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A HISTORICAL REVIEW OF THE PHYSICAL AND BIOLOGICAL CHARACTERISTICS
OF THE OCEAN NEAR PUERTO RICO, RELATIVE TO AN OTEC POWER PLANT

by

M. L. HERNANDEZ AVILA, J. A. SUAREZ CAABRO AND GARY C. GOLDMAN

REPORT FOR WORK SUPPORTED BY U.S. DEPARTMENT OF ENERGY THROUGH
LAWRENCE BERKELEY LABORATORY, PROJECT NUMBER 4983802

Gary C. Goldman, Principal Investigator

Center for Energy and Environment Research

University of Puerto Rico

College Station

Mayaguez, Puerto Rico 00708

August 1979

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EXECUTIVE STATEMENT

As Puerto Rico is considered among the prime locations for operating OTEC plants, the U.S. Department of Energy is looking at the oceanographic conditions around the island. The OTEC criteria apply to more than one location around the island, and although this report covers the general characteristics of the waters around Puerto Rico, the primary emphasis is on the Punta Tuna area, on the southeast of the main island.

This document is in response to a portion of a 4-phase project designed to secure and evaluate oceanic physical and biological data at the Punta Tuna site. The phases provide for:

1. The compilation of a yearly set of periodically sampled oceanic data at the benchmark site of Punta Tuna.
2. An interpretation of the relevant literature, recently procured data, and long-term current meter data taken concomitant to this program.
3. A thorough historical literature and data search of oceanic data and an interpretation thereof.
4. Recommendations for future studies of the OTEC oceanographic program.

This document addresses the last two phases of the project.

One of these two phases consists of two major requirements: an historical literature search and a historical data search. The literature search has provided two full bibliographies. Each of these bibliographies appears as a

Separate appendix in this report, one dealing with the Physical oceanography, and the other with biological citations. The data search has reaffirmed to us the fact that this area of the world's oceans has not been sufficiently studied to statistically say, with any certainty, what the year-to-year and month-to-month variations in most of the Physical parameters might be, let alone the short-term variations. We can only begin to identify some trends in most cases (i.e., surface temperature, thermal resource, Subsurface temperatures, and salinity}. The historical record of deep water motion studies in the area is sparse indeed, as are biological descriptions of the area.

The other phase of the project consists of recommendations for future oceanographic studies. These recommendations

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dations are based on both the present understanding of the OTEC concept, and our understanding of the oceanic conditions in the area.

The other two appendices at the end of the report contain pertinent supplemental information. One of these appendices discusses the near shore currents along the south coast, and the other has temperature vs. depth profiles from the historical data sets of the area.

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1.0. INTRODUCTION

Puerto Rico is now considered by the U.S. Department of Energy as being among the prime locations for the placement of one of the first operating Ocean Thermal Energy Conversion (OTEC) power generating plants. The specific area of Puerto Rico that is being considered lies about two

miles southeast of Punta Tuna, a point on the southeast of the main island. This site is close to deep, cold water,

has year-round warm surface water, is reasonably available by air and surface transportation, and could be easily incorporated into the island-wide electrical power grid. These criteria also apply to many locations around the island.

This report covers the general characteristics of the waters around Puerto Rico, but the primary emphasis in the report is placed on the Punta Tuna area.

The intent of this document is to gather and interpret the available information, both published and unpublished, that will enhance the knowledge of the physical and biological oceanography of the area. We have also developed two extensive bibliographies, one of the pertinent physical oceanography, and one of the pertinent biological oceanography. Finally, after a review of the historical results and the fiscal 1979 data collection program, recommendations are made for increasing the effectiveness of the future OTEC field data collection program

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2.0. PHYSICAL OCEANOGRAPHY

2.1. INTRODUCTION TO PHYSICAL OCEANOGRAPHY

The Commonwealth of Puerto Rico, associated with the United States by bilateral agreement, consists of a main island and several smaller islands. These islands are

all located along the Antilles Chain of islands, extending almost from Florida, U.S.A. to Venezuela, South America (see Fig. 1). Puerto Rico's approximately half way along the Chain, about 1700 km from Miami, Florida. The nearest large land mass to Puerto Rico is the island of Hispaniola about 130 km to the west. The Chain can be considered the separation between the Atlantic Ocean and the Caribbean Sea. As Puerto Rico is situated along an east-west axis,

the Atlantic washes its north coast, and the Caribbean, its south coast. At the latitude of about 18°N. Puerto Rico is in the trade wind belt, with both the winds and Oceanic currents generally moving east to west past the island.

The main island of Puerto Rico is roughly rectangular in shape, about 180 km east to west, and about 60 km north to south. The island is a mixture of mountains, rolling hills, and broad flat plains. Where the plains meet the sea, the climate is typically tropical marine (except along the ?desert-like southwestern coast)-

This literature review of the physical oceanographic conditions at the proposed Punta Tuna OTEC Site in Puerto Rico will be restricted to the following parameters:

Climate

Wind regime (including hurricanes)

Waves regime

Oceanic and island shelf currents

Salinity and temperature depth distribution

Two distinct seasons appear to emerge in the literature, as seen from the standpoint of the hydrographic conditions of the surface waters along the south coast of Puerto Rico. This assertion is based mainly on climatological processes, in particular the wind system, generate the water circulation patterns (currents) in the upper waters, which affect and modify the distribution of mass as determined by the distribution of temperature and salinity. The available climatic and sea-state observations along the continental shelf of the South Coast are sufficient to indicate a winter trend and a summer trend. The hydrographic data, although sparse and probably insufficient, also reveal

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significant seasonal variations during the winter and summer

months. These winter-summer variations are demonstrated by the existing reports and regional environmental data summaries to be discussed within this report.

Deep water circulation at the Punta Tuna OTEC site needs to be monitored for longer periods of time; the available data are insufficient to characterize the current variations in the area (Webster, 1969).

2.2. CLIMATE

In general, the climate of Puerto Rico is typically tropical marine. That is, during the day as the land mass heats up, a convection cell is developed, causing the winds to move landward from the sea, bringing the moist sea air with them. In the evening as the land cools, the convection cell reverses and the winds blow offshore. Due to the numerous hills and mountains on the island of Puerto Rico, the moist sea air is frequently cooled to saturation while still over the land mass. This causes considerable rainfall, almost daily over some parts of the island.

The Punta Tuna OTEC site, typical of much of the island, also has a tropical marine climate. Using data from the

U.S. Weather Service Command (1974) and the U.S. Air Weather Service, general meteorological statistics. can be developed.

In summary, the meteorological conditions are as follows:

For the north coast area (Fig, 2) there is no summer and winter, but simply a change from wet season to a somewhat drier season. Air temperatures vary within a mean daily range of 10 to 15 Fahrenheit degrees, fluctuating between the low 70's and the low 80's from December through April and between the mid 70's and the upper 80's from May through November.

The lowest value recorded at San Juan Airport was 60.1°F.

Prolonged intervals of either sunny, cloudless weather or completely overcast weather are unusual. The common condition is partly cloudy, in which the cumuit occupy between 40 to 60 percent of the sky. Relative humidities are high during the entire year, usually ranging between 65 and 85 percent. Only rarely does the relative humidity drop below 50 percent. Dense fog is seldom seen. Squalls and thunderstorms are common from May through November.

Although the U.S. Coast Guard has maintained a light station at Punta Tuna for many years, no statistical compilation has ever been made of the weather data observed at

that station. Statistics do exist for San Juan, about 40 km

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northwest of Punta Tuna. Some of these values are shown in Table 1. The thirty-year (normal) values of temperature and rainfall, as well as the 23-year (normal) values of relative humidity, are seen in the table as a function of month.

Values from Punta Tuna would probably be similar to these.

For tropical marine areas, atmospheric pressure changes are normally very small. Changes of 5 mm of mercury (0.2 inches) over a couple of months is rare. However, the proximity of severe tropical weather, such as tropical depressions, waves, storms, or hurricanes, could cause large drops in the atmospheric pressure. These pressure changes, in turn, are instrumental in controlling the local sea level.

As the sea level is changed by such pressure disturbances, deep water is brought up toward, and in some cases, to, the surface. This could bring cooler, more dense water to the surface, which could seriously affect the operation of an OTEC plant. Table 2 shows the expected minimum pressures as a function of frequency in years to return again.

Figures 3 and 4 are reproduced from (Atwood, et al. 1976). Figure 3 shows graphically the monthly maximum, minimum, and mean air temperature for the oceanic area south of Puerto Rico. The data indicate that the maximum temperatures usually occur in late summer, and the cooler temperatures occur in late winter. The monthly mean temperature seems to vary only a couple of Fahrenheit degrees above or below 80°F. The maximum range of values ever expected

would be only +10 F® from the mean. -

Figure 4 shows the frequency of occurrence of values of relative humidity for the same oceanic region south of Puerto Rico. About 85% of the time the relative humidity is above 70%.

Table 3 summarizes the meteorological and climatic factors for the Caribbean Sea, as taken from Publication

H.O. 21, U.S. Dept. of Commerce (1958). The summary indicates there are very small pressure variations throughout the year, and relatively higher temperature and precipitation in the summer and autumn months.

2.3. TIDES

The tides on the Caribbean coasts of Puerto Rico are generally of the mixed diurnal type, with a small semi-diurnal Component. An amphidromie. (nodal) joint of the principal

lunar senidturnal? (¥) tidal constituent lies near the site (Atwood et al., 1976; Dietrich, 1963; Defant, 1961). The nearness to the node implies minimal tidal motion. In addition, as Punta Tuna is on the somewhat exposed eastern side of the island, the tidal system affecting the North Atlantic

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(with its amphidromic east of Newfoundland) may also affect our site. The result could be a moderately confused tidal Current over our area of interest. Figure 5, reproduced from Atwood et al. (1976), shows the predicted tides as taken from the U.S. Department of Commerce Tide Tables (1973) for Puerto de Maunabo, Puerto Rico. This listed station is only about 0.5 km west of Punta Tuna. The figure illustrates the ximun? (spring) typical tidal range (about 55 cm) which coincides with a new moon stage and summer solstice.

