i>Nitzschia kolaczekii</i>	11
<i>Nitzschia microcephala</i>	7
<i>Rhabdonema adriaticum</i>	6
<i>Rhizosolenia hebetata semispina</i>	7
<i>Rhizosolenia stolterfothii</i>	7
<i>Rhizosolenia styliformis</i>	10
<i>Roperia tessellata</i>	10
<i>Thalassiothrix frauenfeldii</i>	6
Dinophyceae	
<i>Ceratium buceros</i>	6
<i>Ceratium candelabrum</i>	6
<i>Ceratium contortum</i>	8
<i>Ceratium fusus</i>	7
<i>Ceratium macroceros</i>	8
<i>Ceratium massiliense</i>	9
<i>Ceratium teres</i>	7
<i>Ceratium trichoceros</i>	9
<i>Ceratium tripos</i>	11
<i>Ceratocorys horrida</i>	9
<i>Ornithocercus steinii</i>	11
<i>Peridinium divergens</i>	15
<i>Peridinium elegans</i>	6
<i>Pyrophacus horologicum</i>	6
Chrysophyceae	
<i>Dictyocha fibula</i>	13
Cyanophyceae	
<i>Skuaella (Oscillatoria) thiebautii</i>	13

accounted for 56% of the chlorophyll a in the upper 200 meters. Abundance was higher in the eastern Caribbean, although spatial distribution was quite patchy. Steven and Glombitza (1972) reported temporal variation at one location west of Barbados, with abundance oscillating from zero to 1×10^6 filaments m^{-3} . Because the genus is capable of nitrogen fixation (Carpenter and Price 1977) it may be of extreme importance in areas of nitrogen deficiency.

Characteristics of the Phytoplankton at Island Sites

THE ISLAND MASS EFFECT

Investigations of the plankton near oceanic islands have repeatedly revealed that taxonomic composition, standing crop and production change with distance from shore. These changes are generally attributed to increased cycling or supply of nutrients to the euphotic zone. Several mechanisms may be involved including: (1) island runoff, which may contain detrital matter and nutrients leached from the soil, (2) equilibrium exchange of nutrients between the benthos and the shallow overlying water (Sander 1973), (3) "straining" of nutrients from the passing water by benthic algae which subsequently become available to the phytoplankton (Doty and Oguri 1956), (4) vertical mixing resulting from the turbulence caused by currents passing through inter-island channels (Gilmartin and Revelante 1974), (5) the "breaking" of internal waves on the sloping island shelf (Sander 1973, 1981), and (6) eddies created in the wake of the island as it "passes through" the waters of a prevailing current (Leming 1971). For islands located in a prevailing current regime, nutrients supplied by one of these mechanisms to the euphotic zone on the up-current side of the

island would soon be advected around to the downcurrent side of the island. The intensity of the island mass effect and the area influenced by it should therefore be greater on the leeward side of the island.

A CARIBBEAN EXAMPLE OF THE ISLAND MASS EFFECT

To date the only complete study of the island mass effect in the Caribbean is that of Sander and Steven (1973), made off the west, or leeward, shore of Barbados. They established several transects with stations located at bottom depths of 10, 25, 50, 100, and 150 m (all less than 2 km offshore), and an "oceanic" station 10 km offshore in 460 m of water, and sampled them over two years.

Cell abundance, chlorophyll a concentration and primary production were all highest at the shallow stations. The changes in these parameters at the inshore stations were relatively small compared with the significant reductions seen at the oceanic station (Table 4). The assimilation ratio (the ratio of carbon fixation rate to chlorophyll a concentration) increased from 2.8 at the oceanic station to 9.2 at the 10 m stations. This ratio may give an indication of the physiological state of the phytoplankton cells, with inshore cells assimilating nutrients and carbon more efficiently, so that less chlorophyll a is needed. The findings of Curl and Small (1965) suggest that assimilation ratios below 3 are indicative of nutrient limitation while those above 5 indicate nutrient-rich water.

In general, changes in the taxonomic composition of the phytoplankton at inshore stations were relatively small, although the relative abundance of dinoflagellates increased and that of blue-green algae decreased by a factor of about 2 as shore was neared (Table 5). At the oceanic station the relative abundance of the blue-green alga Oscillatoria (Trichodesmium) thiebautii was about 20%, 10 times that found at the 10 m stations.

TABLE 4. Mean cell concentrations (cells/l), chlorophyll a concentrations (mg m^{-3}), primary productivity ($\text{mg C m}^{-3} \text{ hr}^{-1}$) and assimilation ratios (mg C/mg Chl a/hr) in surface waters at stations off Barbados (from Sander and Steven 1973).

	10 m stations	25 m stations	50 m stations	100 m stations	150 m station	460 m station
Cell concentration	12398	10978	9919	11172	10773	2704
Mean/mean 460 m station	4.58	4.06	3.67	4.13	3.98	----
Chlorophyll <u>a</u> conc.	0.232	0.228	0.204	0.204	0.200	0.156
Mean/mean 460 m station	1.49	1.46	1.31	1.31	1.28	----
Primary productivity	2.13	2.1	1.89	----	----	0.44
Mean/mean 460 m station	4.80	4.73	4.26	----	----	----
Assimilation ratio	9.2	9.2	9.3	----	----	2.8

TABLE 5. The percentage contribution by the major groups to the surface phytoplankton of inshore stations at Barbados (from Sander and Steven 1973).

	10 m stations	25 m stations	50 m stations	100 m stations	150 m station
Diatoms	83.0	84.1	81.6	86.7	86.8
Coccolithophores	2.9	3.5	4.3	2.8	3.1
Dinoflagellates	10.6	7.9	9.5	5.6	3.7
<u>Oscillatoria thiebautii</u>	2.1	3.3	3.9	2.7	3.7
Total blue-green algae	3.4	4.4	4.6	4.7	6.3
Others	*	*	*	*	*

* less than 1%

STUDIES AT THE PUNTA TUNA, PUERTO RICO BENCHMARK SITE

Studies to establish baseline ecological data have been initiated at a benchmark site off Punta Tuna, Puerto Rico at 17°57'N, 65°51'W. This site is approximately 5 km offshore. The vertical distribution of chlorophyll a and the composition of the phytoplankton community at the site was investigated by Johnson and Horne (1979) using a 25 μ m mesh net. The average surface chlorophyll a concentration from three cruises was about 0.18 mg m^{-3} . This value is approximately the same as the mean surface concentration 10 km (0.156 mg Chl a m^{-3}) and 1.5 km (0.20 mg Chl a m^{-3}) off Barbados (Sander and Steven 1973). It is, however, about 10 times the mean value found in the same area off Puerto Rico in late 1980 and 1981 by Vargo et al. (1981).

Species composition of the phytoplankton in the two published studies at Punta Tuna differ considerably, due to the methods used. Johnson and Horne (1979) reported that Oscillatoria was dominant, diatoms and dinoflagellates were common, and coccolithophores were rare. Vargo et al. (1981) used techniques suitable for nanoplankton and found both coccolithophores and monads were abundant. Considerably more information on the ecology of the phytoplankton at Punta Tuna should be available soon in a report from the Center for Energy and Environment Research at the University of Puerto Rico.

Summary

Several sources of nutrient enrichment exist in the Caribbean which could have an effect upon phytoplankton abundance and production. These sources are the shallow banks of the Lesser Antilles, eddies which form in

the wake of those islands, upwelling which occurs along the coast of Venezuela and Colombia, and upwelling on the periphery of eddies of Amazon River water. All of these sources of potential enrichment are located in the eastern and southern Caribbean. Enrichment effects could be expected to be less noticeable in the northern and western Caribbean.

OCEANIC SITES

Measurements at various oceanic sites in the Caribbean show that the surface chlorophyll a concentration is typically about 0.1 mg m^{-3} , while the standing crop is usually about 15 to 30 mg Chl a m^{-2} . Deep chlorophyll maxima occur and concentrations within these layers can be 2 to 3 times that found at the surface.

Primary production, as measured with traditional ^{14}C methods, ranges from about 0.1 to $0.4 \text{ mg C m}^{-3} \text{ hr}^{-1}$, depending upon location and distance from land. The total production found beneath one m^2 of sea surface is generally about 0.1 to 0.2 g C day^{-1} .

While the compensation depth varies from one location to another, it is typically about 100 m.

The netplankton component of the phytoplankton is dominated by diatoms, dinoflagellates and blue-greens. The nanoplankton component (defined here as those phytoplankters passing through a $20 \text{ }\mu\text{m}$ mesh screen) may account for over 80% of the standing crop and 90% of the production in some areas, although the contribution of picoplankton is generally unknown. The relative contribution of the nanoplankton is greatest at the most oligotrophic sites.

The blue-green algae of the genus Oscillatoria are a significant component of the phytoplankton in some locations. The nitrogen fixing capability of these algae could be of great importance in areas where they are abundant.

ISLAND SITES

Near oceanic islands the taxonomic composition of the plankton changes and standing crop and production increase toward shore. This phenomenon is generally known as the island mass effect.

The island mass effect upon the composition, standing crop and production of the phytoplankton has been observed at stations on the west (or leeward) side of the island of Barbados, where inshore stations (less than 2 km from shore) were compared with an offshore station (10 km from shore). Cell concentration increased steadily from offshore to inshore; the mean surface concentration at inshore stations was about 4 times higher than found at the offshore station. Surface chlorophyll a concentration showed a slight increase from offshore to inshore as well (from 0.156 mg m^{-3} 10 km offshore to 0.200 mg m^{-3} 1.5 km offshore). There was also an increase in primary production; production rates at inshore stations were about four times those offshore. The assimilation ratio (carbon fixed per hour per mg Chl a) was about 3 times as high at inshore stations, showing that the cells there were able to utilize their chlorophyll more efficiently. Composition was also different at the inshore stations. The relative abundance of dinoflagellates and blue-green algae was lower at the inshore stations, where the phytoplankton community was dominated by diatoms.

Similar chlorophyll a concentrations (0.18 mg m^{-3}) have been found at the Punta Tuna benchmark site, about 5 km off the southeast coast of Puerto Rico. At that location, however, the blue-green Oscillatoria were abundant.

CHARACTERISTICS OF THE ZOOPLANKTON COMMUNITY

It is difficult to make comparisons of the abundance and biomass of zooplankton in the Caribbean because a variety of instruments and methods

have been used in sample collection and treatment (Moore and Sander 1976). Abundance and biomass figures are given in terms of the amount caught per unit time, the amount in a one m^2 water column, or the amount per m^3 . Biomass has been measured as displacement volume, wet weight, dry weight, or carbon weight. The type, size and mesh of the net used will all affect the abundance and relative composition of the zooplankton caught, as will the speed, depth, and time of day of the tow. In spite of the above difficulties, certain generalizations can be made as to abundance, biomass, and community composition.

Characteristics of the Zooplankton at Oceanic Sites

ABUNDANCE, BIOMASS AND DISTRIBUTION

The most thorough survey of offshore zooplankton in the Caribbean region has been that of Michel and Foyo (1976) in which 105 stations were occupied during eight cruises. At each station hydrographic data were collected and the zooplankton was sampled at the surface and at selected depths to 4000 m. Although flowmeters were not used, tows were taken in the same manner so the findings are comparable from one station to another and give an accurate indication of distributional ranges, areas of abundance, and the relative abundance of species. Of the over 450 species of copepods reported from the Caribbean, twenty common species were selected for individual identification and enumeration. Each of these species is known to have a broad vertical range. All other copepods were identified to their taxonomic order and counted. Ten species of siphonophores, 23 species of euphausiids, 8 species of heteropods, 22 species of chaetognaths, and 4 species of salps were also identified and counted.

Michel and Foyo found that the abundance of each group, as well as the total abundance of all groups, varied throughout the Caribbean. The

greatest numbers of zooplankters were found in the central Caribbean and the areas of upwelling in the Central American bight. At two stations in the eastern Caribbean Owre and Foyo (1964) found a high proportion of immature copepods and suggested that the relatively quiet waters of that area might serve as a zooplankton nursery ground for the rest of the Caribbean, and thus explain the very large numbers collected directly downcurrent in the central Caribbean (Michel and Foyo 1977).

Abundance and biomass of zooplankton are greater in surface samples than in oblique tows (Table 6). Michel and Foyo (1976) found the greatest numbers in TSW (Tropical Surface Water) and SUW (Subtropical Underwater). Below this, the zooplankton becomes relatively sparse in individuals but not in numbers of species. Often a secondary numerical maximum is found in the vicinity of 500 m, in the upper NACW (North Atlantic Central Water), where mesopelagic species are common. In samples off Bermuda Deevey and Brooks (1971) found that the total abundance in the 500-1000 m, 1000-1500 m, and 1500-2000 m layers was 13.0%, 5.2%, and 2.6%, respectively, of that in the upper 500 m. However, displacement volume did not decrease as rapidly with depth. The corresponding figures were approximately 47%, 25%, and 16%. This indicates an increase in the mean zooplankter size with depth, particularly in the first 1000 meters.

TAXONOMIC COMPOSITION

Copepods are numerically the dominant animal group in the Caribbean, where they comprise about 3/4 of the zooplankters identified (Table 7). Their dominance is, however, not quite as notable when judged by volume or weight. Large organisms such as chaetognaths, siphonophores, and euphausiids may constitute a considerable portion of the zooplankton

TABLE 6. Zooplankton numerical abundance and biomass at oceanic sites in the Caribbean and Sargasso Seas.

Location	Depth of tow (m)	Abundance (#/m ³)		Displacement volume (ml/m ³)		Dry weight (mg/m ³)		Source
		Mean	Range	Mean	Range	Mean	Range	
Barbados	0	368	41-2320	0.028	0.003-0.098	2.40	0.30-11.73	Moore and Sander 1977
Barbados	0-40	155	26-1073	0.020	0.005-0.063	2.18	0.25-6.61	Moore and Sander 1977
Jamaica	0	823	145-2445	0.021	0.002-0.105	3.30	0.22-12.21	Moore 1967
Sargasso	0-500	284	129-583	0.030	---	2.72	---	Deevey 1971
Oligotrophic Caribbean	---	---	---	---	0.04-0.14 ¹	---	---	Margalef 1971

¹ Volume calculated from Margalef's wet weight data using conversion factor of 73% from Weibe et al. 1975.

TABLE 7. Average contribution of the major zooplankton groups (expressed as % of total number of zooplankters present) at oceanic sites in the Caribbean and Sargasso Seas.

Location	Depth of tow(s)(m)	Copepods	Fish eggs	Foramini-ferans	Chaetognaths	Larvae	Ostracods	Tunicates	Coelenterates	Source
Barbados	0	62	20	10	3	2	2	2	-	Moore and Sander 1977
Barbados	0-400	65	12	7	5	3	4	2	-	Moore and Sander 1977
Sargasso Sea	0-500	70	-	-	3	-	7	8	3	Deevey 1971
Caribbean (various sites)	0-400	89	-	-	7	-	-	1	1	Michel and Foyo 1976
South of Puerto Rico	0-100	81	-	-	5	-	-	14	-	Yoshioka et al. 1983

biomass in terms of weight and volume even though they are relatively unimportant numerically (Deevey 1971). This is illustrated in data from Deevey (1971) and Menzel and Ryther (1961, from Deevey 1971). Sampling at the same location, although at different times, copepods constituted 70% of the zooplankton by number (#) and 44% by volume (v), chaetognaths 3% (#) and 15% (v), and coelenterates 3% (#) and 13% (v).

Copepods

Considerable difference exists in the species which were dominant in different studies and in the relative importance of those dominant species. In three studies 32 different species were listed as frequent or abundant. However, 20 of them were listed by only one of those studies (Table 8), six species were listed as abundant in two studies and only six others were found to be abundant by all three authors. Michel and Foyo (1976), using small mesh (100 μm) nets and sampling to 4000 meters, found a very diverse assemblage in which 20 dominant species comprised only 18% of the copepods collected. On the other hand, Moore and Sander (1977) used 239 μm mesh nets to sample the top 400 meters and found much less diversity; only 12 species accounted for about 75% of the copepod numbers.

Siphonophores

The horizontal and temporal distribution of siphonophores is quite patchy. Michel and Foyo (1976) found the greatest numbers in upwelling areas and in the eastern Caribbean. Sander and Steven (1973) reported that siphonophores contributed 2.9% of the zooplankton abundance in surface tows at their station off Barbados. However, Moore and Sander (1977), whose data is from the same station but covers a slightly different time period,

TABLE 8. Abundant copepods in the Caribbean Sea.

	Michel and Foyo (1976)	Bjornberg (1971)	Moore and Sander (1977)
Calanoida			
Acrocalanus longicornis	X		
Clausocalanus furcatus	X	X	
Euchaeta marina	X	X	X
Haloptilus longicornis	X		
Lucicutia flavicornis	X		
Mormonilla minor	X		
M. phasma	X		
Paracalanus aculeatus	X	X	X
P. parvus		X	X
Rhincalanus cornutus	X	X	
Scolecithrix danae	X		
Undinula vulgaris	X	X	X
Nanocalanus minor		X	
Neocalanus gracilis		X	
Eucalanus attenuatus		X	
Calocalanus pava		X	X
Ischnocalanus plumulosus		X	
Temora stylifera		X	
T. turbinata		X	
Centropages furcatus	X		
Calanopia americana		X	
Cyclopoida			
Conaea gracilis	X		
Farranula carinata	X	X	X
F. gracilis	X		
Oithona plumifera	X	X	X
O. setigera			X
Oncaea mediterranea	X		X
O. venusta	X		X
Corycaeus speciosus		X	X
Harpacticoida			
Aegisthus aculeatus	X		
Macrosetella gracilis	X	X	X
Microsetella rosea	X		

did not record siphonophores as being a major zooplankton group. Deevey (1971) found the annual mean abundance in the upper 500 m of the Sargasso Sea off Bermuda to be 6.45 m^{-3} , and recorded concentrations as high as 15 m^{-3} .

Chaetognaths

Of the 24 species of chaetognaths reported from the Caribbean, Michel and Foyo (1976) collected 22 in their survey. They found that almost all had extensive vertical ranges, but that each was abundant in a relatively restricted vertical range.

The offshore waters of the Caribbean are characterized by the species Sagitta bipunctata, S. lyra, S. minima, S. serratodentata, Krohnitta pacifica, K. subtilis, and Pterosagitta draco (Bjornberg 1971). Coastal waters are characterized by the species Sagitta friderici, S. helenae, and S. hispida, which are useful as indicator species to mark the presence of such coastal waters at offshore sites. S. lyra, S. macrocephala, and Eukrohnia bathyantartica are deepwater species whose presence in near-surface waters can be used as an indication of upwelling (Michel and Foyo 1976).

Euphausiids

Michel and Foyo (1976) state that the euphausiids, which can be classed as plankton or micronekton depending upon their size, were poorly sampled in their survey due to the small size and low towing speeds of their nets. Estimates of abundance or biomass of the euphausiids are lacking for the Caribbean. Sander and Steven (1973), sampling off Barbados, found that the average euphausiid contribution to the zooplankton abundance was 1.9% for surface tows and 3.9% for vertical hauls from 400 m. However, at the same

location, Moore and Sander (1977) did not record the presence of euphausiids. Because of their large size, euphausiids could be expected to have a greater importance in terms of biomass than their numbers would indicate.

Tunicates

Both thaliaceans (salps) and larvaceans are relatively abundant in the Caribbean. The larvacean tunicates are more numerous, accounting for 14% of zooplankton off southern Puerto Rico (Yoshioka et al. 1983) and constituting 5% and 2.4% of the plankton near Barbados (Sander and Stevens 1973; Moore and Sander 1977). Deevey (1971) found salps were usually present in small numbers but she once found them highly concentrated (197 m^{-3}). Like siphonophores, which also have a life cycle of alternating sexual and asexual stages, salps are most abundant in upwellings and in the eastern Caribbean (Michel and Foyo 1976).

Foraminifera

Michel and Foyo did not include the Foraminifera among the zooplankton groups which they counted in their survey. However, Moore and Sander (1977) found that they accounted for 9.6% of the surface zooplankton numbers at Barbados. Because of their small size, their contribution to the zooplankton biomass would be smaller than their numerical abundance would indicate.

Microzooplankton

The above discussion has been concerned exclusively with the zooplankton retained by the most commonly used nets. Although Michel and Foyo (1976) used a smallest mesh size of approximately $100 \mu\text{m}$, most zooplankton

studies have used mesh sizes of 202 μm or 239 μm . This agrees well with the size categories suggested by Dussart (1965), who used a logarithmic scale with the boundaries being at 2 μm , 20 μm , 200 μm , etc. We consider microzooplankton to be those animal plankters which are not retained by a 200 μm mesh net. Data on the abundance and biomass of the microzooplankton appears to be completely lacking for the Caribbean, at least for oceanic sites.

Beers and Stewart (1969) sampled both the microzooplankton and the larger zooplankton at five stations in the northeast Pacific. The microzooplankton was collected with a pumping system and was divided into size fractions by passing it through 103 μm and 35 μm mesh filters, while the larger zooplankton was sampled with a 202 μm mesh net. The figures that follow are for the euphotic zone, which varied at the 5 stations from 66 m to 108 m in depth.

The portion of the microzooplankton sample retained by the 103 μm mesh filter was dominated by metazoans, which accounted for 80 to 85% of the numbers and 97 to 98% of the biomass. Post-naupliar copepods were the dominant members of the Metazoa, while radiolarians were the most important of the protozoans, both in abundance and in biomass.

In the portion of the samples that passed through the 103 μm mesh filter but was retained by the 35 μm mesh filter the protozoans accounted for 42-68% of the numbers and 7-32% of the biomass. Tintinnid ciliates accounted for 60-80% of protozoan biomass and numbers. Naupliar copepods were the dominant metazoans.

The portion of the samples which passed through the 35 μm mesh filter was dominated by the protozoans; the only metazoans found were naupliar copepods. The protozoans accounted for 97-99% of the numbers and 77-95% of

the biomass in this size fraction. Of the protozoans, the ciliates were the most important, accounting for about 95% of protozoan numbers and biomass.

The mean displacement volume (in the top 100 m) of the large zooplankters ranged from 42 to 68 $\text{mm}^3 \text{m}^{-3}$ (0.042-0.068 ml m^{-3}), while the mean estimated volume (also for the top 100 m) of the total microzooplankton population ranged from 11 to 18 $\text{mm}^3 \text{m}^{-3}$. The contribution of the microzooplankton to the total zooplankton volume ranged from 30% at a station over the continental slope to 17% at a deep water station further offshore.

VARIATIONS IN THE ZOOPLANKTON AT OCEANIC SITES

Seasonal Variations

Seasonality has not been well established in the plankton of the eastern Caribbean, yet the recent study and discussion by Yoshioka et al. (1983) supports the concept that such cycles are present. They found biomass was highest in the summer, a trend they cite as also occurring north of Puerto Rico, at Barbados and off the northeast coast of South America.

Diel Variations

"Diel vertical movements occur in all planktonic phyla and in most of the smaller taxonomic groups" (Longhurst 1976). In general this consists of a migration from deep water toward near-surface layers, where they plankters spend the night and then descend again at dawn. The plankters do not necessarily rise all the way to the surface; aggregations tend to occur at the level of the deep chlorophyll maximum and abundance in the surface layer may even decrease during nighttime hours as a result of a downward

migration of surface dwelling zooplankters to the chlorophyll maximum layer. Such a situation was recorded by Steen et al. (1982) at a station in the Gulf of Mexico. They found that, for all size classes from 200 μm through 7 mm, the abundance in the 0-50 m layer was greatest during the daylight hours and fell significantly at night, while the inverse was true of abundance in the 50-100 m stratum. Their data indicated that migration to the 50-100 m layer was occurring both from above and below.

Our searches revealed little in the way of estimates of the increase in zooplankton abundance or biomass in the surface layer of oceanic sites. Steen et al. (1982) found that the abundance in the upper 50 m decreased by a factor of about 10 during the night hours. Commins and Horne (1979) found in their sample at the Puerto Rico benchmark site that the zooplankton abundance at 25 m at night was about half of that measured during the day.

Characteristics of the Zooplankton at Island Sites

ABUNDANCE AND BIOMASS

Because of the increased primary production, zooplankton abundance and biomass may also be greater at nearshore sites. Evidence of such an island mass effect has been found at Barbados and Jamaica. Sander and Steven (1973) found that the mean zooplankton biomass at inshore stations (10 m water depth) was 1.67 (by dry weight) to 1.71 (by displacement volume) times that found at an offshore station. Even greater differences were found at Jamaica by Moore (1967); mean dry weight and displacement volume at an inshore station were 2.5 and 2.0 times that found at an offshore station. The numerical abundance of zooplankton may also be

greater at inshore stations; mean surface abundance at Moore's inshore station was 1.94 times that found at her offshore station. It appears that displacement volume is about 0.02 to 0.03 ml m^{-3} at stations 10 km offshore, rising to about 0.4 ml m^{-3} at stations 1 to 2 km offshore and to even higher levels further inshore. Values for dry weight appear to be more variable. Moore and Sander (1976) state that the mean dry weight of 8.28 mg m^{-3} shown in Table 9 for the inshore station at Jamaica was due to the collection of a large number of pteropods on one occasion, the shells of which contributed greatly to the dry weight of that sample. Excluding that sample the mean dry weight at that station would have been about 4.6 mg m^{-3} . It appears that a mean dry weight of 3 to 5 mg m^{-3} could be considered typical of stations 1 to 10 km offshore. Mean surface abundance is even more variable than dry weight.

TAXONOMIC COMPOSITION

Copepods appear to be even more important numerically nearshore than they are at oceanic sites. Sander and Steven (1973) found that the relative abundance of copepods increased from 60.7% at their offshore (460 m) site to 87.4% at the 10 m stations. Moore (1967) also found an increase in the relative abundance of copepods from her offshore site (57%) to an inshore site (65%). Sander and Steven (1973) believed that the increased primary production at their inshore sites was utilized mainly by copepods. Copepods also appear to exhibit less diversity at nearshore sites; Youngbluth (1979) found that there were 9 copepod species which accounted for at least 75% of the total copepod abundance at each of his 7 stations. These species, Paracalanus aculeatus, Undinula vulgaris, Paracalanus quasimodo, Clausocalanus furcatus, Temora turbinata, Acartia spinata, Oithona plumifera,

TABLE 9. Mean displacement volume, dry weight and abundance of surface zooplankton at island sites in the Caribbean. All samples were taken with 203 μm or 239 μm mesh nets.

Location	<u>Indicators of island influence</u>		Displacement volume (ml m^{-3})	Dry weight (mg m^{-3})	Abundance (No. m^{-3})	Source
	Distance off- shore (km)	Water depth (m)				
Puerto Rico	0.5-1.0	10	0.086	--	818	Youngbluth 1979
Barbados	<1	10	0.049	4.00	---	Sander and Steven 1973
Barbados	<1	25	0.041	3.05	345	Moore and Sander 1976
Barbados	10	460	0.028	2.40	368	Sander and Steven 1973 Moore and Sander 1977
Jamaica	1	35	0.043	8.28	1600	Moore 1967
Jamaica	8	900	0.021	3.30	823	Moore 1967

Oithona setigera and Farranula gracilis, were also among those identified at Barbados and Jamaica (Moore and Sander 1976, 1977).

Larvaceans and chaetognaths are also important members of the inshore zooplankton community. Because these are large zooplankters, their contribution to the biomass of the inshore community is greater than their abundance would indicate. At Puerto Rico, Barbados and Jamaica the larvaceans present belong to the genera Oikopleura and Fritillaria (Moore and Sander 1976; Youngbluth 1979). Nine species of chaetognaths were identified in Youngbluth's (1979) study at Puerto Rico. However, only 4 of those, Sagitta hispida, S. serratodentata, S. tenuis and Krohnitta mutabbii (= K. pacifica), were relatively abundant. The other species appeared infrequently and then only in small concentrations (less than 0.1 m^{-3}).

Meroplanktonic larvae may also be an important part of the inshore zooplankton at some locations. While Sander and Steven (1973) stated that the relative abundance of larvae at their offshore and inshore stations was very similar (1.7-4.8%), Youngbluth (1979) found that at Puerto Rico the meroplankton accounted for an average of 11% of the zooplankton abundance with the relative abundance at some stations being as high as 17%.

VARIATIONS IN THE ZOOPLANKTON AT ISLAND SITES

Seasonal Variations

The occurrence of "true" seasonal changes in the zooplankton is not well established. Some studies (Moore 1967; Sander and Steven 1973; Moore and Sander 1976, 1977) have failed to detect any regular seasonal variations in zooplankton abundance, biomass or composition while other studies (Kidd and Sander 1979; Youngbluth 1979; Yoshioka et al. 1983) have found evidence of seasonal changes. If true seasonal variations do occur

they may be relatively small. Yoshioka et al. (1983) state that for most higher taxa the mean abundance varied by a factor of about 3.

Diel Variations

Zooplankton abundance and biomass may, at least at some island sites, increase at night. Sander and (1973) state that surface zooplankton biomass was 2 to 4 times greater at night at their inshore stations at Barbados. At Youngbluth's (1979) inshore Puerto Rican stations the biomass and abundance were, on the average, twice as great at night and the abundance of chaetognaths, larvaceans, decapod larvae and cirripede nauplii was 5 to 12 times greater. However, Yoshioka et al. (1983) found that day/night variations in abundance off Puerto Rico were either non-significant ($P \geq 0.05$) or inconsistent.

Summary

OCEANIC SITES

Most of the available quantitative data on zooplankton is from sites relatively close to land rather than mid-ocean sites. Mean abundance near the surface is in the 400 to 800 m^{-3} range, while for the upper 400 to 500 meters the mean is in the 150 to 300 m^{-3} range. Mean displacement volume is about 0.02 to 0.03 ml m^{-3} and dry weight is between 2 and 3 mg m^{-3} . Zooplankton abundance decreases with depth, but the size of the individuals increases. Michel and Foyo (1976) found that "By far the greatest numbers...are found in TSW (Tropical Surface Water) and SUW (Subtropical Underwater), approximately the upper 200 m".