?The tidal currents in the Punta Tuna area are expected to move generally east and west. The tidal current is expected to move westerly during the flood tide, and easterly during the ebb tide. The actual result of this tidal motion on the prevailing water motion at Punta Tuna is still unknown.

2.4 WIND REGIME

The periodicity and overall stability of the wind regime and atmospheric pressure variations along the north coast of Puerto Rico, being under the influence of the Trade Wind system, are documented for all to see. This is illustrated in Tables 4 and 5, taken from the U.S. Coastal Pilot, Area 5 (U.S. Dept. of Commerce, 1976), and from the U.S. Naval Weather Service Command (1974), respectively. Table 4 shows the summary of weather data observed at the San Juan airport. The results are similar to, but not the same as, the oceanic conditions along the south coast. Table 5 summarizes the wind observations at Vieques, the large island east of the main island (Fig. 2).

The U.S. Coastal Pilot, Area 5 (U.S. Dept. of Commerce, 1976), summarizes the wind regime on the coasts of the island as follows:

The prevailing winds over Puerto Rico are the E trades, which generally blow fresh during the day. The center of

the Bermuda High shifts a little N in Summer and S in winter changing the direction of the winds over that island from NNE in winter to ? in summer.

Factors which interrupt the trade wind flow are frontal and E wave passages. As the cold front approaches, the wind shifts to a more S direction, and then as the front passes there is a gradual shift through the SW and NW quadrants back to NE. The E wave passage normally does not bring a W wind but is usually characterized by an ENE wind ahead of the wave and @ change to ESE following the passage.

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Major disturbances to the normal trade wind circulation are caused by the passage of easterly waves, hurricanes, tropical storms, squalls, and thunderstorms. Hurricanes and tropical storms are the two most important influences. Dur-

ring the winter months, cyclones originate over the Gulf of Mexico and move northward along the east coast of the United States. These depressions move slowly out into the North Atlantic where they can generate southward-moving waves having large heights and long wave lengths. Swells produced in this manner commonly approach the study area.

The distribution of wind speed for the area near Vieques is given in Figure 8. The most frequently occurring wind speeds lie between 5 to 8 m/s, occurring 37.3% of the year. Wind speeds between 3 and 11 m/s occur 75.7% of the year and indicate the predominance of moderate wind speeds in the study area. High wind speeds in excess of 14 m/s occur only 4% of the year.

The percentage of the year that wind speeds at Vieques exceed a given value is shown in Figure 9. The average wind speed is 6 m/s. Winds exceed 18 m/s about .1% or approximately 9 hours a year.

Extreme wind speeds associated with hurricanes are given in Figure 10. The Figure gives the percentage of time the wind speed will exceed a given value for the duration of one hour and the return interval for extreme winds. The annual maximum wind speed for one hour is expected to be between 23 and 28 m/s. The maximum wind speed lasting one hour expected

in ten years is between 29 and 39 m/s.

The distribution of winds over the principle compass directions is given in Figure 11, Winds from the east dominate the statistics, occurring 52.5% of the year. The next most likely wind direction is northeast, occurring 23.9% of the year. Winds with an easterly component (NE, E, Sé) account for 89.5% of the observed winds.

Atwood, et al. (1976), summarized wind regime data for the area taken from Publication H.O. 21, U.S. Dept. of Commerce (1958), and from the USNOO, Environmental Acoustic Atlas of the Caribbean Sea and Gulf of Mexico (Vol. II, Mar. Envir., SP 189, 1972). The data show that windspeeds

average from 4.5 to 5 m/s in autumn, to 6 to 8 m/s in summer, with strong northerly winds of greater than 14 m/s occurring from November to April when the passage of fronts and: easterly waves interrupt the normal trade wind pattern. The frequency of these northerly winds, according to the data in SP 189IT, is about 2% of the year. Northerly winds are also common during the nighttime when diurnal variations in the Trades are accentuated by the landbreeze system generated by the island of Puerto Rico landmass. Figures 7 to 10 of the

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Figure 11, Annual frequency distribution of vinds? over
the principal coupass directions.

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Atwood report (reproduced here as Figures 12 to 15) show a crude summary of the oceanic wind conditions around the island of Puerto Rico," (Atwood, et al. 1976).

Lee, et al. (1978) summarized the wind regime of a nearby area in their assessment of an OTEC site off the island of St. Croix, U.S. Virgin Islands. They referred to the slight seasonal variation of the Trade Winds system which generates high winds from 7 to 13 m/s during summer. The average monthly wind speeds range from 5 m/s

in October to 8 m/s in July (Miller, 1977--cited by Lee, et al. 1978), with an annual mean of approximately 6 m/s, according to Burns, 1977, cited by Lee, et al. 1978. Citing the above investigators, the wind regime variations are Summarized as follows:

The wind direction is out of the eastern quadrant throughout the year. Winds are generally due east

during the summer, when the doldrum belt is over Venezuela and the Bermuda High is most intense and extensive. At other times of the year, when the doldrum belt is south over the equator, the Bermuda High weakens and winds are more out of the northeast. Tropical storm force winds (17 m/s) have been observed in all months. ~

Easterly waves occasionally affect

the Virgin Islands area. During Summer, 1977, two waves passed in

the vicinity of St. Croix causing an increase in wind speeds (up to 15 m/s) and heavy rains. These tropical waves form to the north of the inter-tropical convergence zone in the deep easterly flow that flows clockwise around the Southern portions of the Azores anti-cyclone (H.O. Pub. 22). During the Passage of an easterly wave, winds are ENE ahead of the wave and ESE following

(Burns, 1977)."

2.5. HURRICANES

The characteristics of hurricanes reaching the United

States have been intensively studied; however, similar infor-

mation is not available for hurricanes at lower latitudes.

The study site does, in fact, lie somewhat along the hurricane

track as the storms transit westward from the Atlantic to

the Gulf of Mexico.

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Some information about hurricanes affecting the study site can be determined from the U.S. Dept. of Commerce review of major hurricanes between the years 1873 and 1967. During these 94 years there were 94 hurricanes reported, an average of one hurricane per year. Many of these hurricanes passed to the north or south of the proposed site, and would have affected weather conditions around it. Figure 16 shows the track of two such hurricanes. There were 30 hurricanes during the 94-year period that passed within 100 km of Vieques. The intensity range of the storms, in increasing order, is: average, major, extreme, and great hurricanes, as given in Table 6. The mean recurrence interval for hurricanes strongly affecting Vieques is about 1 per 3 years. These storms, however, are not uniformly distributed over the years. As shown in Figure 17, the hurricanes affecting Vieques have occurred in groups. ?In some years (1933 and

1955) two hurricanes occurred in one year. During some other periods, no hurricanes occurred for many years.

Atwood, et al. (1976) and Lee, et al. (1978) showed the tracks of some devastating North Atlantic hurricanes in their reports. These hurricanes must have affected the Proposed Puerto Rico OTEC site. The map of these hurricane tracks is reproduced here as Figure 18. Figure 19 shows the graph for the occurrence of tropical cyclones in the five degree square bounded by $150^{\circ}\sim 20^{\circ}\text{N}$, $65^{\circ}\sim 70^{\circ}\text{H}$, from Atwood, et al. (1976). Recurrence probability of tropical storms in the Puerto Rico area is about 70% annually; mean translation velocity movement of these storms is about 12 kts towards the west-north-west (U.S. Naval Weather Service Command, 1974). Clearly, August and September are the most affected months, with a significant number occurring in July and October as well.

2.6. WAVE STATISTICS

Wave statistics for the study area were taken from the Summary of Synoptic Meteorological Observations (SMO),

Area 23, which is near Vieques, P.R. Wave statistics for the

\$8M0 data are based upon several years? visual observations.

In addition, one year of measured data reported by Deane (1974) was also used.

The distribution of significant wave heights for the area of Vieques is given in Figure 21. The most frequently occurring wave height is in the interval of .3-.8 m occurring 418 of the year. The average significant wave height is Tmepetave, netghts in the range from <3 to 1.4 m occur 79.3% of the year. Large wave heights greater than 2.3 m occur rather infrequently, accounting for only 1.3%.

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Figure 16, Track of hurricanes affecting the study site.

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The distribution of wave periods for Area 23 is given in Figure 22. The dominant wave period is less than 6 sec, accounting for 78.7% of the year. The average wave period is 5.9 sec. Wave periods indicative of swell (greater than 9.5 sec) occur only 1.8% of the year.

The percentage of wave heights that exceed a specific value is given in Figures 23 and 24. Figure 23 gives the cumulative percent of low to moderately large wave heights.

Wave heights exceed 3 m only about 0.5% of the year, or about 2 days (43.8 hours) per year. The extreme wave height cumulative percentages and return intervals are given in Figure 24. Two lines are shown which give conservative (larger value) and liberal (smaller value)

height values. Wave heights between 5.5 and 6 m would recur on an average of once every 3 years. Wave heights of above 8 m are expected very infrequently, recurring on the average of about once every 100 years.

Wave height versus wind speed for the study area is shown in Figure 25. Wave height increases slowly with wind speed until about 6 m/s, then there is a rapid increase in wave height. At a wind speed of 4 m/s, the significant wave height would be about 0.3-0.5 m; for a

8 m/s wind, the significant wave height is 1 to 1.2 m, and for a 9 m/s wind, the significant height is about 1.5 m.