Copepods are by far the most abundant macrozooplankters in this region. Various surveys have found that copepods generally account for 60-90% of total abundance. Of the copepods collected by Michel and Foyo (1976),

49.4% were calanoids, 45.4% were cyclopoids, and only 5.2% were harpacticoids. Other abundant zooplankton groups are larvaceans, chaetognaths, ostracods and foraminiferans.

It appears that there is little data available on the microzooplankton (those animals passing through a 200 μm mesh screen) in the Caribbean region. In other regions it has been found that microzooplankton may make up as much as 17 to 30% of the total zooplankton volume. The composition of this component of the zooplankton will vary with size, but radiolarians, ciliates and copepod nauplii appear to be the most important groups.

Peak zooplankton abundances have been found in the summer in some locations, which indicates the possibility of seasonal variation.

Diel variations in abundance are obvious; however, the nature of the variation changes with depth. Zooplankters which undertake vertical migrations do not necessarily rise all the way to the surface waters; many appear to aggregate at the level of the deep chlorophyll maximum. In addition, studies off Puerto Rico and in the Gulf of Mexico have found that zooplankton abundance in the upper 50 meters may decrease significantly at night, apparently as the result of a downward migration to the level of the chlorophyll maximum.

ISLAND SITES

The island mass effect is reflected in an increase in zooplankton biomass from oceanic and offshore sites to inshore sites. At inshore sites (1 to 2 km from shore) the mean surface displacement volume is typically about 0.04 ml m^{-3} . Mean dry weight for surface samples is more variable, but values from 3.5 to 5.0 mg m^{-3} can be expected.

Zooplankton composition may also be different at inshore sites, with the relative abundance of copepods being even greater than at offshore or oceanic sites. The relative abundance of the meroplankton appears to vary considerably with location; at Barbados mean relative abundance was 1.7-4.8%, while at Puerto Rico it has been found to reach 17%.

Regular seasonal variations may occur at some inshore sites; while some authors have concluded that seasonal changes do not occur, other studies have found evidence of such changes.

Zooplankton abundance and biomass may increase an average of 2 to 4 fold at night at some island sites. However, not all zooplankters show the same degree of increase, and one study has found the increase off Puerto Rico to be statistically non-significant or inconsistent.

CHARACTERISTICS OF THE FISHERIES

The Fishery in Oceanic Waters of the Caribbean

GENERAL DESCRIPTION AND HISTORICAL BACKGROUND

The fishery in the oceanic waters of the Caribbean has two main components. There is a long line fishery for the larger species such as albacore, bigeye and yellowfin tunas, with sharks and various billfishes being taken incidentally. The long line fishery has been pursued primarily by large, modern vessels from Cuba, Venezuela, Japan, South Korea and Taiwan (Kawaguchi 1974; Griffiths and Simpson 1968). There is also a pole and line, live bait fishery, pursued mainly by Cuba, for the smaller surface schooling tunas such as skipjack and blackfin. The larger tunas are generally caught in oceanic areas, while most of the skipjack catch is made

in more coastal waters (Matsumoto 1974). High wind speeds and limited concentrations of fish make purse seine operations impractical in almost all areas of the Caribbean (Juhl 1971; Evans et al. 1981).

The long line fishery began in 1954 and grew rapidly. By 1958 there were 51 Japanese vessels operating in the Caribbean (Kawaguchi 1974). However, a decrease in the catch rate by the Venezuelan fleet was noticed in the early 1960's (Griffiths and Simpson 1968), and the records of the Japanese fleet show that the catch rate of yellowfin tuna in the Caribbean fell from approximately 12 fish per 100 hooks in 1957 to about 1 per 100 hooks in 1965 (Jones 1969). By 1974 the size of the Venezuelan long line fleet had decreased by 40% from what it had been in 1970, while the catch had fallen by a nearly equal amount (Ramos-Sifontes 1976). Studies of the long line fishery indicate that the tunas caught by long line are, with the possible exception of the bigeye, being exploited at or near the maximum sustainable yield (Matsumoto 1974).

COMMERCIALY IMPORTANT SPECIES AND THEIR CURRENT STATUS

Because tunas and billfishes are highly migratory species which inhabit and are caught over a wide area, catch statistics are collected over large areas. Table 10 shows the 1970-1980 catches in the FAO western central Atlantic statistical region. This zone extends from 40°W to the coastline of the Americas, and from 35°N to 5°N. Therefore, it includes the area from roughly the middle of the Atlantic westward, and from near Cape Hatteras, North Carolina, to near the northern border of Brazil. While these figures give a general idea of the region's long line fishery, the total regional catch is not a particularly good indicator of the importance of some species in a more restricted area like the Caribbean.

TABLE 10. Estimated catch (in thousands of pounds) of commercially important tunas and billfishes in the western central Atlantic (FAO statistical area 31). This area lies between 5°N and 35°N, and from 40°W to the coastline of the Americas. Data was converted from metric tons by multiplying by 2204.6, and results were rounded to the nearest 1000 pounds. 1975-1980 data from FAO 1981. 1974 data from FAO 1980. 1973 data from FAO 1979. 1972 data from FAO 1978. 1971 data from FAO 1977. 1970 data from FAO 1975.

Common name	Scientific name	Year										
		1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Tuna												
Albacore	Thunnus alalunga	10582	18078	16094	13889	19235	12504	18245	18704	14303	12401	13236
Bigeye	Thunnus obesus	3968	3086	1543	1543	979	2586	4751	3150	1107	1810	2705
Blackfin	Thunnus atlanticus	220	220	220	441	273	395	198	370	134	212	597
Bluefin	Thunnus thynnus	882	1102	220	661	1060	2694	4645	6025	5681	5523	5692
Skipjack	Katsuwonus pelamis	3527	3748	5071	4189	6779	6486	10452	13329	4103	4586	5787
Yellowfin	Thunnus albacares	8157	16755	13669	12125	21528	14449	13166	9599	6852	10229	9579
Total		27336	42989	36817	32848	49854	39114	51457	51177	32180	34761	37597
Billfish												
Blue marlin	Makaira nigricans	2425	4409	2205	2205	2174	3426	1709	1162	1294	1411	1195
White marlin	Tetrapturus albidus	661	1102	882	661	734	822	813	143	7	22	22
Sailfish	Istiophorus platypterus	220	661	220	220	225	240	511	60	20	9	9
Unidentified		--	441	882	1102	1091	919	1149	1479	1453	664	227
Total		3306	6613	4189	4188	4224	5407	4182	2844	2774	2106	1453
Total catch		30642	49602	41006	37036	54078	44521	55639	54021	34954	36867	39050

The albacore (Thunnus alalunga) is the most important species in the region's long line catch. The main migration route of albacore in the Caribbean region follows the Atlantic side of the Lesser Antilles. During some years, however, large numbers of fish may move into the Caribbean. When this happens the albacore season begins in the northeastern Caribbean in May or June, with the fish apparently disappearing after a short period. The season resumes in the waters south of Jamaica and Hispaniola in October or November, and moves southeasterly until the fish leave the Caribbean in about January (Kawaguchi 1974).

The yellowfin tuna (Thunnus albacares) has been a mainstay of the long line fishery in the Caribbean. The season begins in May or June when fish appear in the southeast region of the Caribbean, where they may remain as late as December. In some years good catches may occur off Colombia and Nicaragua in August and September or in January and February (Kawaguchi 1974).

The bluefin tuna (Thunnus thynnus) is apparently uncommon in the Caribbean proper. Most catches in the region are from waters off the Bahamas and off the east coast of Florida (Kawaguchi 1974). Griffiths and Simpson (1968) stated that it is occasionally caught by Venezuelan long line vessels, and Erdman (1956) has recorded it from the waters around Puerto Rico. However, the catch increase shown in Table 10 is mostly due to Japanese long line operations in the Gulf of Mexico and off the east coast of the United States.

The bigeye tuna (Thunnus obesus) also appears to be much less common in the Caribbean than either albacore or yellowfin. Griffiths and Simpson (1968) reported that they are occasionally taken by the Venezuelan long line fleet, and Kawaguchi (1974) stated that some catches are made in the eastern and southern parts of the Lesser Antilles during the winter months.

The skipjack tuna (Katsuwonus pelamis) is a small, surface schooling tuna and is common throughout the Caribbean. It is seldom caught on long line gear due to its small size. It is harvested mainly with pole and line gear or, in the eastern tropical regions of the Atlantic and Pacific, with purse seines (Matsumoto 1974). Japanese vessels began exploratory pole and line operations off the north coast of Venezuela in 1973 with great success (Ramos-Sifontes 1976), and the reported catch of skipjack in the region increased for a short time.

The blackfin tuna (Thunnus atlanticus) is also a small surface schooling tuna which is usually found closer to shore than the larger tunas. Due to its small size it is not often caught on standard long line gear (Bane 1965). From Table 10 it appears to be less abundant than skipjack.

Blue marlin (Makaira nigricans), white marlin (Tetrapturus albidus) and sailfish (Istiophorus platypterus) are also taken in the Caribbean long line fishery. Kawaguchi (1974) states that blue marlin are present in the long line catch from June to October and that "There is an abundance of white marlin in the Caribbean from February to October with a peak about June,...". However, examination of Table 10 shows that the regional catch of all three species has dropped in the last 5 to 7 years; for white marlin and sailfish the decrease has been a drastic one. In examining recreational and long line catch data for the years 1972 through 1974 Beardsley et al. (1975) noted that "...there is a very real possibility that what we are now measuring is a population that has already stabilized at a very low level of abundance". From the data in Table 10 it appears that in the last few years the billfish stocks, particularly those of white marlin and sailfish, may have again experienced considerable reduction.

THE FUTURE OF THE OCEANIC FISHERIES IN THE CARIBBEAN

It appears that there is little chance that the total catch in the oceanic fishery of the Caribbean will increase significantly. It has been known for several years that albacore and yellowfin tuna are being exploited at or above the maximum sustainable yield level in the Atlantic (Matsumoto 1974; Evans et al. 1981). Although the billfishes were already a rather minor part of the total catch, their contribution has dropped rather severely in the past few years.

Any major increases that do occur in the oceanic fishery catch in the Caribbean are likely to be the result of increased exploitation of the skipjack tuna, the only significantly exploited species which is still below the MSY level (Matsumoto 1974; Evans et al. 1981). Much of the skipjack catch in the eastern central Atlantic region is the result of purse seine operations. For purse seining to be successful, hydrographic conditions must be such that the fish are unable to escape beneath the net before it is pursed. Evans et al. (1981) have identified the waters off the north coast of Venezuela as one area in which purse seining might be successful. Outside of this area any increase in the catch will have to be the result of pole and line operations, which are not as adversely affected by a deep thermocline as purse seining (Matsumoto 1974). Exploratory fishing has shown that pole and line fishing is feasible in the northern and eastern Caribbean (Wagner 1974), but the greatest part of any increase in the catch is likely to occur off the north coast of Venezuela, where upwelling occurs, purse seining may be possible and Japanese vessels have already shown pole and line operations to be successful.

The Inshore Fishery of Puerto Rico and the U.S. Virgin Islands

GENERAL DESCRIPTION

The commercial fishery in Puerto Rico and the Virgin Islands can be divided into several elements by either the type of gear or the kinds of fish typically caught. Demersal fish caught in fish traps or "pots" and by hand lines account for the majority of the catch in both Puerto Rico and the Virgin Islands. Next most important are the shellfish, including spiny lobster, conch and other species, which are caught with fish and lobster pots and by hand. The coastal pelagic fish component, in which hand lines and nets are the principal gear types, plays a lesser role in the fishery. The majority of the boats used in the fishery are small, open "yolas", typically 16 to 18 feet in length and powered by outboard motors of from 15 to 25 horsepower (Caribbean Fishery Management Council--hereafter cited as CFMC 1978).

HISTORICAL BACKGROUND

Puerto Rico and the Virgin Islands are notably lacking in fishing traditions. Few, if any, of the aboriginal Indian fishing techniques were passed on to the early Spanish settlers. The "native" fishing methods used today are, in fact, of African origin, having been introduced to the region by slaves from the Guinea Coast. Throughout the colonial period domestic fishing never played more than a minor role in the economy of the islands, and family and regional traditions of fishing as a vocation never developed.

Prior to World War II the commercial fishery in the area consisted of a small, poorly organized fish pot fishery. The lack of preservation, transportation and marketing systems often made fish unavailable except in areas near the fishing villages. The influx of military personnel to the islands during World War II greatly increased the demand for high quality fishery products, with a resultant rise in prices. Demand remained high in Puerto Rico after the war due to the development of the tourism industry. Post-war development of the fishery in the Virgin Islands has lagged 10 to 15 years behind that in Puerto Rico in terms of improvements in production and marketing practices (CFMC 1978). In recent years demand has far exceeded supply in both Puerto Rico and the Virgin Islands (Swingle et al. 1970; CFMC 1978).

SOURCES AND ADJUSTMENTS OF FISHERY STATISTICS

With a few noted exceptions, all figures and amounts used in describing the inshore commercial fishery in Puerto Rico are from the following publications: for the year 1972 - Suarez-Caabro 1973; for 1973 - Suarez-Caabro and Rolon 1974; for 1974 - Rolon 1975; for 1975 - Suarez-Caabro and Abreu Volmar 1976; for 1976 - Abreu Volmar 1978; for 1977 and 1978 - Weiler and Suarez-Caabro 1980. Similarly all uncited figures and amounts given for the inshore commercial fishery in the U.S. Virgin Islands are from Mudre and LaPlace 1980.

Catch and value figures as given in the Puerto Rico fishery statistics publications are estimated to be 80% of the actual catch for years prior to 1978; for 1978 the amounts are estimated to be 91% of actual catch. Because of this bias the values presented here have been adjusted to show the actual catch.

The reporting period for fishery statistics in the U.S. Virgin Islands, referred to here as the "Virgin Islands", runs from July through June. We refer to a year's catch as that recorded for 12 months prior to the reporting date, i.e., the figures for the period from July 1979 through June 1980 are referred to as the 1980 figures. The Virgin Islands statistics for catch and value are adjusted for the number of fishermen not reporting but are not adjusted for underestimates of catch by fishermen who do file reports. Therefore, it should be recognized that the catch and value figures given for the Virgin Islands in this report may be considerably less than the true amount.

THE IMPORTANCE OF THE COMMERCIAL FISHERY

The commercial fisheries of Puerto Rico and the Virgin Islands, although small, contribute several million dollars to the economy of those islands and provide employment for several thousand persons. The catch in Puerto Rico is marketed through a system of fishermen's cooperatives and wholesalers so the market value is much greater than the ex-vessel value shown in Table 11. In the Virgin Islands, however, no such system exists; most of the catch is marketed by the fishermen, and the market price and ex-vessel price are essentially the same. Some estimates of the market value of the total estimated catch in the Virgin Islands are: 1968-\$781,896 (Dammann 1969); 1975-\$1,159,200, 1976-\$1,187,566 (CFMC 1978); 1980-\$2,533,809 (Mudre and LaPlace 1980). We were unable to locate estimates of the total contribution of the commercial fishery to the economy of the area, or of the total number of people employed as a result of the fishery (i.e., including those employed in boat building, equipment sales, transportation, marketing, etc.).