"Seas and swells" observations are reported daily

to the U.S. Naval Oceanographic Data Center (NODC). This governmental agency compiles all the observations reported by ocean going ships, and statistically summarizes the characteristics and range of the waves. Tables 9 to 11 are reproductions of summaries published by the U.S. Naval Weather Service Command in the SSMO (1974). An analysis of these tables reveals a winter-summer wave regime difference. Table 9, the tabulated annual summary, points out the known dependent relationship between the wind system and generated swell variations. Wave periods, although very infrequently, may reach values greater than 10 seconds, the mean range being from 4 to 8 seconds for a mean wave height range of .6 to 2m. A summary of the Sea swell data in the tables indicates that the values for direction and period for the swells in the winter are similar to those of autumn, and those occurring in the Spring are similar to the summer values. In the winter, the swells of period less or equal to 5 seconds usually come from the east or northeast, about equally divided. In summer, the direction comes from the east almost all the time. For the 6-9 second period swells, the winter values are usually from the east, with a significant percent from the northwest to northeast. In the summer, the number from non-east directions is almost zero. Finally,

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some swells of period greater than 9 seconds occur in the winter, going from north to east. During the remainder of the year almost none of these long waves can be expected.

Figures 26 to 32 are reproductions of Figures 15 to 19, and 21 to 22 in the Atwood, et al. (1976) report.

These figures show # seas and swells analysis for different months of the year as taken from the data contained in

SP 18911 for the oceanic region surrounding Puerto Rico.

The authors point out that these data "do not take into account the masking at Yabucoa by the islands of Puerto Rico and Vieques." According to these investigators the information in these figures is given for "its value as @ guide to the conditions which may be expected while the Plant is being towed to the site from its place of construction." The data in the mentioned report are summarized as follow:

The percentage of "calm" swell is over 85% for winter and summer in coastal waters and less than 19% in the open ocean. Similarly, swell

in the coastal area is never ob-

Served in the quadrant ? to E (0° to 90°) but in the open ocean this quadrant accounts for over two-thirds of all observed swell, and nearly all observations greater than 12 feet high (3.6 meters).*

Bretschneider (1977) calculated by hindcasting methods a design wave for potential OTEC sites which included the Punta Tuna site in Puerto Rico. Table 12 shows the results of the analysis conducted by Bretschneider (1977) for hurricane wave and wave spectra parameters for the sites

considered. From this table the most probable hurricane is Predicted as having a wind of greater than 41 m/s, with waves averaging over 7m, and peaking at about 20'm. The Results of a frequency and spectral density analysis for various sea state and wind velocity spectrums are illustrated on pages 19 to 39 of Bretschneider's report, by means of Spectral density curves and tables.

2.7. WATER MASSES

The water masses in the Caribbean have been discussed by many authors (Wust, 1963; Atwood et al. 1976; Craig et al. 1976, Lee et ai. 1978}, but for completeness they shall be mentioned again here in this report in order to consolidate the information.

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intake opening at 1000 m depth, the intake water would come from approximately 50-100 m above and below that depth.

Therefore, for the purposes of this report, the water masses

in the upper 1100 m of water in the northern Caribbean will be considered,

The upper water mass is named the Tropical Surface Water. The origin of this water is under the equatorial atmospheric trough (low), which is a tropical rain belt located to the northeast of South America. As this water mass is influenced by the precipitation in that area, it is also influenced by the rain and runoff in the drainage basins of the Amazon and Orinoco Rivers in the northeastern part of South America. The water mass is then driven by the winds and the earth's rotation into the Caribbean Sea. By the time it reaches Puerto Rico, the temperature and salinity of this upper water mass has been further affected by the general and local climate of the area through which it is passing.

Further precipitation, runoff, and evaporation from wind and insolation could further influence both the temperature and salinity. Typical ranges of these parameters seen in the Tropical Surface Water are salinities varying from 33-36 (with excursions both above and below these values), and temperatures from 25°C to 29°C. This water mass may attain its maximum depth and actually be wedge-shaped along the northern Caribbean, due to the geostrophic subsidence as the water moves westward. However, the actual depth of the water mass, may be influenced greatly by the atmospheric pressure and its variation. Normally, the pressure changes little, with

changes of 3-6 cm of mercury in a month considered large. However, as a tropical pressure trough moves through the Caribbean, the pressure is severely reduced, causing the water level to be raised, pushing the upper water mass to the side, and upwelling the cooler, more saline lower water mass. These conditions would occur in the case of a hurricane, but also to a lesser degree during a tropical wave or a tropical storm. The effect on an operating OTEC plant could be at least to severely reduce its efficiency, in the case that the plant had not already been shut down.

The water mass directly below the Tropical Surface Water is called the Subtropical Underwater. This lower water mass originates directly beneath the Bermuda atmospheric high pressure zone. This high pressure zone is the atmospheric downwelling component of the Hadley cell which gives rise to the Equatorial Atmospheric Trough, which in turn is related to the origin of the Tropical Surface Water discussed above. The air and climate under the Bermuda High is warm and dry. Also, due to the relative humidity, evaporation is great and Salinity is increased, making this water the most saline in all the Caribbean. This water mass then descends to form the upper portion of the thermocline in the Caribbean. The salinity seen within the Subtropical Underwater ranges from

36.8‰ to 37.2‰. As the water rarely comes into contact

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with any diluting agent, the salinity remains quite high, and relatively invariant. Furthermore, as mentioned above, during conditions of low atmospheric pressure, this water can push upward, and the very high salinity seen in the surface water during these times is evidence of this water mass having been upwelled.

The temperature range within this water mass is greater (20°C-24°C) than the water mass above. As the heat may be conducted upward or downward, the temperature does not remain as invariant as the salinity. The density difference between the Tropical Surface Water and the Subtropical Underwater is large enough to maintain the two water masses as quite distinct. The Subtropical Underwater moves generally south and westward into the Caribbean, under the faster moving, more turbulent surface water mass. AS the lower water mass moves westerly into the Caribbean, it is seen to

dilute to about 36.5‰–36.6‰ in the Yucatan Strait. In the vicinity of Puerto Rico, the water moves southward through both the Anegada and Nona Passages, then south and westward through the Caribbean. The core of this water mass is frequently seen to lie at about 150 m depth in the Puerto Rico area

Below this water mass lies a transition zone of indistinct characteristics. The transition zone contains the lower portion of the thermocline, and extends into the definite area of the cold water zone. This transition water is a mixture of North Atlantic Central Water and diffused and diluted Mediterranean Water. The salinity ranges about 36.8‰, from the water mass above it, down to about 35‰. The temperature ranges from 20°C to about 7°C. This transition zone reaches from about 200 m to 600 m depth. Just below this zone lies the oxygen minimum, which many people define as the boundary of the cold water zone in the oceans.

The Antarctic Intermediate Water is found just below this transition zone. This water is formed at the Antarctic Convergence Zone, about 45°–55° latitude. The water tends to

be low in salinity, as it is formed in an area where precipitation far exceeds evaporation. The water mass is seen moving northward from its area of formation, and makes its way into the Caribbean over the moderately deep sills of the Lesser Antilles, the Anegada Passage, and the Windward Passage, between Cuba and Hispaniola. This water mass generally is seen spreading from these sills out to cover much of the Caribbean Basin. The movement near the southeast Coast of Puerto Rico could be expected to be south and west. As the water moves northward through the Atlantic it is in contact with higher saline water, increasing the salinity from its origin of about 34‰ to 34.8‰ off Puerto Rico. The temperature is from 6°C-7°C.

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From 800 m down to 1000 m, between the Antarctic Intermediate Water and the North Atlantic Deep Water, lies another transition zone. From about 1000 m depth and deeper the water mass found in the Caribbean Sea has most of the characteristics of the North Atlantic Deep Water. This water is formed in the high north latitudes, and while descending both in depth and latitude, entrains some of the Mediterranean water, thereby increasing its salinity, density, and depth. This water enters the Caribbean only through the Windward and Anegada Passages. The water moves mainly westward from the Windward Passage, but south and west from the Anegada Passage to fill all the deep basins in the Caribbean. This water is characterized by 4-5°C temperatures, and a salinity of 35.0‰. After this water mass moves into the Caribbean, it is virtually trapped, with only a small passage out through the Yucatan Strait. The water remains in the Basin and is slightly different in silicate content from its origin, the North Atlantic Deep Water, found outside the Caribbean Basin. For this reason, some people choose to call this deep, cold water the Venezuela Bottom Water. In some portions of the Caribbean Basin, this water mass is over 3000 m thick.

2.8. CURRENTS

The general circulation of the Caribbean Sea has been described by Must (1963), Worthington (1971), Gordon (1967) and Perlroth (1971), among others. The Caribbean Current is a warm westward flow which is formed from the junction of the North Equatorial Current and the Guiana Current (Burns and Car, 1975), both generated by the Northeast Trade Winds. There are Seasonal variations in the Caribbean Current. Surface velocities attain their maximum speed during the summer (June-August) and their minimum during October and November. Burns and Car (1975) reported maximum speeds along the north coast of Venezuela of about 43 cm/sec, with a peak of 135 cm/sec. Most of the water entering the Caribbean Sea comes through the straits north and south of St. Lucia (Fig. 1). The main flow crosses the Jamaica Ridge southwest of Jamaica, moves west through the Cayman Basin, and then keeps flowing north through the Yucatan Strait into the Gulf of Mexico, contributing to the formation of the Florida Current (Burns and Car, 1975).

Comprehensive summaries of the water masses and surface circulation of the Caribbean Sea have been given by many researchers. Most of these summaries quote the work of Wust (1963), reproducing this author's descriptive diagrams of the Surface circulation. These diagrams are also reproduced here as Figures 33 to 36. These figures show the tabulated speeds and directions of the surface currents around Puerto Rico for the months of January, April, July, and October. Tables 14 and 15 are summaries of ship drift data taken from the Naval

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Oceanographic Data Center (NODC). These tables are reproduced from Lee, et al. (1978). The data show the surface drift range as being from WSW to NW at 20 to 80 cm/sec with NW currents of about 40 cm/sec as average. Easterly flows have also been reported (Atwood, et al. 1976, and Lee, et al. 1978).