TABLE 11. Ex-vessel value (in thousands of dollars) of estimated total inshore catch in Puerto Rico and number of licensed commercial fishermen in Puerto Rico and the Virgin Islands. Value data has been adjusted to reflect the estimated total catch rather than the reported landings. (From data in Abreu Volmar 1978; Weiler and Suarez-Caabro 1980; Mudre and LaPlace 1980.)

	1972	1973	1974	1975	1976	1977	1978	1979	1980
Value of catch	1930	1866	2261	2903	3741	4352	5271	--	--
Number of fishermen (Puerto Rico)	970	930	1120	1230	1230	1368	1442	--	--
Number of fishermen (Virgin Islands)	--	--	--	450	509	846	276	281	355

The number of commercial fishermen in Puerto Rico has grown continuously since 1973, as shown in Table 11. From 1973 to 1978 the increase was 55%. The number of fishermen in the Virgin Islands has not followed the same pattern, showing instead a great deal of variation and an actual decline in the last several years. In addition to the licensed fisherman there is, on the average, one helper per boat (CFMC 1978), so that the total number of people making at least part of their income from fishing is considerably higher than is shown by Table 11.

THE FISHING VESSELS OF PUERTO RICO AND THE VIRGIN ISLANDS

Several types of boats are used in the inshore fishery in Puerto Rico. The most common boat, called a "yola", is an open skiff, typically 16 to 18 feet long, powered by an outboard motor of about 25 horsepower. In fair weather "yolas" may be used far offshore, but they are not well suited for rough seas. Some single masted sloops, 25 to 40 feet long, are also in use. Some of these are completely decked over and have live bait wells and gasoline engine driven winches for hauling fish pots. Since 1974 the Government of Puerto Rico has made available about 50 new fishing vessels ranging in length from 25 to 51 feet. These boats are of fiberglass construction and are equipped with fishfinders, snapper reels, hydraulic pot hauling winches and provisions for refrigerating or icing the catch (CFMC 1978).

In the Virgin Islands "yola"-type boats are also the most common fishing vessels. They are generally between 14 and 20 feet in length and are powered by outboard motors averaging (in 1969) about 20 horsepower, but ranging to 175 horsepower (Dammann 1969; Olsen and LaPlace 1981). Stock design fiberglass fishing boats are also commonly used (CFMC 1978). Large

inboard powered boats are common on St. Croix, where fishermen venture further offshore; in 1968 only 7% of the boats in use on the islands of St. Thomas and St. John were inboard powered, as compared to 21% of the boats on St. Croix (Dammann 1969).

COMPONENTS OF THE INSHORE FISHERY

More than 170 species are caught in the commercial fishery in Puerto Rico. However, about 50 species generally make up the bulk of the catch (CFMC 1978). The species which are commonly reported in the Puerto Rican catch are shown in Table 12 and the total catch of important species or groups is shown in Table 13. The Puerto Rican fishery consists of three components (shallow reef fish, coastal pelagic and shellfish).

The species present in the Virgin Islands are essentially the same as in Puerto Rico but the catch is recorded by gear type, e.g. potfish, hookfish and netfish, rather than by species. The potfish catch consists primarily of shallow demersal fish, the hookfish catch includes primarily pelagic fish with some demersal carnivores and the netfish catch is of pelagic fish.

Because of the number of species taken and the fact that many species may be taken with more than one type of fish gear, we have divided the fishery into only three elements in this report. By far the most important of these, both in catch weight and in value, is the demersal fish component.

The Demersal Fishery

This component of the inshore fishery is typified by the use of fish pots or hand lines, which combined accounted for 74% of the finfish catch

TABLE 12. Species commonly reported in Puerto Rico's commercial inshore fishery. (Modified from Abreu Volmar 1978.)

Common name	Scientific name	Common name	Scientific name
Atlantic cutlassfish	<i>Trichiurus lepturus</i>	Mojarra, yellowfin	<i>Gerres cinereus</i>
Atlantic Thread herring	<i>Opisthonema oglinum</i>	Mullet	<i>Mugil</i> spp.
Ballyhoo	<i>Hemiramphus brasiliensis</i>	Parrotfish	<i>Sparisoma</i> spp.
Barracuda:	<i>Sphyraenidae</i>	Porgy	<i>Calamus</i> spp.
Great barracuda	<i>Sphyraena barracuda</i>	Sailfish	<i>Istiophorus platypterus</i>
Guaguanche	<i>Sphyraena guachancho</i>	Sardine	<i>Harengula</i> spp.
Blue marlin	<i>Makaira nigricans</i>	Sheepshead	<i>Archosargus rhomboidalis</i>
Bonefish	<i>Albula vulpes</i>	Snapper	<i>Lutjanidae</i>
Dolphin	<i>Coryphaena hippurus</i>	Blackfin	<i>Lutjanus buccanella</i>
Goatfish:	<i>Mullidae</i>	Cubera	<i>Lutjanus cyanopterus</i>
Spotted	<i>Pseudupeneus maculatus</i>	Dog	<i>Lutjanus jocu</i>
Yellow	<i>Mulloidichthys martinicus</i>	Gray	<i>Lutjanus griseus</i>
Grouper:	<i>Serranidae</i>	Lane	<i>Lutjanus synagris</i>
Coney	<i>Cephalopholis fulva</i>	Mutton	<i>Lutjanus analis</i>
Misty	<i>Epinephelus mystacinus</i>	Silk	<i>Lutjanus vivanus</i>
Nassau	<i>Epinephelus striatus</i>	Vermilion	<i>Rhomboplites aurorubens</i>
Red hind	<i>Epinephelus guttatus</i>	Yellowtail	<i>Ocyurus chrysurus</i>
Rock hind	<i>Epinephelus adscensionis</i>	Snook	<i>Centropomus undecimalis</i>
Yellowfin	<i>Mycteroperca venenosa</i>	Squirrelfish	<i>Holocentrus</i> spp.
Grunt	<i>Haemulon</i> spp.	Triggerfish	<i>Balistes vetula</i>
Hogfish	<i>Lachnolaimus maximus</i>	Trunkfish	<i>Lactophrys</i> spp.
Jack:	<i>Carangidae</i>	Tuna:	<i>Scombridae</i>
Black	<i>Caranx lugubris</i>	Blackfin	<i>Thunnus atlanticus</i>
Blue runner	<i>Caranx fuscus</i>	Little tunny	<i>Euthynnus alleteratus</i>
Crevaille	<i>Caranx hippos</i>	Skipjack	<i>Katsuwonus pelamis</i>
Greater amberjack	<i>Seriola dumerili</i>	Yellowfin	<i>Thunnus albacares</i>
Lookdown	<i>Selene vomer</i>	Wahoo	<i>Acanthocybium solanderi</i>
Palometa	<i>Trachinotus goodeii</i>		
Permit	<i>Trachinotus falcatus</i>	Conch, queen	<i>Strombus gigas</i>
Rainbow runner	<i>Elagatis bipinnulatus</i>	Land crab	<i>Cardisoma guanhumi</i>
Yellow	<i>Caranx bartholomaei</i>	Lobster, spiny	<i>Panulirus argus</i>
Mackerel:	<i>Scombridae</i>	Octopus	<i>Octopus vulgaris</i>
Cero	<i>Scomberomorus regalis</i>	Oyster, mangrove	<i>Crassostrea rhizophorae</i>
King	<i>Scomberomorus cavalla</i>	Topshell,	
		West Indian	<i>Livona pica</i>

TABLE 13. Estimated actual catch and value for Puerto Rican commercial fishery for 1976-1978. Amounts are in thousands of pounds and dollars. 1976 data from Abreu Volmar 1978. 1977 and 1978 data from Weiler and Suarez-Caabro 1980. See footnote below.

	1976		1977		1978	
	Amount	Value	Amount	Value	Amount	Value
Ballyhoo	46	19	50	23	36	18
Barracuda	46	24	80	47	79	51
Blue marlin	3	3	9	5	9	6
Dolphin	24	13	21	11	54	36
Goatfish	363	139	369	160	325	159
Groupers	664	359	804	479	924	601
Grunts	1155	444	1266	525	1167	560
Hogfish	69	43	94	60	82	59
Jacks	89	43	81	44	113	58
Mackerel	238	155	268	180	322	232
Mojarra	21	10	30	13	31	15
Mullet	90	43	108	65	105	53
Parrotfish	379	98	301	92	301	99
Porgy	81	44	79	45	70	42
Sardine	29	18	33	21	32	22
Snapper:						
Lane	154	99	189	119	405	288
Mutton	96	55	86	56	149	103
Silk	524	470	461	448	600	636
Yellowtail	160	100	203	148	243	182
Other	85	50	96	62	115	78
Snook	54	30	51	30	54	32
Squirrelfish	83	21	136	35	123	30
Triggerfish	96	44	124	57	120	50
Trunkfish	38	16	78	40	87	44
Tuna	185	81	150	71	180	85
Other fish	199	86	235	121	327	164
Conch	255	168	314	242	391	340
Land crab	13	14	5	8	5	15
Lobster	480	913	526	1033	496	1125
Octopus	10	9	14	13	5	7
Oysters	95	95	75	76	75	75
Turtles	29	33	0	0	0	0
Other shellfish	21	20	14	13	5	7
Total finfish	4968	2501	5400	2946	6056	3704
Total shellfish	903	1240	948	1385	990	1582
Total	5870	3741	6348	4331	7046	5286

The figures given in Puerto Rico's fishery statistics publications are estimated to be 80% of actual production for 1976 and 1977, and 91% of production for 1978. The published figures were adjusted by dividing by 0.8 for 1976 and 1977 and by 0.91 for 1978.

in Puerto Rico in 1978 (Table 13). Although the same species are frequently caught by both types of gear, they are used in different circumstances. Trot lines and gill nets are also used to catch shallow reef species, however, their role is relatively minor. Pots are fished in rocky or reef areas where the use of nets would be difficult or impossible. They require less training and expertise to use than do other types of gear (Dammann 1969, 1980), and are soaked several days between hauls so little attention is required. However, the use of fish pots is expensive. They cost \$30 to \$100, will last only 9 to 12 months before they need to be re-covered or replaced, and many are lost due to rough seas, vandalism, theft, or the inadvertant cutting of buoy lines by other vessels (CFMC 1978).

Hand lines are frequently used in shallow water, with many fishermen employing both hand lines and fish pots. The fish that predominate in the fish pot catch, such as grunts, porgies, parrotfish and squirrelfish, are either herbivorous or have diets that consist largely of benthic invertebrates. The bulk of the shallow water hand line catch, such as snappers and groupers, are piscivorous.

Beyond 20 fathoms the hand line is the principal gear type used; it catches many of the same snapper and grouper species present at shallower depths. In addition, some species, such as the silk snapper and the misty grouper, are caught at depths exceeding 150 fathoms (275 meters) and are not present at depths of less than 40 fathoms (73 meters) (Brownell and Rainey 1971). Some of the deep water species are highly esteemed. Silk snapper was the only finfish to command an ex-vessel price of more than \$1.00 per pound in Puerto Rico in 1978 (Table 13) and accounted for more than 40% of the total hand line catch in that year. The governments of both Puerto Rico and the Virgin Islands have made efforts in recent years

to increase the exploitation of deep water species, in hopes of diversifying the fishery and decreasing the fishing pressure on the heavily exploited shallow reef species.

Demersal fish are currently being fished at or near the maximum sustainable yield (MSY). In 1978 the Caribbean Fishery Management Council estimated in their Draft Fishery Management Plan for shallow reef fish that the MSY of Puerto Rico's fishery was 4,980,000 lbs. The 1975 estimated catch for fish pots and hand lines was 3,717,000 lbs. From 1975 to 1978 the number of fishermen increased by 17%, the number of fish pots increased by 54% and the number of hand lines increased by 146%. The estimated total fish pot catch increased by only 28% and the total hand line catch increased by only 45%. The 1978 estimated total catch for both gear types was 4,893,000 lbs, very close to the estimated MSY. Thus, the demersal fishery in Puerto Rico appears to be fully exploited as of 1978.

The demersal fish component of the fishery appears to be fully exploited in the Virgin Islands as well. The Caribbean Fishery Management Council's estimate of the MSY of shallow reef fish in the Virgin Islands was 1,850,000 lbs. The estimated total finfish catch (of which the "potfish" and "hookfish" catches comprised 92% in 1980) has remained relatively constant in the last several years despite large variations in the number of licensed fishermen. Since 1975 the largest catch, 1,288,215 lbs, was in 1980 while the smallest, 1,015,977 lbs, was in 1976 (Mudre and LaPlace 1980). These figures would appear to be well below the MSY. However, while these figures have been adjusted for the number of fishermen not filing reports, they have not been adjusted for underreporting of the catch by those who do file reports. It has been estimated that those fishermen who do file reports show only about 19 to 43% of their actual

catch (Mudre et al. 1980). Thus, the actual catch may be more than twice the amount shown above, and greater than the estimated MSY. Mudre and LaPlace (1980) noted that although the number of pot fishing trips by the fishermen on St. Thomas and St. John had increased by 8% from 1979 to 1980 their estimated fish pot catch had increased by only 3%. The authors stated, "This seems to lend credence to the now generally accepted tenet that the Virgin Islands shallow water reef fishery is presently being fished at or very near maximum sustainable yield (MSY).

The Coastal Pelagic Fishery

The other finfish component of the inshore commercial fishery is based on catching coastal pelagic species with troll lines, beach seines and gill nets. Troll lines are used to catch fast, highly pelagic species such as tuna, mackerel, barracuda and dolphin. Blue marlin are also taken, but may be an incidental part of the catch. The individual species of tuna and mackerel caught in the region can be seen in Table 12. The beach seine catch is composed primarily of hogfish, jacks, barracuda and little tunny, Euthynnus alleteratus, which comprises 16% of the Virgin Islands netfish harvest. Gill nets are effective on ballyhoo, mullet, mackerel and snook.

In Puerto Rico gill nets, beach seines and trolling each account for 7% of the total harvest. In the Virgin Islands nets account for 7% of the reported catch and the hook fishery for 11% of landings (Mudre et al. 1980). The estimate for the Virgin Islands is low because those fishermen who did file netfish catch reports reported only 19% of the amount actually caught. Without adjustment for this bias, total catches with these gear (21% from Puerto Rico and 18% from the Virgin Islands) overestimate the catch of pelagics because they include some demersal species. For example,

snappers, grunts, and trunkfish are caught in beach seines adjacent to reefs. Yellowtail snappers accounted for about 3% of the 1978 "pelagic" harvest in Puerto Rico and 5% of the 1980 Virgin Islands "pelagic" catch.

In Puerto Rico the relative importance of the pelagic fish catch appears to be increasing. The contribution of troll lines has remained relatively constant at about 7.2%. However, the contribution of beach seines has been increasing; in 1974 only 4.1% of the total catch was made with beach seines, compared to 4.9% in 1976 and 6.6% in 1978. Dammann (1969) stated that net fishing in the Virgin Islands had declined as more of the beaches became privately owned or became part of the Virgin Islands National Park.

The Shellfish Component

The shellfish catch is dominated by the spiny lobster and the queen conch but also includes oysters, portunid crabs, land crabs, octopus and the West Indian topshell, or whelk.