Very few water current measurements have been made near Punta Tuna. Burns and Car (1975) reported current measurements in the southeast part of Puerto Rico. Figure 2 indicates the location at which their arrays were moored. Tables 16 and 17 show the results reported by Burns and Car (1975) that apply to this study, as do Figures 37-40. Speed direction histograms are shown in the figures. Mean currents from 2 to 15.7 cm/sec were measured at depths ranging from 100 m to 1910 m over the three arrays. Direction of currents varied from 001 degrees (°T) to 349 degrees (NW) including all quadrants of the compass. In Array 11 (Lat. 17°50' 53"N, Long. 65°47' 37"W), south of Punta Tuna, P.R., a total of 2,722 observations were made at a depth of 220 m (water depth:

1975 m). The direction histogram indicates that about 20% of the direction measurements lie between 240 and 255 degrees in a WSW azimuth. Approximately 75% (cumulative) of the time, the current at this depth moves towards the western quadrants (SW, NW). Speeds ranged from 5-35 cm/sec; 34.7% of the time the current speed was about 15 cm/sec. For this array and depth, the authors found the mean current to be 15.7 cm/sec towards 252°. | Progressive vectors and spectral energy diagrams are shown in the Burns and Car (1975) publication for all three arrays.

Current measurements in Array 14 (Lat. 17°52'53"N,

Long. 65°54'36"W) were made at depths of 100, 105, 810, 1905, and 1910 m at ten minute intervals (Figures 38 and 39). Current direction fluctuates around the compass at all depths, the most frequent direction being towards the western quad-

rant (210°-300°). Speeds ranged from 0 to 30 cm/sec at the 100 and 105 m levels, and from 0-10 cm/sec at the 810 and 1905 m depths. The records show a definite current speed profile that changes with depth. For this array, the mean current at 100 m and 105 m was 4.4 cm/sec (250°) and 4-9 cm/sec (265°) respectively. The mean current at 810 m was 4.2 cm/sec toward 260°.

Current statistics in Array 14A (closer to Vieques than to Punta Tuna) show variations from Arrays 11 and 14. The location of Array 148 is at 17°53'24"N, 65°37'46"W; the station lies northeast of stations 14 and 11. Direction histograms (Figure 40) indicate that at 240 m depth, 70% of the measured water direction was toward the northwest quadrant. Speeds range between 0 and 25 cm/sec with a mean of about 10 cm/sec. At a depth of 605 m the direction is mostly to the northeast quadrant at speeds ranging from 0-20 cm/sec and a mean of about 5 cm/sec. The actual mean current at 240m and 605 m

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was found to be 8.0 cm/sec (289°) and 5.4 cm/sec (061°) respectively. The direction was seen to be significantly variable at depths below 1335 m. The histograms show the number of observations in any direction about equal throughout the compass. Speeds at these depths are below 10 cm/sec 90% of the time.

Oser and Freeman (1969) report the installation of two deep-water current meter arrays in the area during December of 1968. The arrays were located between Vieques and Punta Tuna in about 1000 m and 1500 m deep water respectively. The generalized results of these arrays are that the upper meters (about 500 m depth) recorded up to 25 cm/sec as a maximum speed, and the primary direction was westerly. A meter at about 600 m showed a maximum speed of about 50 cm/sec, with the primary direction indicated as northeast. The 1000 m deep meters show northwest and east as the two primary direc-

tions, with about 15 cm/sec as the maximum speed. No other information is given for these measurements.

Ostericher (1967) also reports both current meter and ?drogue measurements were made just south of Punta Tuna in 1967. The current meter data is not given in the report, but may be in the naval archival files. The érogue data

indicate that a general west or southwest drift is seen in the surface waters during up to six hours of observations.

Predictions of reversals of deep water currents in the Punta Tuna sector and the northern Caribbean Sea have also been reported by Atwood, et al. (1976), based on the dynamic height method of calculation. Figure 31 in Atwood, et al.

(1976) shows the subsurface current profiles extracted from the SP169 IT publication. In station 41, their closest location to the Punta Tuna site, the current profile indicates water movement towards the northeast at a depth of about 600 m, while above 500 m and below 800 m the current direction is westward at speeds approaching 52 cm/sec (1 kt).

Station 42, west of Punta Tuna, and station 40 to the north, Show steady westward flow along the water column to depths Of approximately 900 m. Geostrophic velocities, as calculated by Atwood, et al. (1976) along a transect extending from Puerto Rico to the coast of Venezuela (Figure 32 in the

original publication), indicate an eastward flow in dune 1972, between Lat. 17° and 16°N, at speeds reaching above 20 cm/sec in the near surface waters and 5 cm/sec at approximately 500 m depth. Further to the south, the current direction is westward. The October 1972 geostrophic velocity calculations show westward flow near the coasts of Puerto Rico and Venezuela and an eastward flow in the center of the Caribbean Sea.

Ekman currents analyses were made by Bretschneider

(1977) for all the proposed OTEC sites; this is a comprehensive work in which calculations have been performed, taking

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into consideration wind speeds, design wave heights, significant periods, and depth intervals down to about 150m.

Bretschneider's calculations also indicate wind drift. current

flow reversals below 100 m depending on sea state. Velocities ranged from 78.98 cm/sec at the surface (for a 100-year exceptional hurricane) to .09 cm/sec at 100 m depths for sea state 4 (wind speeds of 17 knots, 5-ft wave heights and a wave period of 5.34 seconds). For the 100-year exceptional hurricane there are no current reversals (east) above 350 m.

Although the above reported measurements and calculations have been made in locations near the Punta Tuna OTEC site the resultant variability indicates that further and more precise monitoring of water circulation in this area should be undertaken. The characterization of the water circulation, as needed to evaluate the environmental conditions for an OTEC site, necessarily entails long term observations.

2.9. SALINITY AND TEMPERATURE DISTRIBUTION

The seasonal salinity and temperature distribution in the Caribbean Sea has been reported and reviewed by Dietrich (1939), ust (1963), Sturges (1965), Fukuoka (1965), Worthington (1966), Gordon (1967), Periroth (1971), Sands, et al. (1978), Hamnski (1975), Shanley and Duncan (1972), Munir, et al. (1978), and Craig, et al., (1978). Hydrographic stations data near the Punta Tuna OTEC site area have been reported by Shanley (1971), Atwood, et al. (1976), Lee, et al. (1978), Oser 3rd Freeman (1969), Ostericher (1967), and Wood, et al.

1975).

2.9.1. Salinity

Salinity profiles measurements at the Punta Tuna OTEC site were performed by Atwood, et al. (1976). Figures 52 to 56 of their report show the salinity profiles at the OTEC Site as monitored during four cruises undertaken in September, 1975 and in January, March and May of 1976. These figures are reproduced in this report as Figures 4i to 4j. Surface Salinities lower than 34.8‰ were not observed at the site according to these profiles. Also, from Atwood's figures of the individual cruises, as well as the composite curve (Fig. 4j), it is apparent that below the salinity maximum (100-200 m), there is little change in salinity with time, certainly not enough change to affect an OTEC power plant. From this observation, it is clear that the salinity of the upper 200 m is more variable, and consequently of more concern to this study.

The measurements of salinity discussed by Wood, et al. (1975), show similarities with those of Atwood, et al. (1976). The stations visited were about 5 km west of Punta Tuna. For

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the surface salinity, Wood, et al. (1975), found values of about 38.7‰, 35.7‰, 35.5‰, and 33.5‰ for winter, spring, summer, and fall, respectively during 1973-1974. These data do not differ greatly from those of Atwood, et al. (1976), except for the intrusion of fresh water, lowering the Salinity in the fall, as seen by Wood et al. AS this is the Peak of the rainy season, the reduction is not unexpected.

Ostericher (1976) took 7 hydrocasts in the Punta Tuna area in April, 1967. During that time, he found the surface salinity to vary from 36.30‰ to 36.35‰, These values tend to be somewhat higher than those of Atwood or Wood.

Oser and Freeman (1969) discussed their measurements of salinity made in the Punta Tuna area in December, 1968. Their measurements showed a surface salinity range of 34.71‰ to 34.81‰. These lower values again occurred at the end of the rainy season, and are not unexpected. They lie between those appearing in the Atwood and Wood studies.

Table 18 shows the summary of surface salinity values seen by Shanley and Duncan (1972) during 1971. The overall values range from 34.18‰ in October to 36.00‰ in March.

These values were measured at one of two stations south of Puerto Rico which were visited monthly. Table 19 shows the summary of NODC-collected data (Munier, et al., 1978) from 1953-1968. (Appendix II contains the original NODC data).

Munier shows the surface salinity ranging from 33.51‰ in August of 1967 to 36.45‰ in April, 1953.

Figure 46 graphically shows a seasonal summary of both Shanley and Duncan (1972) and Haminski (1975). Although the high values that have been measured over the years do not vary much seasonally, the low values have been measured as low as 25‰, due to rainfall, runoff, and source-water dilution by the Amazon and Orinoco Rivers.

The value of the depth of the salinity maximum, which occurs within the core of the Subtropical Underwater, gives an indication of the water mass structure. This water mass, usually located close to the thermocline, has the highest salinity in all the Caribbean, regardless of depth. Again, Tables 18 and 19 give the values of this salinity maximum, with their observed depths. The total range seen for all these measurements is from 36.88‰ to 37.14‰. The salinity may not actually have changed to the extent indicated, as the inability to locate the absolute maximum is

probably the cause for the variation. The depth range of the maximum is more apparent, with the listed values ranging from 100 m to 187 m. This variation may be another manifestation of the inability to locate the exact maximum, but the depth is also related to the atmospheric pressure above the water: lower pressure tends to draw the lower water closer

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Table 18

Summary of Surface and Maximum Salinity Data

Reported by Shanley and Duncan (1992)

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to the surface, exposing more of the higher salinity water to surface conditions.