Although shellfish landings are a minor part of the total catch, the prices are much higher than those paid for finfish. In Puerto Rico the 1978 shellfish harvest was only 14% of the total catch, but comprised 30% of the value. Comparable figures for the Virgin Islands for 1980 were 13% and 20%. Thus, the shellfish component is of considerably more importance to the fishery than the catch figures alone would indicate.

The majority of the spiny lobsters are caught incidentally as part of the regular fish pot catch. Some fish pots are used directly for lobsters and an increasing part of the catch is made with Florida-style wood slat lobster pots. They are also caught by divers who catch them by hand or with spears or snares (CFMC 1981). Interest in fishing for lobsters has

increased recently, with Puerto Rican lobster pots increasing 260% between 1975 and 1978.

The lobster harvest appears to be near or at the MSY level. The Caribbean Fishery Management Council (1981) has estimated the MSY to be 610,000 lbs. for Puerto Rico and 219,300 lbs for the Virgin Islands (116,900 for St. Thomas-St. John; 102,400 for St. Croix). The commercial catch in Puerto Rico in 1979 was about 564,000 lbs (CFMC 1981), while the 1979 Virgin Islands reported catch was 162,686 lbs (122,105 for St. Thomas-St. John, 40,581 for St. Croix). These estimates from the Virgin Islands, however, have not been adjusted for the fact that catch reports showed, on the average, only 41% of the amount actually landed. Therefore, the actual lobster catch in the Virgin Islands may be considerably over the MSY level, particularly on St. Thomas and St. John.

The Management Council (1981) stated that indicators such as mean lobster size, size distribution of the catch and catch per unit effort show that the lobster stocks are in "a reasonably healthy state" except in some limited areas. However, they also show that mean carapace length (CL) in a 1957 survey was 4.0 inches (CFMC 1981). In a 1978-79 survey of the commercial catch it was found that the mean carapace length in Puerto Rico was 3.68 inches and that 40.6% of the catch had a carapace length below 3.5 inches. This same survey showed that mean carapace length in the Virgin Islands was greater, being about 4.52 inches, and that only 4.0% of the catch had a carapace length below 3.5 inches (Castillo-Barahona 1981). This would seem to imply that Virgin Islands stocks were not as heavily exploited as those in Puerto Rico. As shown in Table 14, the lobster catch in Puerto Rico has increased almost continuously through 1979. The catch in the Virgin Islands also increased through 1979. However, the 1980 catch

TABLE 14. Estimated total spiny lobster catch in the commercial fishery of Puerto Rico and the Virgin Islands. Dash indicates data not available. See footnote below. From data in Suarez-Caabro 1973; Suarez-Caabro and Rolon 1974; Rolon 1975; Suarez-Caabro and Abreu Volmar 1976; Abreu Volmar 1978; Weiler and Suarez-Caabro 1980; Mudre and LaPlace 1980; CFMC 1981.

	1972	1973	1974	1975	1976	1977	1978	1979	1980
Puerto Rico	296,000	313,000	304,800	389,000	480,000	526,000	495,000	562,600	--
Virgin Islands									
St. Thomas-									
St. John	--	--	--	31,200	24,283	75,220	120,145	122,105	89,333
St. Croix	--	--	--	18,400	62,262	54,534	21,283	40,581	19,762
V.I. Total	--	--	--	49,600	86,545	129,754	157,098	162,686	109,095

Data for Puerto Rico for 1972-1978 have been adjusted to show estimated total catch rather than reported catch (See Table 13). 1979 data for Puerto Rico is from CFMC 1981. Their published figure of 618,901 lbs contains a 10% increase over the commercial landings to account for the recreational catch. This increase has been removed here so that the figure for that year can be compared with those for previous years, which do not contain an adjustment for the recreational catch.

decreased by 33% from the 1979 level (27% on St. Thomas-St. John, 51% on St. Croix). This decrease in spite of increased fishing effort was interpreted as an indication of fishing at or beyond MSY levels (Mudre and LaPlace 1980).

The Caribbean Fishery Management Council (1981) has recommended that a size limit of 3.5 inches minimum carapace length be adopted. In view of the great demand for lobster in the area and the high ex-vessel value of the catch, it is apparent that catch amounts and the size distribution of the catch will have to be monitored closely to prevent over-exploitation and reduction of the stocks.

The other major species in the shellfish harvest, the queen conch, does not command as high a price as lobster, but the ex-vessel value is higher than that of most finfish (Table 13). The Puerto Rican conch catch has increased in recent years from 4.5% of total catch in 1976 to 6.5% in 1978. The size and value of the conch catch in the Virgin Islands is probably underestimated because a significant part of the catch is reported as "other species" rather than as conch. The estimated total conch catch in 1980 was 54,533 lbs, while the equivalent figure for the "other species" category, most of which was probably conch, was 17,310 lbs. Almost all (98.3%) of the conch catch was from St. Croix. Significant underreporting of the catch may be occurring with this species as well. Mudre and LaPlace (1980) report that a prominent St. Croix conch fisherman estimated that the actual catch has been relatively stable at about 200,000 lbs per year, which is apparently the saturation point of the conch market.

Conch are collected by hand, by free divers or by SCUBA divers. In other parts of the Caribbean they are also collected from boats by fishermen using long poles with hooks on the end to reach over the side and lift the

conch to the surface (Brownell and Stevely 1981). In spite of the increasing catch in Puerto Rico (Table 13) and the indication that conch landings on St. Croix had been relatively stable, Mudre et al. (1980) state that both conch and whelk "are present now in numbers only fractions of even recent historic abundance." They go on to suggest that management measures may be necessary to preserve the commercial conch resource.

The Recreational Fishery in Puerto Rico and the Virgin Islands

There is little information available on the recreational fishery in this area. There has been only one comprehensive survey of the sport fishery in Puerto Rico and none have been made in the Virgin Islands (CFMC 1978). However, from the limited information available it appears that the recreational fishery may be of considerable importance to the economy of the islands and may have a significant impact upon local fish and shellfish.

In the survey in Puerto Rico, which was made in 1972-73, a questionnaire was mailed to 1564 persons. Of the 412 who replied, 284 were active sport fishermen. They estimated their total catch during 1971 to be 214,708 lbs. From this it was estimated that the total sport fishery catch in 1971 was more than 1,000,000 lbs. It was also estimated that about 2500 sport fishing boats from 20 to 45 feet in length were registered in Puerto Rico at that time.

There are currently about 1250 powerboats in the Virgin Islands that are registered as being for recreational use. Although it is not possible to estimate how many of those are used in the sport fishery or the level of fishing they engage in, the majority must be involved to some extent, since Virgin Islands waters are not conducive to water skiing, racing or cruising (CFMC 1978).

From the data obtained in a recent mail survey of the recreational billfish and shark fisheries (covering the period from May 1977 to April 1978), Hamm and Slater (1979) estimated there were 322 boats in the billfish fishery in Puerto Rico and another 65 in the Virgin Islands. Billfish catch in the area was estimated to be 1077 blue marlin, 111 white marlin and 173 sailfish.

The sport fishery is important to the tourism industry as well as to local residents. Hamm and Slater (1979) found that only about half of the billfish catch in the area was made by boats registered with Puerto Rico or the Virgin Islands; the remainder of the catch was taken by boats from outside the area or by Coast Guard documented (charter) vessels. Although it is not known how many dollars are brought into the economy of these islands as a result of fishing-induced tourism, there can be little doubt that the amount is substantial.

Puerto Rico and the Virgin Islands have a considerable reputation for excellent sport fishing, as witnessed by articles which frequently appear in the popular literature. Species for which the area is known include blue and white marlin, sailfish, wahoo, yellowfin tuna and bonefish (cf. Botty 1977; Cunningham 1977; Mermon 1977; Henry 1979). Many gamefish records have been set in Puerto Rico and the Virgin Islands. The 1982 edition of the International Game Fish Association's World Record Game Fishes lists 15 records in various line classes for dolphin, king mackerel, skipjack tuna, wahoo and blue marlin, including the current Atlantic blue marlin all-tackle record of 581.51 kg (1282 lbs.) taken off St. Thomas in 1977.

Part of the recreational catch consists of fish and shellfish taken by free divers and SCUBA divers. As with the other elements of the sport

fishery, little is known about the amount of the catch or the species caught. However, there are several diving organizations in the Virgin Islands that sponsor spearfishing competitions (CFMC 1978).

The future of the sport fishery is intimately connected with that of the commercial fishery, since many of the same species are sought in both. The fact that commercial harvest is at or near the MSY for many species indicates that the two fisheries are in competition for an already limited resource. The one species group which does not appear to be in great commercial demand but which is avidly sought by sportsmen consists of the billfish: blue marlin, white marlin and sailfish. These species are already overexploited in the North Atlantic as a result of heavy recreational fishing pressure and a large bycatch by foreign and domestic long line vessels. The catch of white marlin, which had been fished at or near the MSY level from the mid-1960's to the mid-1970's, dropped dramatically in 1977 and remained low in 1978. The heavy fishing pressure on this species early in the decade may have severely reduced the stock size. The stock condition for sailfish is currently unclear (South Atlantic Fishery Management 1980). Although management measures are being taken to limit the catch of billfish within the Fishery Conservation Zone (FCZ), billfish are highly migratory species, and fishing effort outside the FCZ may further reduce the stocks, especially of blue and white marlin, which range further offshore than sailfish. The future of this segment of the sport fishery is therefore uncertain.

Summary

THE OCEANIC COMMERCIAL FISHERY

The commercial fishery in the oceanic waters of the Caribbean consists of a long line fishery for tunas, with billfish (blue and white marlin and

sailfish) being taken as an incidental part of the catch. The fishery is dominated by large, modern vessels from Japan, Korea, Taiwan and Venezuela. Albacore and yellowfin tuna are the mainstays of this fishery, with bigeye tuna of less importance. All of the major species caught in the long line fishery are currently fully exploited. Both blue and white marlin have been overexploited for several years, and the catch of these species has decreased considerably, indicating that the stocks have probably been decreased, particularly in the case of the white marlin. It is doubtful that there will be any major increases in the catch in the long line fishery.

Blackfin and skipjack tuna (particularly the latter) are relatively common in the Caribbean, but are seldom caught on long line gear due to their small size. Skipjack tuna are caught with pole and line gear in the Caribbean. Any major increase that does occur in the oceanic fishery will most likely be as the result of pole and line or purse seine fishing for skipjack tuna in the southeastern Caribbean.

THE NEARSHORE COMMERCIAL FISHERY IN PUERTO RICO AND THE VIRGIN ISLANDS

The commercial fishery in Puerto Rico and the Virgin Islands is a small scale nearshore fishery in which the dominant gear type is the fish trap or "pot". The dominant fishing boat type is a 16-20 foot open skiff-like "yola" powered by an outboard motor of about 25 horsepower. There has been a trend toward larger boats and motors in recent years. However, the investment potential of the fishermen is limited, so the trend is quite slow. Despite its small-scale nature, this fishery makes a significant contribution to the economy of Puerto Rico and the Virgin Islands. Total ex-vessel value of the catch is over 7.5 million dollars and several thousand people are employed in some aspect of commercial fishing.

The fishery can be described in terms of several main components which overlap slightly. The most important of these, both in weight and in value, is the demersal fish component, in which fish pots and hand lines are used to catch shallow reef species and deep water snappers and groupers. This component of the fishery accounts for about 70% of the fish pot catch, while snappers and groupers account for over 80% of the hand line catch.

The second component of the fishery is for coastal pelagic fish, using troll lines, beach seines and gill nets. These three gears account for about 21% of the total catch in Puerto Rico, but only about 16% of its value. Mackerels and tuna account for about 1/3 of the catch in this category. Other species which contribute more than 5% of the catch are snappers, mullet and grunts.

The shellfish component of the fishery accounts for only about 15% of the Puerto Rico catch, but about 30% of its value. Spiny lobster landings account for over 50% of the shellfish catch and 70% of its value. The majority of the lobster catch is made with fish pots, although lobster pots and hand collecting also play a significant role. The only other major shellfish species is the queen conch.

It appears that most demersal fishes, the spiny lobster and the queen conch are being exploited at or near the MSY level. It is possible that exploitation of deep water snappers and groupers can be increased to some degree. A recent drop in the spiny lobster catch in the Virgin Islands, despite increased effort, indicates that this species may be overexploited in that area.

THE RECREATIONAL FISHERY IN PUERTO RICO AND THE VIRGIN ISLANDS

The economic importance of the recreational fishery has not been evaluated. However, it has an international reputation and is of considerable importance to the tourism industry as well as to local residents. Its importance to tourism is indicated by the fact that 1361 blue and white marlin and sailfish were caught in the area from May 1977 through April 1978, and that about half of those were caught by Coast Guard documented charter vessels or boats from out of the area. The most important species in terms of its contribution to the tourism industry is the blue marlin, of which an estimated 1077 were caught during the period mentioned above. Other species for which the area is known are yellowfin tuna, wahoo, bonefish and some of the larger reef species.

The future of the recreational fishery is closely tied to that of the commercial fishery, since many of the same species are sought in both. The only major recreational species group not intensively sought by the commercial fishery is the billfish, which are already overexploited in the Atlantic. Therefore, the future of this segment of the recreational fishery is uncertain.

DISTRIBUTION AND ABUNDANCE OF EGGS AND LARVAE OF COMMERCIALY AND RECREATIONALLY IMPORTANT FISH AND SHELLFISH AT POTENTIAL OTEC SITES IN THE CARIBBEAN

In this section we examine (1) potential effects that the hydrographic regime may have upon the distribution of eggs and larvae, (2) reproductive strategies of some of the species, reef fish in particular, and (3) data on the spawning period of some species. These elements enable us to make generalizations on the expected distribution, both in time and in space, of

the eggs and larvae of some species. The ability to make such generalizations is important since actual data on abundance and distribution is rather scanty. The fourth and fifth elements of this section will present data on the observed distribution and abundance in oceanic waters and in the nearshore waters of island sites.

Although this section will deal primarily with fish eggs and fish larvae, the spiny lobster and the queen conch are also important commercial species in the nearshore fisheries of Puerto Rico and the Virgin Islands. Therefore, some data on these species and on decapod and gastropod larval abundance will also be presented.

Factors Affecting the Distribution of Fish Eggs and Larvae in the Caribbean

CURRENTS AND EDDIES

The surface current charts given in Wust's (1964) oceanographic atlas of the Caribbean show a simple westward drift of 1 to 1.5 knots ($0.5-0.75 \text{ m sec}^{-1}$) over much of the Caribbean, with only a few large gyres being present. This implies that the distribution of fish eggs and larvae should be relatively easy to predict if spawning areas are known. The abundance of nearshore species would be greatest near the coast of South America and near the Lesser Antilles, with a decreasing number of eggs and larvae down-current from these sources. However, such a simple picture of egg and larval transport raises questions, such as how adult populations in the Lesser Antilles could be maintained. More recent investigations have shown that the pattern of surface currents is not as simple as is pictured in the charts mentioned; eddies of various sizes have been found to exist in many parts of the Caribbean.

Molinari et al. (1980) used satellite tracked surface drifters to map the currents in the Caribbean. They found that while the overall flow closely resembled the patterns shown by Wust (1964), there were several differences. Eddies, generally less than 50 km in diameter, were abundant in the region between the Lesser Antilles and 65°W , and north of 13°N . Large, apparently temporary meanders with north-south amplitudes of 150 to 200 km were found in the mid-Caribbean from 65°W to 72°W . Transit times for some areas were considerably in excess of what would be predicted from Wust's atlas. The observed residence times of buoys in the area from 62°W to 65°W and north of 15°N was 30 to 40 days as compared to the prediction of 10 to 20 days.

Currents in the Puerto Rico-Virgin Islands area frequently do not follow the pattern of a generally northwest drift. Although Metcalf and Stalcup (1974) found that returns of drift bottles released near St. Croix were in general agreement with the pattern shown by Wust (1964), Molinari et al. (1980) found that the average current in the $2^{\circ} \times 2^{\circ}$ square centered on 18°N , 67°W was to the southeast, with a current speed of about 25 cm sec^{-1} . Frye et al. (1981) found that the mean current speed at 125 m near the Puerto Rico benchmark site was 13.4 cm sec^{-1} , with the flow being predominately to the southwest. Lee et al. (1978) measured surface current speed and direction from 7/20/77 to 9/27/77 at a station 15 km north of St. Croix. They found that the current was highly variable, particularly during periods of low current speed. From 7/20 to 8/9 the current was predominately to the east, with a speed of about 25 cm sec^{-1} . From 8/10 to 8/22 the current was to the west, with a speed between 25 and 50 cm sec^{-1} . From 8/22 through 8/28, a period of spring tides, a strong diurnal tidal current developed, with speeds of 25 cm sec^{-1} and direction alternating between east and west. From 8/28 to 9/27 the current was weak and highly variable

in direction. Significantly, on the one occasion when a vertical profile of the currents was made the current at the surface was to the east, while the current at 100 m was to the west. Although the reasons for the complex and variable current patterns in this area are not known, it seems likely that tidal forces and water exchange through the Mona and Anegada-Jungfern Passages may play an important part. Another possible cause of the observed variability of the currents is the formation of eddies in the lee of the islands.

Eddies, or vortexes, have been found in the wake of oceanic islands in a variety of locations throughout the world, and their occurrence may be quite common (Emery 1972). In the Caribbean they have been found in the wake of Barbados (Emery 1972), St. Vincent and St. Lucia (Leming 1971). Eddies may also be formed by other mechanisms. Leming (1971) believed that some of the eddies found to the west of St. Vincent and St. Lucia may have been formed by a jet action of the strong currents passing through narrow passages between the islands. In addition, eddies quite commonly form on the downcurrent side of coastal points or promontories (DeFant 1961). Wood (1975a, b) believed that small eddies formed by wind and tidal action may be a regular feature of the inshore waters of southwest Puerto Rico.

The significance of high current variability, current reversals (either with depth or with time), and eddies is that they provide mechanisms by which the residence time of eggs and larvae in an area could be greatly increased. If the residence time near an oceanic island is long enough the fish population could be self-supporting and would not be dependent upon the recruitment of larvae from the populations of upcurrent islands.

While there is little information available on the length of the larval stage of reef fishes, it is known that certain families have prolonged oceanic larval phases. Among these are the jacks (Carangidae), groupers (Serranidae), goatfishes (Mullidae) and surgeonfishes (Acanthuridae). However, the larvae of some important reef fish families have not been found in the oceanic plankton. Presumably the larvae of these families have only a brief planktonic phase. Included among these are snappers (Lutjanidae), grunts (Pomadasyidae) and parrotfishes (Scaridae).

The simplest way for nearshore fish to ensure a maximum residence time for their offspring would be to have demersal eggs and larvae that remained inshore, perhaps in the boundary layer near the bottom. However, the inshore environment, especially in the area of coral reefs, is particularly hazardous for eggs and larvae (Johannes 1978). At a coral reef off the southwest coast of Puerto Rico it was found that zooplankton abundance decreased by 60% in passing over 100 to 200 meters of the reef (Glynn 1973a). It appears that as a response to the heavy predation pressure, many inshore species have evolved a different reproductive strategy: pelagic eggs and spawning habits and locations that result in the eggs being rapidly carried offshore.

THE REPRODUCTIVE STRATEGIES OF REEF FISH

Johannes (1978) divided reef fish into five categories according to their reproductive strategy: (1) migrating spawners with pelagic eggs, (2) non-migrating spawners with pelagic eggs, (3) non-migrating spawners with demersal eggs, (4) live-bearers, (5) other or unknown strategies. By far the greatest number of commercially important nearshore species in the area of Puerto Rico and the Virgin Islands fall into the first two categories.

Migrating spawners move from their normal inshore or reef habitat to deeper waters to spawn. Munro (1974, as reported in Johannes 1978) stated that many commercially important species in the Caribbean form spawning aggregations that "appear to often be located on promontories on the seaward edge of a reef system, as far out in the open water as is possible without actually leaving the reef." Olsen and LaPlace (1979) investigated a grouper spawning aggregation in the Virgin Islands that took place on the 100 fathom curve, i.e., at the shelf break. Since leaving their normal habitat increases the risk of predation, spawning migrations are generally limited to larger species (Sale 1980; Johannes 1978). Such spawning migrations have been documented or are suspected to occur in one or more species of sphyraenids (barracuda), serranids (groupers), lutjanids (snappers), carangids (jacks), scarids (parrotfishes) and gerreids (mojarra) (Johannes 1978).

Non-migrating spawners with pelagic eggs also have spawning behaviors that increase the chances of their eggs being carried offshore. One common behavior begins with a rapid upward dash. Gametes are quickly released at the top of this dash, after which the fish immediately dive to the bottom. This behavior pattern is known to occur in at least some species of scarids, mullids, acanthurids (surgeonfish), and labrids (wrasses and hogfish) (Johannes 1978; Munro 1976). Other species have evolved a similar behavior. Spawning takes place above a large coral head or rock. The fish are thus well above the bottom but are still relatively close to shelter.

The production of demersal eggs and the live-bearing of young appear to be strategies used mainly by the smallest and commercially unimportant reef fish. Among the major species in Puerto Rico's commercial catch only the triggerfishes (Balistidae) have demersal eggs.

Johannes stresses that little or nothing is known about the reproductive habits of many species. In addition, some species do not fit into any of these categories. However, it appears that almost all of the commercially important species in the Puerto Rico-Virgin Islands area have pelagic eggs and larvae, and exhibit reproductive behaviors that enhance the probability that their eggs will be rapidly carried away from the reef and into offshore waters.

The results of larval distribution studies in the Hawaiian Islands support the hypothesis of offshore transport of eggs and larvae of reef fish. Sale (1970) found that acanthurid larvae were more abundant in tows made 48-58 km off Oahu than in tows made 4.8 to 8.0 km offshore. Working at several island sites Miller (1974) found larvae of acanthurids, labrids, scarids and chaetodontids comprised only 0.2% of the ichthyoplankton even though those families dominate the inshore population. In another survey Leis and Miller (1976) found that the relative abundance (i.e., the % contribution made to the total abundance) of the larvae of reef fish with pelagic eggs was greatest (about 30%) at the stations furthest offshore (10-12 km). The larvae of reef species with demersal eggs had their greatest relative abundance at the most inshore stations (0.5 km), while the larvae of coastal pelagic species were fairly evenly distributed. As in Miller's (1974) study, the larvae of such oceanic families as the myctophids, gonostomatids and scombrids were surprisingly abundant in inshore waters. Leis (1982) found that the concentration (no. m^{-3}) of the larvae of reef fish with pelagic eggs in tows 3.0 km offshore was 1.6 times that found in tows made 0.2 km offshore, while the abundance (no. m^{-2}) was 16.6 times greater.

The pattern of greater abundance of reef fish larvae at offshore sites is not limited to the Hawaiian Islands. This same pattern has been observed off the northwest coast of Cuba (Dekhnik et al. 1973) and for eggs at several other sites in the Caribbean (Moore 1967; Sander and Steven 1973; Moore and Sander 1976).

SPAWNING SEASONS

Many tropical marine fish have very long spawning seasons. However, the tropical marine environment is not entirely without variation. Within this extended spawning season there may be one or more peaks in spawning, and for many species the peak periods coincide. As a result, there is considerable seasonal variation in the abundance of eggs and larvae in the Caribbean.

Munro et al. (1973) investigated the spawning periods of reef fish off Jamaica and presented detailed information on 35 species. Erdman (1977) has compiled the results of more than 20 years of observations in Puerto Rico and the surrounding area and presented data on over 300 species. Unless otherwise noted, the information that follows comes from one or both of these sources, and often is a synthesis of the two. Since Erdman presents data basically on a presence/absence basis and does not indicate the percentage of fish found in spawning condition, most of the information on peak spawning periods comes from Munro et al.

Balistidae--Spawning occurs from January to July, with an apparent peak in February.

Carangidae--Spawning occurs throughout the year, with the peak occurring in February through May.

Holocentridae--Spawning in this family appears to occur throughout the year, at a continuously low level of activity.

Labridae--Spawning appears to begin in November or December and continues until April for the hogfish (Lachnolaimus maximus). Some of the commercially unimportant wrasses may spawn throughout the year.

Lutjanidae--Spawning appears to be almost continuous in many species. In some species there were no signs of spawning in late fall months (October through December). Peak spawning for most species occurs in February through May, with a secondary peak in September or October.

Pomadasyidae (grunts)--At least some species spawn throughout the year, with a peak in activity in February through April. There may be a secondary peak in activity in September. Some species appear to remain at a low level of activity, without any peaks in spawning.

Scaridae--Spawning occurs mainly in January through June, with a peak in February and March. Some species exhibit a secondary maximum in August and September.

Serranidae--Spawning is, for most species, confined to the period from January through May, with the peak being in February or March. Members of the genus Epinephelus appear to have more extended spawning periods than members of the genera Mycteroperca and Serranus.

Sparidae (porgies)--The season extends from November to March, with peak spawning being in February.

Sphyraenidae--It appears that spawning occurs in February through May (with a peak in March and April), and again in August and September. There may be a low level of spawning during June and July.

Scombridae--Many species spawn throughout the year, with a peak in the summer months. In some species, such as the little tunny (Euthynnus alleteratus) and the king mackerel (Scomberomorus cavalla), spawning appears to be limited to the period from May through October.

Istiophoridae (billfish)--The spawning season for the blue marlin (Makaira nigricans) extends from April to September. White marlin (Tetrapturus albidus) are known to spawn during April and May, while for sailfish (Istiophorus platypterus) the season runs from May through September. Sailfish may spawn only off the east coast of Florida (South Atlantic Fishery Management Council 1980).

Panulirus argus (spiny lobster)--In Jamaican waters berried (egg carrying) females have been found throughout the year, with the greatest frequency occurring in June, followed by March (Aiken 1977).

Strombus gigas (queen conch)--Spawning in the Virgin Islands begins in February or March and ends in November (Randall 1964). In Venezuela it was found that spawning did not begin until July (Brownell et al. 1977).

As can be seen from the information above, many reef fish species spawn from January or February through May. From their data for Jamaica, Munro et al. (1973) computed the expected seasonal pattern of relative abundance of reef fish eggs for that area and found that abundance from February through April could be as much as 12 times greater than the abundance in June through December (Fig. 3). Due to the lack of information on the fecundity of reef fish, Munro and his colleagues were forced to assume that egg production per unit body weight was the same for all species. Therefore, while still valuable, their results must be considered a rough approximation only.

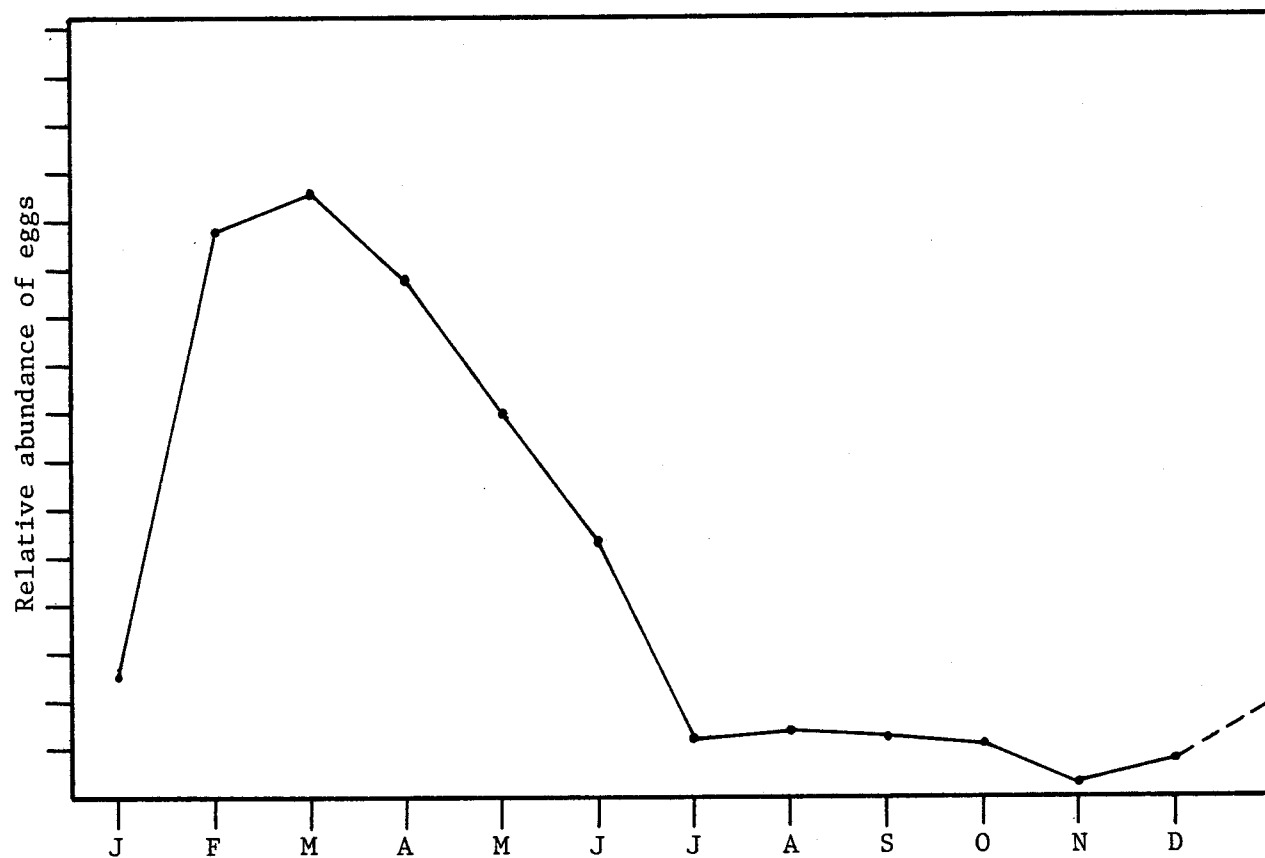


FIGURE 3. Computation of relative monthly abundance of reef fish eggs in the plankton, based upon the observed monthly incidence of ripe fishes of the twenty most important species on the shallow reefs at Port Royal, Jamaica. These species collectively comprise about 70% of the reef fish biomass as indicated by trap catches. (From Munro et al. 1973.)