2.9.2. Temperature

?Some upper water temperature measurements have been made in the northern Caribbean Sea near Puerto Rico, but not many.

The temperature profiles for the oceanic area near the Punta Tuna OTEC site are shown in Appendix 8. These profiles are

constructed from NODC computer data-listings up to 1977.

Figure 47 indicates the geographical sectors, divided into S-minute squares, in which the area was partitioned to construct the composite temperature profiles in Appendix 8.

An analysis of the surface temperature range from these profiles indicates the minimum recorded value was 24.7°C, seen in February, 1971 (Square 14), and the maximum recorded was 30.7°C, seen in September, 1971 (Square 10). In that year the surface temperature varied by 6.0°C.

Figure 48 shows the NODC data processed and averaged by OOs1 (1977). The average surface temperature usually varies from slightly more than 26°C in October. This implies an average annual variation of only about 3°C.

Table 20, after Craig et al. (1978), tabulates an observed temperature for each month of the year. The data source extends from 1953 to 1968. Again, the low value is seen in February, but the highest value is seen in September. Another fact seen in this table is that the temperature maximum does not always occur at the surface, but may actually be seen up to 50 m below the surface. Table 21, showing typical temperatures reported by Shanley and Duncan (1972)

has similar trends, with the highest temperature seen in

September, and lowest in March. The maximum temperature frequently occurred at the surface, but during the cooler, winter months, the maximum was often as much as 50-70 m below the surface,

In the Caribbean Sea, near Punta Tuna, the top of the thermocline is usually found between 80-100 m. The bottom of the thermocline usually is located about 260 m below the surface. Atwood, et al. (1976) indicates that a wedge of warm water is always found in the northern Caribbean Sea.

They conclude from the data that:

"The 25°C isotherm lies at about 100 meters, with small variations. This ensures a thick warm surface layer which is accentuated in the summer months by an increase in temperature of the water above 100 meters to as much as 29°C."

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Table 21

Typical Temperatures of the Caribbean Sea, South of Puerto Rico

Month

January

February

March

April

May

May

August

September

October

November

December

after Shanley and Duncan (1972)

Surface Temp. (°C)

26.36

25.91

25.82

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2.9.3. Mixed Layer Depth

This parameter is important both to design engineers and to environmentalists. The designers must use great volumes of water to run the power plant. The plant intake openings will have some non-zero vertical dimensions. The designers must know to what depth they can reach to maintain the same surface water characteristics, with little or no chance of the intrusion of subsurface water to reduce the thermal efficiency or to change the water chemistry in other ways. The environmentalists are aware that the upper mixed layer is usually identified with the Tropical Surface Water, the upper water mass in the Caribbean Sea. This water has certain ranges of temperature, salinity, and light transmission.

Also, many organisms spend much of their life in, or reacting to, this water mass. If this water mass is altered unnaturally, by the presence of one or many OTEC plants, this may affect the natural balance between predator and prey, or between flora and fauna, in ways we cannot even begin to understand.

The actual definition of Mixed Layer Depth (MLD) varies from person-to-person, group-to-group. Molinari and Chew (1979) define the MLD as "the depth to the center of the first depth interval in which the temperature changes by 0.3°C ."

This definition is very tight in terms of temperature, but leaves much room for ambiguity in the definition of the other words used. Sands, et al. (1978) on the other hand, uses a definition that is easier to understand and use, but not as thermally restrictive. Sands says that the MLD is the depth where the temperature drops 1°C from that of the surface value. Unfortunately, the latter definition could result in a great loss of thermal efficiency in an OTEC power plant. The MLD may also be defined in terms of salinity instead of temperature (Lee, et al., 1978).

Using the thermal criterion of Sands, a drop of 1°C from the surface value, we can show how the depth of the MLD has changed over the years, using the historical data of ODSI (1977). The criterion of a change of 1°C is not difficult to justify, since usually the temperature is invariant with depth to the lower limit of the MLD. At that point the temperature undergoes a great change within a small vertical distance overcoming both the 0.3°C and the 1°C criteria at about the same depth.

Figure 49 shows the results of the data compiled by DSI (1977). Shown in the figure are the most probable values and the maximum and minimum values seen in the literature. The general trend is for the maximum depth of the MLD to be greater in the winter months, and then to rise in the spring

and summer. The Tate summer and fall months are times of water mixing with severe storms occurring most frequently

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during this time, but again, the MLD starts to show a decrease toward the winter values.

2.9.4. Thermal Resource

Although this parameter is discussed last, it is the single most important parameter in an OTEC power plant. The plant is designed to maximize efficiency depending on the value of the thermal resource, and how the thermal resource changes throughout the year.

The thermal resource is the heat energy available between the surface mixed layer and the deep, cold water. Usually the practical definition of the thermal resource is the temperature difference (ΔT), in Centigrade degrees, between

the surface water and the water at 1000 m depth.

Many authors have discussed this parameter directly (Atwood, et al., 1976; Wolff, 1978; Sands, et al., 1978, and ObSI, 1977). AS most of the authors tended to use the same Sparse data, and ODSI compiled the results, Figure 48 shows the values discussed by ODSI. In-the figure, the average values of the thermal resource (Delta-T from surface to 1000 m) are given for each month. The values for the Punta Tuna area range from about 20°C to about 23°C throughout the year.

Tables 20 and 21 show the observed 1000 m depth temperature both for the Craig, et at. (1978) computation, and for the Shanley and Duncan (1972) data. In the Craig data, the 1000 m temperature varied by less than 0.40°C over 15 years. The Shanley and Duncan data show a variation of less than 0.30°C. These small variations may be real, or merely measurement errors, but both confirm that the Thermal Resource will tend to vary with the surface temperature, with little apparent change in the cold water temperature. This is also shown in Figure 48, where the thermal resource seems to follow the surface temperature values. Therefore, the surface temperature itself may be a good indication of the available thermal resource.

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3.0. MARINE BIOLOGY

3.1, INTRODUCTION TO MARINE BIOLOGY

The scope of this section is to relate the marine biota to the presence and/or operation of an OTEC power plant in the northeastern Caribbean based on the available historical information.

Margalef (1971) compares the Caribbean and the Gulf of Mexico (the American Mediterranean) with the European Mediterranean with regard to productivity. He mentions that even though with the few available data, it seems that the American Mediterranean is more productive than its old world counterpart, and that its resources are under-exploited. However, as determined mostly by C-14 uptake tests, the primary production in the Punta Tuna area is only 80 mg/m² day, making it one of the lowest areas in the Caribbean.

There is not much biological information from the proposed site of the OTEC plant, near Punta Tuna, Puerto Rico, or the surrounding area. However, the most important biological characteristics of the area closest to Punta Tuna will be discussed. Also, as the oceanic conditions for the OTEC plant require being at least 3-km from shore in that area, and being over at least 1000 m deep water, we would expect predominantly open ocean water, however, there still should be some coastal species present, at least in the upper waters.

Cabo Mala Pascua, located about 3 km west of Punta Tuna, was the site of an environmental study undertaken by the staff of the Puerto Rico Center for Energy and Environmental Research (formerly the Puerto Rico Nuclear Center). The report from the Cabo Mala Pascua study discusses the biological information related to physical, chemical, and geological parameters, zooplankton, benthic invertebrates and fish studies, and plant associations (Dood et al., 1975). Although this study did not consider conditions in water much greater than 300 m deep, much of their relevant information will be discussed within this review.

There is no doubt that an OTEC plant would produce some kind of disturbance in the ecological pattern of any Site area. However, some people believe that this type of activity would have little effect on the biota. It is difficult to predict what would happen or how serious any alteration of the biological system would be, were an OTEC Plant to be located or operating in an area.? There is

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very little information that is known about the biology of the prime Puerto Rico OTEC site. Nevertheless, this report shall attempt to summarize and evaluate the available information. Only after several years of research, both before and after the existence of the OTEC plant, will anyone actually know the effects of such a perturbation on the biological environment.

As an OTEC plant will be both in deep water and also relatively near shore, this biological section will deal

with both the nearshore and open ocean environments.

Furthermore, the various subsets of the oceanic biota shall be considered, where applicable, such as: primary Production, phytoplankton, zooplankton, benthos, and fish.

3.2. BIOLOGICAL ENVIRONMENT

3.2.1. Nearshore Life

3.2.1.1. Productivity

Margalef (1971), in his paper related to the pelagic ecosystem of the Caribbean Sea, stated that cruises and Surveys in this area have been? insufficiently coordinated and have rarely been repeated frequently enough to give a fair idea of the yearly cycle, -and much less of the inter-annual changes.

In the Gulf of Cariaco, northern Venezuela, in the Caribbean Sea, the extraction of fish approaches up to 59 C/m²/year with a primary production of the order of 800 g C/m²/year (Margalef, 1971).

In regard to the euphotic: layers, the circulation of the American Mediterranean can be described in an oversimplified form as an anticyclonic gyre (Wust, 1964; Bogdanov,

1965). Figure 50 shows data on geopotential topography
Summarized-and based on Duxbury (1962) and Gordon (1967).
The areas of low topography, (areas where dense water
approaches the surface) have been striped, and the areas
of high topography (where nutrient poor water of low
density accumulates) are cross hatched. As we can see,
Puerto Rico is located far from the nutrient rich water
masses located in the southeast Caribbean.

It is known that areas of high fertility may also be
associated with the discharge of rivers. A river as large
as the Mississippi contributes high amounts of phosphate
(2 to 16 mg P/n? on the surface); a great number of fresh
water diatoms (over 1000 Melosira per ml), and huge amounts
of detrital chlorophyll. ?The observed increase in plant
biomass is in great part due to the augmented productivity

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of local marine populations (Thomas and Simmons, 1960;

Simmons and Thomas, 1962). It is important to mention

that in Puerto Rico there are no large rivers. Although

the effluent from the Amazon and Orinoco (both in South America) probably reaches the Puerto Rican shores, enough time has elapsed to consume all the excess surface nutrients.

Some values of the primary production in the Caribbean, as determined by ^{14}C uptake, are shown in, Figure 51. This method gave figures between 25 and 50 $\mu\text{C}/\text{m}^2/\text{year}$.

Cell counts fall mostly between 5 to 15 cells/ μm^3 (Hulburt, 1963, 1966, 1968), and pigment concentration between 0.05 and 0.3 $\text{mg chlorophyll } a/\text{m}^3$. Phytoplankton extend to relatively major depths; diatoms are represented primarily ~ by only those species associated with ciliates, such as *Chaetoceros coarctatus*. There are also sizeable populations of coccolithophorids, dinoflagellates and blue-green *Qscillatoria* (Hart, 1959, Ivanov, 1966).

3.2.1.2. Phytoplankton

There is no published information on the phytoplankton of the coastal waters of Puerto Rico, particularly at the benchmark site. Nor are there any specific data on marine

productivity. However, considering some available information from the Punta tuna site, we can speculate on the actual conditions at this area and the possible changes that would occur if an OTEC plant were established in this region.

The only known studies related to the phytoplankton of Puerto Rico are on the tintinnids by Duran (1957) and various studies of Margalef (1957, 1960). The former mentions and illustrates 22 different species. In the Coastal area of Punta Tuna, and towards the southeast, facing Cabo Mala Pascua, one could find the same as in the wrorgan Mediterranean, uch as the tintinnids species! of the *Stenosotella* genus and other similar genera should be found that present an outer sheath or heavy lorica. These Genera develop together with the first stage of succession of the phytoplankton, coinciding with upwelling movements of the water. This succession may occur around the OTEC Site due to the production of an abnormal upwelling that Could bring the ocean bottom water, rich in nutrients, to the surface. According to Margalef (1967) the *Eutintinnus* and *Favella* genera are genuinely peragic forms which have a very thin and light sheath or lorica, which are physical characteristics of the final stages of succession.

A great number of other genera and different species

g{ohytoplankton should be found, among which are dino-
agellates like Noctiluca, which are carnivorous; Ceratium,
which has a size varying from 200 to 500u; and Peridinium,?

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Size of 200 to 250u. Furthersore, in this env ronment
genera such as Pyrocystis are common, which together with
the Noctiluca, are responsible for the luminescence in
tropical waters. The other important group of phytoplankton
is composed of the diatoms, with probably the most common
being: Coscinodiscus, Rhizosolenia, Bacillaria, Hemidiscus,
Syrosigna, Biddutphia, Asterionelta and Thalassiothrix.

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filamentous consistence, which appears in the form of small bundles on the plankton. The appearance of these and similar species in large quantities, caused by an upwelling rich in nutrients, might produce difficulties in the operation of an OTEC plant, located downstream from the effluent of a first plant.

Reference should also be made to some common planktonic organisms like the Foraminifera, Globigerina, Radiolaria, Vike Acanthometra, about 200 μ in diameter; coccolithophorids of the CoccaTithus genus; and finally the silicoflagelates, which are very small like the Dictyocha that are frequently found in the copepod's intestines.

3.2.1.3. Zooplankton

The data available on zooplankton in the Punta Tuna nearshore region are more complete than the phytoplankton data. Estimates of the abundance and diversity of zooplankton in the surface waters along the eastern portions of the south coast of Puerto Rico (Fig. 52), including the Cabo Mala Pascua area (3 km SW of Punta Tuna), are reported in Wood, et al. (1975). About 39 species of copepods were identified. Also, the total number of copepods, chaetognaths, larvacean, veliger larvae, caridean larvae, brachyuran larvae, (cirripede nauplii, number of fish eggs, holo-

Plankton, and meroplankton were counted (number/m³)

According to the above authors, seasonal changes in the abundance of the total zooplankton at any Station

(Figs 52) or among all samples were within the same range (Table 22)." The highest concentrations occurred in December. These large densities, however, probably represent the typical patchiness among tropical zooplankton communities in the coastal waters around Puerto Rico rather than a recurrent seasonal pulse, since the 95% confidence intervals from each station overlap (Table 23).

These fluctuations in density refer primarily to holoplanktonic organisms (permanent plankton) since they amounted to, in most cases, 60 to 90% of the total zooplankton. Meroplankton or temporary plankton formed 3 to 27% and were more numerous during April and August. The dominant meroplanktonic groups were prosobranch veligers and caridean larvae (Table 24).

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Table 24

Total number of holoplankton (nusber/n?)

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Fish eggs were abundant in this area

40% of the total zooplankton (Table 25).? The largest

density 229/m, was observed at Station "5" on February

13, 1974. Fish eggs were more numerous throughout the

area on this date than any other, averaging 177/m and forming 31% of all zooplankton collected. Most of the eggs were round and 0.5 to 2 mm in diameter. Oblong eggs were also common. It is not reported which groups of fish are represented by most of the eggs.

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Diurnal changes in zooplankton density were large in February and small in August. A detailed account of the magnitude of fluctuations among several groups was reported earlier (Youngbluth, 1974a and 1974). Nearly all organisms were much more numerous at night during this period but only two groups, the larvaceans and the gastropod larvae, were observed in greater numbers at night during August (Table 26). Sea state and sky conditions were similar during each period, i.e., calm and moonless at night, lightly choppy and 'sunny' during the day.

Copepods formed 60 to 85% of the zooplankton community, with 39 identified species. The report did not have a detailed examination of species abundance at a1) stations, however, one sample from their Station "2" for each period was selected for study. Table 27 shows the Species most numerous, those commonly observed, and others occasionally observed.

Table 28 shows the total number of chaetognaths.

This group was very numerous during February 1974, but not many different species were found. The variety and abundance of zooplankton observed at the Cabo Mala Pascua site, both nearshore and offshore, were similar throughout the year. Diurnal changes in densities varied. Large increases in nearly all groups were observed at night during February. In August no obvious differences were noticed except among larvaceans and prosobranch veligers.

Copepods always dominated both the zooplankton community and the holoplankton (Table 29). The larvae of gastropods and decapods (Table 26 and 30) were the major meroplanktonic organisms. The largest proportion of

meroplankton occurred during April and August. Fish eggs were very numerous during February 1974 (Table 31).

Because the nearshore area where the above research was performed is located near the prime future OTEC plant Site, we can presume similar conditions in the coastal waters of Punta Tuna. Any change in the food chain produced by the upwelling that would occur in that region would surely change the quantity and distribution patterns

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Table 26

Total number of larvaceans (number/10m³)

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?Total number of veliger larvae (number/10n°)

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Table 27

o Copepod populations observed at the Cabo Mala Pascua Site.

Species usually most numerous (5 individuals /m)

Clausocalanus furcatus

9 *Faracatanus*

Farranula gracilis o. sop)

Dithona spp. (0. *plunifera*, 0. spp.

Reartfa spinal ae

?*Tenora turbinata*

TaTanopia americana

Species commonly present (observed on 5 or more sampling periods)

Corycaeus spp. (*C. giesbrechti*, *C. pacificus*, *C. speciosus*)

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TaTocaTanus pave

o Euchaeta marina

re ~ NannocaTanus afnor

Tabfdocera spp.

CandacTa pachydactyla

ecynocera cTaus

?evoeaYanas:Tangicorats

° Tesora stylifere

Spectes occasionally present

Oncaea spp. (O. mediterranea, O. venusta, O. spp.)

Goryaeus spp. (C. subuTatus, ©. Sp.)

Q Preudedtaptomys coker

{aYoesTands.pavontnis

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Sentropager furcatus

EneaTanis spp-

Locteutia favicornis

Miracta eftersta

Copitia spp

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Table 30

Total number of caridean larvae (number/10x"

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Total nusber of brachyuran Yarvae (nunber/10a°)

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Nearshore Replicate Tows Nearshore Tows Offshore Tows

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of the previously mentioned zooplankton, as more phytoplankton would be available for grazing upon.

The total biomass of zooplankton (Table 32) expressed in m/m was calculated as wet volume (Ahistrom and Thraikil, 1962). Wood et al., (1975) mentioned that this estimate is subject to considerable error and should be viewed only as a rough measure of standing stock. The measurements were reproducible but are undoubtedly biased

toward higher than actual values by the variable proportion of interstitial water and detritus.

3.2.1.4. Benthos

The effect of an OTEC plant on the benthos of Punta Tuna is relative, and will depend on the type of power Plant that is established. If the generating plant is shore-based, there is no doubt that it will influence the benthic organisms along the shore, both flora and fauna. However, if the power plant is afloat more than 3 km from Punta tuna, the resulting environmental changes to the benthos will be minimal for the inhabitants in the zone between the shore and the 100 m isobath, except where a power line may pass.

Yoshioka, in Wood et al., (1975), reports the results of benthic and fish studies conducted at the Cabo Mala Pascua site. Most of the effort involved mapping-and describing major benthic communities, in an area located between the shore and the 20 m isobath, off the coast from Punta Tuna to Punta Viento (Fig. 53). Macroinvertebrates, algae and fishes were observed at selected stations.