THE THEORETICAL DISTRIBUTION OF EGGS AND LARVAE IN SPACE AND TIME

From the information presented above we can draw a general picture of the distribution of the eggs and larvae of the important commercial and recreational species in the Puerto Rico-Virgin Islands area. The eggs of reef species will be most abundant during the late winter and early spring, with a pronounced decline in abundance during June and July. The eggs of billfish and tuna will be most abundant during the summer. Eggs of some tuna species will be present throughout the year, although in reduced numbers.

Distribution in space will be more complicated. Reef fish eggs and larvae should be more abundant at locations more than 3 km offshore than at locations closer to shore. Peak abundance may occur more than 10 km offshore, after which the abundance will again decrease. Peak abundance may exceed the abundance at inshore locations by as much as an order of magnitude. Significant numbers of the larvae of oceanic species may appear at inshore locations.

Abundance, Distribution and Kinds of Larval Fish--Measurements and Observations

OCEANIC SITES

Most of the investigations at oceanic sites in the Caribbean have been made by Cuban or Russian investigators. Many have been concerned solely with scombrid larvae due to the economic importance of that family. To date the only complete survey of which we are aware has been that conducted by Richards (1981, in press) as part of the MARMAP program.

During this survey a total of 5,569 larvae were collected at 65 stations during the summer of 1972, while 3,928 larvae were collected at 45 stations

during the winter of 1973. Richard's data (in press) show that the mean abundance during the summer cruise was about 509 larvae under 10 m^2 of surface, while the corresponding figure for the winter cruise was about 300 larvae under 10 m^2 . Mean concentrations in the upper 200 m (the nominal depth of the tows) were about $243/1000 \text{ m}^3$ and $137/1000 \text{ m}^3$, respectively. Richards did not find any trends in abundance with latitude or closeness to land, or a relation between the hydrography and abundance at a station.

As would be expected, the most abundant larvae were those of the myctophids and gonostomatids. Larvae of the families Scaridae and Labridae were highly abundant, as were those of the family Gobiidae. Larvae of the families Bothidae, Carangidae, Nomeidae and Scombridae were also abundant. Among the scombrids the most common larvae were those of the skipjack tuna, Katsuwonus pelamis. The most common larvae of the genus Thunnus were those of the blackfin tuna, Thunnus atlanticus. Larvae of the genus Auxis, of the little tunny (Euthynnus alleteratus), chub mackerel (Scomber japonicus), wahoo (Acanthocybium solanderi) and the Atlantic bonito (Sarda sarda) were also taken, although in small numbers. Scombrid larvae were more abundant during the summer, when 125 larvae were collected (1.95 larvae per station), than during the winter, when only 25 larvae were taken (0.56 per station).

Richards (1981) stated that the abundance of the larvae of many oceanic species in his samples was similar to that found by Ahlstrom (1971, 1972) in the eastern tropical Pacific. However, the areas differed in that scombrid larvae were more abundant during winter in the eastern tropical Pacific (Ahlstrom 1972). In addition, the ichthyoplankton in the Caribbean appears to be somewhat more diverse than in the eastern tropical Pacific. In

Ahlstrom's studies 10 families accounted for over 90% of the larvae, while in the Caribbean the top 15 families accounted for only 69-74% of the larvae (Richards in press).

The ichthyoplankton in the eastern Gulf of Mexico has been surveyed by Houde et al. (1979). The composition of the larval fish catch there was quite different from that in the eastern tropical Pacific or in the Caribbean, presumably because of the expanse of continental shelf in the Gulf of Mexico and the fact that many of the stations were located over the shelf. However, it should be noted that larval abundance was similar to that found in the other surveys, the mean number of larvae under 10 m^2 being about 425.

In all three surveys larvae of the billfishes (Istiophoridae) were conspicuously uncommon; only two larvae were collected in the eastern tropical Pacific (Ahlstrom 1971), only two in the Gulf of Mexico (Houde et al. 1979) and only four in the Caribbean region (Richards in press). However, while billfish larvae are relatively uncommon, they are neustonic and are particularly agile swimmers. Because of this they will be under-sampled by the nets and oblique tows used in all three surveys (Houde et al. 1979; Richards in press).

NEARSHORE SITES

Larval fish concentrations are somewhat higher at stations off the southeast coast of Puerto Rico than off the west coast of Barbados or in the Hawaiian Islands. Examination of the data of Vargo et al. (1981) shows that the mean concentration (over three cruises) for stations 2 to 20 km off Punta Tuna was $670/1000 \text{ m}^3$ in the upper 25 meters and $550/1000 \text{ m}^3$ in

the 200-25 meter stratum. This is equivalent to a standardized abundance of 1130 larvae beneath 10 m^2 . Powles (1975) found that the mean abundance in the upper 60 meters at stations 1.5 to 38.6 km off Barbados was $434/1000 \text{ m}^3$, while Miller (1974) recorded mean values of 60 to $140/1000 \text{ m}^3$ at stations less than 5 km off Hawaiian islands.

The larvae of mesopelagic species may comprise a major part of the catch at island sites, while the larvae of commercially important fishes may comprise only a small part of the catch. Myctophid and gonostomatid larvae accounted for over 38% of the catch in Powles' (1975) survey off Barbados. In contrast, Powles noted that the numbers of larvae of commercially important fish "were small relative to numbers of other fishes." His data show that larvae of the families Carangidae, Labridae, Serranidae, Lutjanidae, Holocentridae, Scaridae, Sphyraenidae and Balistidae comprised only 9% of the total catch, with larvae of the Scombridae accounting for another 1.5%.

The larvae of oceanic fishes may be particularly abundant at inshore sites. Powles (1975) found that the concentrations of myctophid, gonostomatid, scombrid and bregmacerotid (codlet) larvae were higher at stations on the 180 m contour than at stations further offshore, although the difference was not statistically significant for the first three families. In the Hawaiian Islands Miller (1974, 1979) also found gonostomatid and scombrid larvae to be more abundant at sites close to land.

Abundance of larvae of inshore fishes appears to vary seasonally, roughly following the pattern predicted for reef fish eggs by Munro et al. (1973). At Barbados the abundance of larvae was high during spring and low in summer (Powles 1975). The abundance of larvae taken in the upper 25

meters off Puerto Rico by Vargo et al. (1981) increased from 170/1000 m³ during the November cruise to 370/1000 m³ during February and to 1460/1000 m³ in May. Corresponding values for the 200 to 25 meter stratum were 120, 360, and 1160/1000 m³, respectively. Powles (1975) found the abundance of scombrid larvae to be highest during July and lowest during February, in agreement with the pattern seen at oceanic sites by Richards (1981).

THE VERTICAL DISTRIBUTION OF FISH LARVAE

Most fish larvae are found in the upper 150 meters, inhabiting the mixed layer and the upper portion of the thermocline. Vargo et al. (1981) caught very few fish larvae below 200 meters at their stations off Punta Tuna, and concentrations in the upper 25 meters were higher than those in the 200-25 meter stratum. However, the differences were quite small.

The concentration of larvae may vary considerably within the upper 150 meters. It has been found that zooplankton and fish larvae may aggregate along chlorophyll maxima (Hobson and Lorenzen 1972; Lasker 1975). With continuous recording plankton samplers it has been found that these chlorophyll maxima may occur as very thin layers, no more than a few meters thick (Parsons et al. 1977). Fish larvae feeding on these thin layers of phytoplankton and zooplankton may also be concentrated in very thin layers, making the use of continuous recording samplers or highly stratified sampling with nets necessary to accurately determine the vertical distribution of fish larvae at any given site.

Abundance and Distribution of Fish Eggs--Measurements and Observations

Data on fish egg abundance at nearshore sites are available from several zooplankton studies made in the Caribbean. While the data are not

conclusive, they do tend to support the theory that reef fish eggs are rapidly transported away from reef areas and into offshore waters.

ABUNDANCE AT NEARSHORE SITES

While most of the abundance figures are given as percent of total zooplankton, it appears from information on zooplankton and the few data on egg concentrations (Table 15) that the decrease in relative abundance of eggs near shore is due to a decrease in the egg concentration rather than an increase in the concentration of other organisms.

SEASONAL VARIATIONS

Measures of larval abundance support the prediction that egg abundance is greatest in late winter and early spring months, with a secondary maximum in late summer. At Moore's (1967) offshore station at Jamaica values over 400 m^{-3} were recorded in January, February, March and August. The greatest single monthly value (575 m^{-3}) occurred in March. At the inshore station sampled during this same study the results were somewhat less supportive of the expected seasonal cycle, with the highest monthly value being recorded in June. Near Puerto Rico, Youngbluth (1975) found that the highest concentrations at his stations 2.6 km off the coast were recorded in February (204 and 229 m^{-3}). However, during the previous February the concentration was only 37 m^{-3} . Thus, while some support is given to the predicted seasonal abundance pattern, it appears that the inherent patchiness in fish egg distribution is great enough to largely obscure any pattern that does occur.

TABLE 15. Mean numerical and relative abundance of fish eggs in surface tows at island sites in the Caribbean.

Location	Indicators of island influence		Mean abundance (3/m ³)	Relative abundance (%)	Source
	Distance offshore (km)	Water depth (m)			
Jamaica	8	900	236	28.7	Moore 1967
Jamaica	1	35	79	4.5	Moore 1967
Puerto Rico (Cabo Mala Pascua)	2.5	---	84	---	Youngbluth 1975
Puerto Rico (Cabo Mala Pascua)	0.5-1	10-20	50	---	Youngbluth 1975
Barbados	10	460	---	30.9	Sander and Steven 1973
Barbados	2	35	---	4.8	Moore and Sander 1976
Barbados	< 0.5	10	---	1.8	Sander and Steven 1973

THE VERTICAL DISTRIBUTION OF FISH EGGS

The great majority of fish eggs should be found in or above the upper portion of the thermocline, the steep density gradient at the thermocline being an effective barrier to further downward drift (cf. Ahlstrom 1959; Coombs et al. 1981). What little data is available from the Caribbean is in agreement with this prediction. At the offshore station at Barbados both Sander and Steven (1973) and Moore and Sander (1977) found that the mean relative abundance of fish eggs in oblique tows from 400 m was only about 60% of that from surface tows. Southeast of Puerto Rico Vargo et al. (1981) found concentrations in the upper 25 m were higher than in the 200-25 m stratum, particularly during the May cruise when concentrations were highest.

DIEL VARIATIONS

Diel variations in fish egg concentration may also occur. Youngbluth (1979) found that the mean night/day catch ratio for six inshore stations was 1.2. In a separate study of the zooplankton in a shallow embayment Youngbluth (1980) noted diel differences in the types of eggs present. During the day oblong eggs, perhaps of engraulid or gobiid species, were more common, while large, spherical eggs were more common at night. Johannes (1978) cited several studies which have found reef fish egg concentrations at night to be as much as 7 times those found during the day, and stated that spawning during twilight or night hours may serve to decrease predation both on the spawning adults and on their eggs (the presumption here being that the eggs will be carried away from the reef before the next morning).

Distribution and Abundance of Spiny Lobster and Queen Conch Larvae

LARVAL STAGES

The spiny lobster (Panulirus argus) has a prolonged planktonic larval phase. There are 11 larval stages, termed phyllosoma larvae, which represent molt changes, as well as a puerulus post-larval phase. The planktonic phyllosoma phase lasts from 6 to 9 months. Apparently most studies have been concerned solely with the distribution of larvae, and we have been unable to find the data needed to determine abundance and concentration. In addition, it is not possible at this time to identify Atlantic Panulirus phyllosomes to species (Richards and Potthoff 1981).

The long duration of the larval phase makes it difficult to determine the source of recruits to a given area or the destination of larvae spawned in that area (Richards and Potthoff 1981). It has long been thought that, as a result of the long larval phase and the prevailing large scale circulation pattern in the western Atlantic, recruits must have their origin a considerable distance upstream. Therefore, the adult population in the Puerto Rico-Virgin Islands area may not be self-supporting in terms of providing its own recruits. However, if recruits originated at sites considerable distances upstream, then genetic differences between populations in the area should be minimal due to dispersion of larvae (Menzies and Kerrigan 1979). Recent research has shown that definite genetic differences exist among populations in the Caribbean. This implies that the populations in these genetically distinct areas (of which the Virgin Islands is one) must be essentially self-supporting; if even a few percent of the recruits were from outside populations any genetic differences would

be wiped out in a few generations (Menzies 1981). This does not preclude the arrival of larvae from other areas. However, any larvae which do arrive apparently do not survive to maturity, perhaps due to environmental factors (Menzies 1981).

The queen conch (Strombus gigas) has a planktonic veliger larval phase which, in tank reared specimens, has been found to last from 27 to 35 days. For the first 19 days the larvae occur primarily at the surface (Brownell et al. 1977). Young larvae may therefore be undersampled by commonly used oblique zooplankton tows.

ABUNDANCE AND DISTRIBUTION OF LOBSTER LARVAE

Some data on the abundance of lobster larvae are available from micro-nekton samples taken off Puerto Rico by Vargo et al. (1981). Unfortunately, larvae less than 20 mm in length were not counted in their study. The larvae counted would therefore correspond to stage X or stage XI phyllosoma larvae or to puerulus post-larvae (Richards and Potthoff 1981). Vargo et al. (1981) found that the mean concentration of counted lobster larvae in the upper 25 m during their November and February cruises were $0.1606/1000 \text{ m}^3$ and $0.3346/1000 \text{ m}^3$, respectively. Corresponding figures for the 200-25 m stratum were $0.0906/1000 \text{ m}^3$ and $0.1313/1000 \text{ m}^3$. This decrease in observed concentration may not be due solely to a decrease in actual abundance. A change in the size composition of the larvae could result in the same observations since only larvae of 20 mm or more in length were counted. Concentrations of larvae were greater at night. The night/day concentration ratios in the upper 25 meters during the November and February cruises were 12.5 and 3.8, respectively. It is not clear whether net avoidance during daylight hours or diel migrations are responsible.

Moore (1967) stated that phyllosoma larvae were collected at her offshore station at Jamaica on two occasions, at concentrations less than $1/\text{m}^3$, and were not found at her other stations.

ABUNDANCE AND DISTRIBUTION OF GASTROPOD LARVAE

Mean surface concentration at Moore's (1967) offshore station at Jamaica was 23 m^{-3} . Her data at this station does show some evidence of seasonal variations in concentration, since the lowest concentrations were generally found in December through February. However, this pattern was not apparent in the data for her inshore station. Mean surface concentration at the latter station was 56 m^{-3} .

Youngbluth (1979) found that the mean abundance of gastropod larvae constituted about 4% of total zooplankton abundance at his 6 inshore stations at Puerto Rico, with values for individual stations ranging from less than 1% to 7%. Mean concentration for the six stations was 28 m^{-3} . Mean night/day concentration ratio at three of his stations was 2.1.

We were unable to locate information on the vertical distribution of gastropod larvae. However, as discussed previously, it appears that queen conch larvae, at least, may be much more abundant in the surface layer.

Summary

Based on the known spawning periods, the reproductive strategies of the fish and the information gained in fish egg and larvae surveys in the Hawaiian Islands, it appears that reef fish eggs should be most abundant during the months of February through April, with a marked decline occurring in June. Abundance should be greatest at locations 3 to 10 km

offshore. Considerable numbers of myctophid, gonostomatid and scombrid larvae may be present at inshore stations. Tuna larvae will be considerably more abundant during summer months.