Tables 33-36 list the species observed and collected during these studies. Of all these species, probably those most affected by a shore-based OTEC plant would be the following: the zoanthid *Palythoa*, an encrusting organism, as well as, the gorgonians, core?? sponge and fish. species as observed at station "Sei2" (Fig. 33), which are mentioned in Table 345 *Gaulerpa*, *Udotea*, *alophila* and *Halimeda*, as observed at Stations *S-2?eand "eso"; and tnethevaras between the 10 and 20 m isobath at Station "s-10", a decrease of organisms typically associated with hard substrates, which includes *Montastrea cavernosa*, a hard coral, and various species of Sponges such as *Catlyspongia vaginalis*, *Haliclona rubens*, *Verongia longissima* and. *Treintastrabilinay* ?Riss, cheeges

Stributfo could be produced among the fishes of this region (Tables 33-34) but they would not be as marked a5 in the case of the sedintary invertebrates and the aforementioned plants.

un

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zt" 640" EO" _BEO"/EBO TLO" ¥hO"/6L0 9E0"/z80" ¥e0"/9B0" ¥HLZOEL

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Table 33 (from Wood, et al. 1975).

o

Shoreline fishes of the Cabo Mala Pascua site

27 Feb 73 27 Feb 73,

Seine Rotenone

° FAMILY

?Muraenidae

Echidna catenata wz

Ophichthidae

° Myrichthys acuninatus 1 1

Gobusocidae

Arcos macrophthalmus 1

?rcos Fubringenosus 6

Toniéodon Fasctatus 1

9 Frcos artius 2

?Scorpaenidae

Scorpaena plunieri 1

Gerreidae

- Eucinostomus melanopterus 1 -

Ponacentridae

Abudefdfuf taurus 6

?MbudeFaut saxatilis 19

9 Mugitidae

Mugil ize 2

Labridae

Doratonotus megalepis 1

o WaTchoeres imscurptina

Scaridae

Sparisona rubripinne 2

Blenni idae

° Entomacrodus nigricans 10

Clinidae

Enblemariopsis leptocirris

abrisoms gup i

Tabrisomus hatttensis

° Labrisonus nuchipinnts 1

14

---Page Break---

Table 33 (Cont.)

p 27 Feb 73 27 Feb 73

seine Rotenone

Gobi tdae

?Awgous taiasice n

?Sathyaobius soporator 8

?povenT ineatus, 1

?Goathol iis: thomasoni 7

Gonionellus baleosona. 1

Balistigne

Aluterus schoepfi 1

---Page Break---

Table 34 (from Wood, et al. 1975).

> Macroinvertebrates, algze and fish observed at
selected stations at Cabo Mala Pascua

sz siz 58

22 Aug 74 2% Aug 74 22 Aug 74

PLANT

?KINGDOM,

Phylum Rhodophyta

2 Gracilaria sp. x

Phylum Chlorophyta

Caulerpa mexicana

ialineda sp.

Penicillus capitatus

° ?Wastex consutina

?Wastes fTabetton

?Wotea spinuTosa

Phylum Spermatophyta

phila baillonis x

?ANTAL

Phylum Porifera

Agelas

3 ?*Agelas* *ignifera* *varians*

Cartyspongia *avaginata* *Ts*

?*Gondria* *ta mucuta*

Cinachyra *cavernosa*

Tiodia *sp.*

Rattina *rubens*

Trewia *sp.*

?*Tetrochota* *birotulata*

iguTosa

Neoriularia massa

UT TgocerOs Tenorrhages

?Verongra Tacunosa x

gra Tongissyma

TongTseTna,

Phylum Onidara

2 Class Anthozoa

Subclass Octocoral ia

Briareum asbestinun x

Exythoropodtun sp. x

us

---Page Break---

Table 34

Phylum Onidaria (cont.)

Eunicea laxispica

unicea Sp.

Gorgonia sj

Maries? sp.

Hurfesopsts sp.

Flours fTexudsa

Plexaura honomal Ya

eeudopTesaurs 5

Preodopterogoraie sp.

Pees spe

Subclass Zoanthar?a

Acropora cervicornts

Keropora palmata =

Igariella sp.

Cotopophylla sp.

Dichocoenia Bichcanta ities:

Diplopora Tabyrinthifera

Sibthornia Doe

Eula fastigiata

SophyTT inal EfTora

feenna ss be

Hittoria s

Wontastrea Caverosa

Palythos spe

Portia astreoides

?Siderastrea radians

?Sphaerastrea siderea

?Seepharoecia

Phylum Chordata

Subphylum Vertebrata

Class Pisces

Family Dasyatidae

Unis. Dasyatid

Family Mursenidae

Gymnura moringa

(Cont.)

2 siz

22 hug 74 22 Aug 74

sa

22 Aug 74

---Page Break---

Table 34 (Cont.)

se siz

a/ee 8/22

Phylum Chordata (cont.)

Family Holocentridae

Holocentrus sp.

Hyripristis Jacobus

Family Aulostomidae

Aulostomus maculatus

Family Sphyraenidae

Sohyraena barracuda

Family Serranidae

Gephalopholis fulva

iid. serranid

Family Gramnistidae

Rypticus sp.

Family Echeneidae

Echeneis naucrates

Family Carangidae

x

ecient sp.

Famtly Lutjanidae

Lutianus sp.

Family Ponadasyidae

Haemulon flavolineatun

Family Sciaenidae

Eauetus sp.

Family Sparidae

Calamus bajonado

Family Rul lidae

Pseudupeneus maculatus

Family Chaetodontidae

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ans

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8/22

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---Page Break---

Table \$4 (Cont.)

se sia 58

eee 8/22 2138/22 lane

' Phylum Chordata (cont.)

Family Pomacentridae

Chromis cyaneus x

Ehrhartsia fucata

Ponacentrus partitus x x

Fonacentrus sp. x x

° Family Labridae

Bodianus rufus x x

?Thalassona bifasciatun x x x

Halichoeres sp. x x

Jabrid x

° Family Scaridae

?Sparisona sp. x

nid: searia x x

Family Acanthuridae

?Acanthurus. sp. x x

Family Bal istidae

alistes sp. x x

HEHE iuta x

---Page Break---

Table 35 (from Wood, et al. 1975)

Cabo Mala Pascua shore collections

Station B1

22 March 1973,

Phylum Chlorophyta

Caulerpa racemosa

?*Shanera peniculum*

Enteromorpha sp.

Ulva lactuca

Enteromorpha flexilis

Enteromorpha flexilis

fea flabelTun

ietuca

Phylum Phaeophyta

Dictyota ciliolata

?dentata?

bat

Dietyots sp.

Patite' sp.

?Sargassum hystrix

?SEgUSSUR poTycePative ?

Phylum Rhodophyta

Bryothannion triquetrum

Galaxaura sp.

?ania adherens

revels pal

Polysiphonia sp.

Phylum Spermatophyta

Syringodiun fi1iforne

Speietan Ingodtun

fassia testudinum

ANIMAL

INDORE

Phylum Mousca

Class Gastropoda

Acmaea antiNlarun

Kstrace tuber

ula striate

Station 82.

22° March 1973,

---Page Break---

Table 35 (cont.)

Station 81 Station B2

° 22 March 1973 22 March 1973

Phylum Mollusca (cont.)

Class Gastropoda

4 *Gastropoda* vertabte, x

i *CoTumbelTa mercatoria* x

Wodora viridula

Fissurella barbadensis

ssurella sp.

Hesttons octoradiata

rontx antiquatus

° Eyeeerra Soreguaees

Nerita tesseltata

Taevigata

TequTs excavate

° Class Pelecypoda

Barbatia domingensis

todakia orbicularis

Phylum Arthropoda

0 Order Decapoda

Suborder Brachyura

Callinectes danae x

icrophrys antitTensis x x

° Phylum Echinodermata

Class Echinoidea

Iripneustes esculentus x x

121

---Page Break---

Table 36

Species and individuals per species collected in 1/4 m?

° quadrat at Cabo Mala Pascua

s7. si

222/73, 2/22/73

PLANT

° KINGDOM

Phylum Phaeophyta

Dictyota sp. x

Phylum Rhodophyta

Amphiroa sp. x

ANTHAL

KINGDOM

°

Phylum Sipunculida

Phylum Annelida :

Class Polychaeta

Arabella. opatina

Euntee fucata

Eanes \$55

Hermentia? verruculosa

Cactinotce Einberatt

Uopidonotae op"

Uiabrfaerets 6p.

tystatee suteata

° Wipes fegatts

Rapes \$5"

tenet

Wfeafon kingerratt

eration Spe

5 Phyl ioddce" papttiosa

Fantly Sabet! idae

Family Serpulidae

syltis sp.

Herebart! sp.

Family Terebellidae 2

Und, polychaete 1 2

122

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Table 36 (cont.)

s7

2yeei73

Phylum Mollusca

Class Gastropoda

Colunbella nercatoria

?Tucapina sonerbiy

Class Pelecypoda

rbatia domingens is 2

hana ss geass

ToraT1Tophaga coral iophaga

Toberus castaneus

nS UTE

Tietoohags igre

Uinta pelecypod"

Phylum Arthropoda

(Order Stomatopoda

Unid. stonatotopoda, 1

Order Isopoda

->~Girolana parva 1

Spaerona walkeri

ares oper 1

Order Decapoda

Suborder Natantia

Family Alpheida

ti ete

rnfa mexeana

Saar Spree aprenden ?mecTendent

Suborder Brachyura

Mithrax pleuracanthus

Phylum Echinodermata

Class Echinoidea

Eucidarus tribuloides 1

Class Asteroidea

Asterinides sp. 1

Class Ophiuroides

Unid ophiuroid 2

123

sl

2/22/73

---Page Break---

Table 36 (cont.)

ra ly Anphiuridae

anphturid

UpntaclS sartanyt

ag

?Spkionerets savanvlosa

Li

Oph ?SP.

fopsila sp.

Bie ka ritse:

?Ophiothrix

Phylum Chordata

Class Ascidacea

Styela partita

128

7

2/22/73

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3.2.2. Open Ocean Life

3.2.2.1. Productivity

Production rates in the open ocean show a general decrease from the coastal margins to the central basin areas (Davis, 1973). In general, tropical ocean waters have low production rates and show little variation with changing seasons of the year. Raymont (1963) states that two compounds, phosphate and nitrate (together with nitrite and ammonia to some extent) are clearly of extreme importance to marine plant growth. In general it may be said that values of both these essential nutrients in the upper photosynthetic zone, which is the only zone directly concerned with basic productivity, are very low and fairly constant in sub-tropical and tropical areas. It would appear, therefore, that only a rather low production is

possible in the tropics and subtropics and that production proceeds at a fairly steady level. The overall production, considered on a yearly basis, may be considerably greater than would first appear, since the nutrients are probably more rapidly recycled at the higher sea temperature of the tropical regions and thus pass through several cycles during the course of a year. Nevertheless, over the tropical Seas of the world, the standing phytoplankton crop tends to be low at any one time, but as Riley (1939) has pointed out, the thickness of the productive photosynthetic layer may be considerably greater in tropical seas, thus expanding the total crop more than expected.