FISH LARVAE--MEASUREMENTS AND OBSERVATIONS

Oceanic Sites

Larval fish abundance at oceanic sites in the Caribbean is similar to that in the eastern tropical Pacific and the Gulf of Mexico. Mean concentration is about 250/1000 m³ during the summer and about 150/1000 m³ during the winter. In comparison, the mean abundance in a survey in the Gulf of Mexico was about 425/10 m².

The most abundant larvae are those of myctophids and gonostomatids. Scarid and labrid larvae are also abundant. The most abundant scombrid larvae is that of the skipjack tuna, while the most abundant larvae of the genus Thunnus is that of the blackfin tuna. Scombrid larvae are about 4 times more abundant in summer than in winter.

Island Sites

A survey at offshore and inshore sites at Barbados showed the mean larval abundance in the upper 60 m to be 434/1000 m³. As at oceanic sites, the most abundant larvae were those of myctophids and gonostomatids. The relative abundance of scombrid larvae was about 1.5%. Larvae of all three of these families were more abundant at stations on the 180 m curve (1.5 km from shore) than at stations further offshore.

At Puerto Rico the mean concentration in the upper 25 m was found to be 670/1000 m³, while the corresponding figure for the 200-25 m layer was

550/1000 m^3 . Abundance there was highly seasonal; concentrations in May were nearly an order of magnitude greater than those recorded in November.

Little information is available on the vertical distribution of fish larvae in the Caribbean. It appears that they are most abundant in the upper 25 m, particularly at night. However, it is possible that aggregations may occur in thin layers at or near the chlorophyll maximum layer. Few larvae are found below 200 m.

FISH EGGS--MEASUREMENTS AND OBSERVATIONS

Oceanic Sites

We were unable to locate data on the abundance or distribution of fish eggs at oceanic sites in the Caribbean.

Island Sites

It appears that fish eggs may be more abundant at offshore sites than at inshore sites, as predicted. Surface concentrations of over 200 m^{-3} have been recorded at stations about 10 km off Barbados and Jamaica. At inshore stations (1 to 2 km offshore) the surface concentration appears to be about 30 to 70 m^{-3} . There is evidence that supports the prediction that egg concentrations will be much higher in late winter and early spring months. However, this pattern, if it exists, is largely obscured by natural patchiness.

Little data is available on the vertical distribution of fish eggs, as most samples have been taken at the surface. Abundance should, however, be much greater in the upper 100 m than below that depth, as the pycnocline will form an effective barrier against downward drift.

It appears that fish eggs are more abundant at night, probably due to increased spawning during twilight and night hours. Night/day catch ratios of 1.2 have been recorded at Puerto Rico. Studies in areas outside the Caribbean have found that ratio to be as high as 7.

SPINY LOBSTER AND QUEEN CONCH LARVAE

The spiny lobster has a very long planktonic larval phase which lasts more than 6 months. As a result, distribution could be expected to be widespread and even, and the recruits to the Puerto Rico-Virgin Islands area should come from adult populations far upcurrent. However, genetically distinct populations have recently been found to exist in some areas (the Virgin Islands being one of these) showing that the populations in these areas must be essentially self-supporting. The queen conch has a planktonic veliger larval phase that lasts about 30 days.

Larval lobster concentrations of 0.1 to 0.3/1000 m³ have been recorded off Puerto Rico. However, these were very late phyllosoma or puerulus larvae, and the concentration of all larval stages may be considerably greater.

We were unable to locate any information on the abundance or distribution of queen conch larvae. Total gastropod larvae surface concentrations at stations 1 km off Puerto Rico and Jamaica ranged from 5 to 56 m⁻³; the abundance appeared to decrease at stations further offshore.

OTHER IMPORTANT BIOLOGICAL RESOURCES

Corals

Living coral reefs are a common feature of the east, west and south coasts of Puerto Rico. They are virtually absent along the north shore due

to the higher levels of erosion, runoff and water turbidity found there (cf. Glynn 1973b; Adey 1977; Sands 1980). Off Cabo Mala Pascua, about 2 km to the west of Punta Tuna, there is a system of inshore fringing reefs and a series of long narrow shelf-edge reefs running parallel to and about 2 km off the shoreline. The basin between the two reef systems reaches a depth of over 20 m (Wood 1975).

Living reefs are also common at St. Croix. The St. Croix shelf extends about 16 km beyond the eastern point of the island. The central part of this shelf, which is generally about 20-23 m deep, is only sparsely covered with coral. However, the shelf is bounded by a raised edge which rises to a depth of 11-15 m and which is richly covered with corals, sponges and gorgonians. The southern shelf is much narrower, about 3-4 km in width. Much of it is covered with inner and middle "bank barrier" reefs (Adey et al. 1977). Extensive reef systems are apparently rare or absent on the west and northwest shore (Ray et al. 1981), although isolated coral heads and patch reefs are present (Dammann 1969, pp. 53-71).

The preservation of living corals is important because of their recreational and tourism value and their importance to many of the fish caught in the nearshore fishery. In addition, the destruction of a coral reef is often followed by an increase in the incidence of ciguatera fish poisoning.

A search of the recent literature did not reveal any investigations of the tolerance of coral organisms to chlorine or cold shock, which they might suffer from if exposed to the discharge from an OTEC plant. However, it is known that many coral species can survive several hours of exposure to 15°C water (Stoddart 1969). This is approximately the temperature that would be found in a mixed discharge from an OTEC plant. However, this

discharge would be diluted by a factor of 4 to 10 or more within a few hundred yards of the outfall (Paddock and Ditmars 1982). Therefore, it does not appear that OTEC plant operations will result in coral mortality from cold shock unless the outfall of a land or shelf based plant is located in the immediate vicinity of a reef.

Endangered Species

A number of marine species which are listed as threatened or endangered, including several species of turtles, are found in the waters off Puerto Rico and the Virgin Islands (Table 16). Leatherback and hawksbill turtles nest at scattered sites throughout the Virgin Islands. About 40 leatherback turtles annually nest at Sandy Point Beach on the southwest corner of St. Croix. This nesting area, along with the adjacent waters out to the 100 fathom line, has been declared a Critical Habitat (National Fish and Wildlife Laboratory 1980; Carr et al. 1982). Although extensive beaches for turtle nesting occur along the north and west coasts of Puerto Rico, continued exploitation has severely reduced the populations and very little nesting takes place on those beaches. Most of the nesting in Puerto Rico takes place on Mona Island or on Culebra and Vieques. There is a sizeable leatherback nesting area on Vieques, and many hawksbill turtles nest on Mona Island (Carr et al. 1982).

Humpback whales are present in the area from January through April, during which time they calve and mate. They are found almost exclusively between the 10 and 100 fathom lines on banks on the Atlantic side of the Antillean islands. The great majority of the whales are found at Silver Bank and Navidad Bank, off the north coast of Hispaniola (Winn et al. 1975).

TABLE 16. Endangered and threatened species found in the waters around Puerto Rico and the Virgin Islands (CFMC 1981).

Common name	Scientific name	Status
Sei Whale	<u>Balaenoptera borealis</u>	Endangered
Humpback whale	<u>Megaptera novaeangliae</u>	Endangered
Sperm whale	<u>Physeter catodon</u>	Endangered
West Indian manatee	<u>Trichechus manatus</u>	Endangered
Caribbean monk seal	<u>Monachus tropicalis</u>	Endangered
Green sea turtle	<u>Chelonia mydas</u>	Threatened
Hawksbill sea turtle	<u>Eretmochelys imbricata</u>	Endangered
Loggerhead sea turtle	<u>Caretta caretta</u>	Threatened
Olive ridley sea turtle	<u>Lepidochelys olivacea</u>	Threatened
Leatherback sea turtle	<u>Dermochelys coriacea</u>	Endangered
Brown pelican	<u>Pelicanus occidentalis</u>	Endangered

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APPENDIX 3: A MINOR INTERNSHIP PRODUCT-

**CIGUATERA FISH POISONING:
A BRIEF SUMMARY OF OUR CURRENT KNOWLEDGE**

CIGUATERA FISH POISONING:
A BRIEF SUMMARY OF OUR CURRENT KNOWLEDGE

R.E. Rose

THE ILLNESS

Ciguatera is an illness caused by eating certain tropical reef fish. The symptoms vary widely, even among individuals who have eaten from the same fish. However, the victims usually exhibit some or all of the following: nausea, diarrhea, weakness or prostration, joint or muscular pain, tingling or itching or numbness of lips and extremities, confusion of sensations of heat and cold, loss of coordination, and difficulty in breathing. In severe cases the loss of coordination becomes general, and paralysis, coma and death as a result of respiratory arrest may occur (Randall 1958; Banner 1976).

Although ciguatera is seldom fatal, the neurological symptoms may last for weeks or months. In addition, victims are apparently sensitized; eating any fish from the area may bring on a recurrence of symptoms even though that same fish would not be toxic to others. Ciguatera can constitute a major health problem in areas where it is common. As yet there is no standard, effective treatment and no antitoxin is available. Treatment is complicated by the variability of symptoms.

Ciguatera can cause economic problems as well as public health problems. It may be weeks or even months before a victim is able to return to work. Local fishermen may find that they are unable to sell their catch. Since certain species of fish are more likely to be toxic than others, the commonly toxic species may be left unfished while species generally considered safe are overexploited (Randall 1958).

The Fish Species Involved

In general, ciguatoxic species are limited to those herbivores which feed on algae or detritus on coral reefs (particularly surgeonfish and parrotfish) and to the larger reef carnivores that prey largely on these herbivores. Carnivorous fish known to cause ciguatera include groupers, jacks, snappers and barracuda. Many other reef species which do not fit into the above categories have also been reported to cause ciguatera on occasion (Banner 1976).

The Distribution of Ciguatoxic Fishes in Space and Time

Ciguatoxic fishes are generally limited to a circum-global band extending from 35°N to 34°S. Within this band toxic fish are much more common near tropical islands than along continental margins. The highest incidence appears to be in the tropical Pacific islands and in the West Indies (Halstead 1978).

The distribution of ciguatoxic fish is extremely patchy. The abundance of toxic fish may vary greatly among neighboring islands, and even at one small island toxic fish may be present only at certain locations (Randall 1958; de Sylva and Higman 1980). The toxic areas are frequently associated with passages or inlets in the reef (Randall 1958; Banner 1976).

The abundance and distribution of toxic fish may also change with time. Fish may suddenly become toxic in an area where ciguatera was previously unknown. Once present, the incidence of toxic fish may remain relatively constant or may decrease over a period of several years. Sudden outbreaks are often associated with damage to reef areas caused by storms or man-made alterations (Randall 1958; Banner 1976).

Not all species at a location will have the same toxicity. When an outbreak of ciguatera occurs it is the herbivores that become toxic first.

However, the carnivores retain their toxicity for a much longer period of time. The most dangerously toxic fish are the large carnivores, suggesting a transfer and concentration of the toxin through the food chain (Randall 1958; Banner 1976; de Sylva and Higman 1980).

Ciguatera in Puerto Rico and the Virgin Islands

The area of Puerto Rico and the Virgin Islands appears to have the greatest incidence of ciguatera in the Caribbean (de Sylva and Higman 1980). The illness is so common in the Virgin Islands that the president of the Virgin Islands Medical Association has estimated that nearly every adult there has been poisoned at least once (Doorenbos 1979). Ciguatera is also seen as a serious impediment to the further development of the fishery in the Virgin Islands (cf. Dammann 1969; Dammann et al. 1970; Brody 1972; Sylvester et al. 1977).

THE CAUSE OF CIGUATERA

Recent studies in the Pacific have revealed that Gambierdiscus toxicus, a previously undescribed benthic dinoflagellate, may be responsible for ciguatera. This dinoflagellate, which is epiphytic on benthic macroalgae, dead coral and detritus, has been found to produce both the fat-soluble ciguatoxin (previously isolated from toxic moray eels) and a water-soluble toxin which has been named maitotoxin (Yasumoto et al. 1977a,b). Scaritoxin, which is also believed to have a role in causing ciguatera, is believed to be a metabolite of ciguatoxin (Bagnis 1981). G. toxicus has been found to occur at the Gambier Islands, Tahiti, Moorea, Bora Bora, Okinawa, Hawaii, and the Virgin Islands (Doorenbos 1979; Yasumoto et al. 1980a; Nakajima et al. 1981; Shimizu et al. 1982).

Subsequent investigations have revealed a number of other toxin producing benthic dinoflagellates. Some of these produce ciguatoxin and maitotoxin, while others produce toxins that are as yet unidentified. It is not yet known whether these other toxins enter the food chain the way ciguatoxin and maitotoxin have been shown to do (Yasumoto et al. 1980b; Nakajima et al. 1981).

These findings do much to explain the nature and pattern of occurrence of ciguatera. The dinoflagellates are ingested by herbivores feeding on algae or detritus on the reef. Maitotoxin is a particularly potent toxin (Yasumoto et al. 1979). Therefore, herbivores might be toxic to man even though they contained only a small amount of maitotoxin. However, since maitotoxin is water-soluble, it might be flushed out of the body of a fish relatively soon after the abundance of the toxic dinoflagellates decreased. Ciguatoxin, while not as toxic as maitotoxin, is fat-soluble and would not be flushed from the body. Transfer and concentration of ciguatoxin through the food chain would result in the large piscivores containing enough toxin to cause ciguatera, and they might continue to be toxic long after the herbivores were safe to eat. The fact that three or more toxins are involved and may be present in varying ratios may be responsible for the varied symptomology of the illness.

FACTORS AFFECTING THE DISTRIBUTION AND ABUNDANCE OF G. TOXICUS

It appears that only one investigation has been made of the environmental factors responsible for the vast observed differences in the abundance of G. toxicus. Yasumoto et al. (1980a) surveyed the abundance of G. toxicus at sites at Tahiti, Moorea, Bora Bora and the Gambier Islands and analyzed water samples taken at those sites. They found that in the Gambier Islands the dinoflagellate was more abundant at sites in a passage between two islands, in accordance with many observations that toxic fish were more common around

passages and reef inlets. However, they were unable to detect any correlation between the abundance of G. toxicus and the level of total and inorganic phosphorus, nitrate, nitrite, silicate, iron, dissolved organic carbon or vitamin B₁₂. They stated that the lack of correlation suggests that benthic community structure may determine the abundance of G. toxicus.

G. toxicus has been found to show a definite preference for certain species of host algae (Yasumoto et al. 1980a; Shimizu et al. 1982). Therefore, it is possible that the abundance and distribution of these macroalgae (and of substrates suitable for their growth) may, at least in part, determine the distribution of G. toxicus.

Bagnis (1981) states that G. toxicus is "weakly endemic most of the time, but proliferates massively on coral beds killed as a result of disturbances which periodically upset reef ecosystems", the denuded coral being a substrate on which benthic algae can settle. However, Banner (1976) has pointed out that other environmental factors must also come into play since many large-scale reef disturbances have not been followed by an increase in the incidence of ciguatera.

In summary, it appears that even if reef disturbances are necessary for a sudden increase in the abundance of G. toxicus, they are not sufficient to cause such an increase. Other factors, as yet unknown, must also be present for a sudden proliferation to take place.

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