Most of the detailed studies on productivity in the Caribbean Sea have been carried out in the Gulf of Cariaco and adjacent regions, off northern Venezuela. In accord with Margalef (1971) the primary production estimates, based on ^{14}C uptake (Fig. 51), are from 600 to 1000 mg $\text{C}/\text{m}^2/\text{day}$ in the central productive area, going down to 50 to 200 mg $\text{C}/\text{m}^2/\text{day}$ in the more offshore or peripheral positions. These values represent something between net and gross production (Ballester and Margalef, 1968) and they harmonize with the limited number of studies of inorganic carbon uptake in the Gulf of Mexico and the

Caribbean.

3.2.2.2. Phytoplankton

rine TRS Portion of the water column with sufficient sunlight to photosynthesize is called the euphotic zone (Duxbury, 1971). It reaches about 100 m in depth. At

the OTEC?plant site the euphotic zone corresponds closely with the Tropical Surface Water (TSH). This water mass may have a thickness of up to 100 m and its characteristics are studied in other sections of this report. Almost all the activities of the phytoplankton organisms take place

in the first 100 m of depth off Punta Tuna.

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No less than 450 species of phytoplankton have been observed in the Caribbean and the Gulf of Mexico (Margalef, 1971). Undoubtedly, 2 catalogue of those species would be defective in many aspects, especially in regard to the smaller and more delicate organisms.

The following species are more common offshore in stable environmental situations, and the meaning of their presence is perhaps more ecological than geographical:

Anphisolenia, Peridinium fatulipes, P. pentagonum latissimum, Ceratium betone, C. (rurcs) hires, ? Taisene ? tunetes

E. vultur, Pyrocystis hamulus, Lauderia annulate, rhizosolenia, Tenta cyindrus, Chaetoceros cosvetetus, Neatautus? ndveus

?and WH. membranaceus

Margalef (op. cit.), studying the pelagic ecosystem of the Caribbean, stated that Chaetoceros curvisetus,

Ch. socialis, Asterionella japonica and Stephanopyxis ?ieTetonea} costata are common species in the upwelled water. Perhaps these species will be identified when and if an upwelling is produced near an OTEC site.

3.2.2.3. Zooplankton

3.2.2.3.1. In the Water Column.

As previously mentioned, there are some surface zooplankton data collected close to the benchmark stations (Wood et al., 1975). According to Michel, Foyo and Haagensen (1976), zooplankton and hydrographic data were collected at 105 stations during nine cruises, in the oceanic Caribbean and adjacent waters, from 1966 through 1969 (Fig. 54). However, of those stations, only two (Station "4", cruise 6-6722, and Station "1") cruise P-6911 are closest to the proposed Puerto Rico OTEC site of Punta Tuna. Both stations are located about 120 km to the east.

Table 37 lists zooplankton species identified at Station "4" (Cruise 6-6722). Three species of Siphonophora, four species of Euphausiacea, and 18 of Copepoda were encountered. No Chaetognatha are mentioned. Other species identified at Station "1" (Cruise P-6911) are registered in Table 38. There are six species of Siphonophora; 18 species of Copepoda; three species of Euphausiacea; 13 of Chaetognathas and two of Salpidae. Two species of Siphonophora; 17 of Copepoda; and one of Euphausiacea are found at both

Stations. Also, Table 38 lists seven species of Thecosomata
(pteropods) encountered near the island of Puerto Rico
(Michel, Foyo and Haagensen, op. cit.)

126

---Page Break---

° Figure 54 Locations of stations at which hydrographic data and

Complete series of plankton samples were obtained (Michel,
Foyo and Hangensen, 1976).

127,

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Table 37

Zooplankton species at Station 4, Cruise 6-6722, situated at 17° 52 N, 64° 49° W, with 2 bottom depth of 4026 mand a fishing depth? of 0-1520 m on 1 Decenber 1967 (Michel et al., 1976).

Phylum Coelenterate

Class Hydrozoa

Depth Estimated

Order Siphonophora (n) ?number

1. Abylopsis tetragona 55 200

2. Diphyes bojani 0 750

3. Eudoxoides mit 55 50

Phylum Arthropoda

Class Crustacea, Subclass Copeoda

Order Calanoida

1. Acrocalanus longicornis 0 55

? 55 600

2, Clausocalanus furcatus np 2950

55 2650

335 5

3 0 150

335 10

4. Haloptilus Jongicornis 335 165

5. Lucicutia flavicornis 0 250

55 150

Normonitla minor 335 cd

581 3

1040 2

1520 6

Me phasma 581 1

1520 1

Paracalanus aculeatus 0 500

55 250

9. Rhincalanus cornutus 335 5

581 3

1060 1

1520 3

128

---Page Break---

Table 37(cont.)

10. Undinula vulgaris

Order Harpacticotda

11. Macrosetella gracilis

12. Microsetela rosea

Order Cyclopoida

13. Conaea gracilis

14. *Farranula carinata*

18. *E. gracilis*

16. *Oithona plunifera*

vv.

18.

Phylum Arthropoda

Class Crustacea, Subclass Malacostraca

Order Euphausiacea

1. *Euphausia americana*

2. *E. brevis*

3. E, tenera

4, Stylocheiron longicorne

129

55

335

55

581

1040

1520

581

1040

0

1520

55

335

1520

55

335

55

335

100

1100

500

50

300

50

8

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Zooplankton species at Station 1, Cruise P-6911,

00" 'N, 64° 49' W, with a bottom

depth? of 0-2337 m on 26 October

Table 38

Class Hydrozoa

Order Siphonophore

1

2

3.

4

5.

Abylopsis eschscholtzis

A. tetragona

Chelophyes appendiculata

Dyphyes bojani

?*D. dispar*

Eudoxoides mitra,

Phylum Arthropoda

Class Crustacea, Subclass Copepoda

Order Calanoida

1

2

3.

4

Acrocalanus longicornis ~

Clausocalanus furcatus

ichaeta mari

Haloptilus lonaicornis.

Lucicutia flavicomis

Normonilla minor

130

Depth

(m)

◦

65

◦

◦

65

2337

250

459

a1

65

250

1835

250

459,

ns

91

B71

1835

situated at 18°

depth of 3008 m'and a fishing

1969 (Michel et al., 1976)

Estimated

?number

120

300

570

390

60

100

8

100

---Page Break---

Table 38 (cont.)

72M. Phasma 250 150

= 9 2

75 27

311

Bn 6

: 1835 0

° 2337 3

8. Paracalanus aculeatus o 90

9. Rhinealanus cornut 459 49

Brincatanus cornutus 459 Fa

° oil 48

Ba @

1835 5

2337 8

° 10. Undinuta vulgaris ° 150

Order Harpacticotda

1. Macrosetela gracilis ° 0

250 250

° 12. *Aegistus aculeatus* out 2

= 137

1835 1

13. *Microsetelta rosea* 9 390

Baresetelis rosea 6 73

° 250 450

459 60

ns 3

on 3

al 4

1835 5

o

Order Cyctopoida

14. *Conaea gracilis* 459 160

75 155

on 37

137 2

1835 n

2337 a

15. *Farranuta earinata* ° 270

131

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Table 38(cont.)

° 16. *Githona plunifera* 9 180

6 760

250 2200

459 200

ns 6

ou n

° wr 3

1835, 10

2337 2

17. *Oncaea medi* 250 300

° 18. *O. venusta* 65 200

280 50

1835 1

Phylum Arthropoda

° Class Crustacea, Subclass Malacostraca

Order Euphausacea

1. Euphausia brevis 65 50

5 2. Nemtoscelis meaalops 250 50

' 3. Thysanopoda sequal is 6 50

Phylum Chaetogratha

1. Eukrohnia bathyantaretica 1371 3

° 1835 1

2337 1

ns 6

su 5

° 3 gacitica ° 5

1835 1

K, subtilis 250 2

?? 459 20

° 5. Pterosagitta draco 65 8

6. Sagitta decipiens 250 102

7. 5. enflata ° 55

- 6 165

8. S, hexaptera ° 5

nexapters 65 10

132

---Page Break---

Table 38(cont.)

9. *S. hispida* ° 20

10. *S. lyra* 280 »

11. *S. macrocephala* ns 3

12. *S. serratodentata* ° »

6 20

13. *S. zetestos* ou 4

Phylum Chordata

?Subphylum Urochordata, Class Thaliacea

Order Salpida, Family SALPIOAE:

1, *Thalia denocratica* 65 800

2. *Weelia cylindrica* ° 75

According to Michel, et al. (1976), seven species of Thecosomata (pteropods) were encountered at sites farther from the OTEC power plant studies, but near the island of Puerto Rico. The seven Thecosomata species are:

Not listed

Class Gastropoda

Subclass Opisthobranchia

Order Thecosomata

?Suborder Euthecosomata

Family Limacinidae

1. *Limacina inflata*

2: *Limacina trochiformis*

Family Cavolinidae

t

St)

jacria trispinosa

8. *Gavotina infers*

Suborder Pseudothecosonata

Family Desmopteridae

7. *Desnopterus papilio*

133

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Michel and Foyo (1971) identified and estimated 86 species within six zooplanktonic groups studied in the Caribbean Sea and adjacent areas. They are listed in Table 39.

3.2.2.3.2. Relative Abundance

Approximately 450 species of oceanic calanoid, harpacticoid and cyclopoid copepods have been reported in the Caribbean. The most numerous of the metazoan plank-

tonic groups and the most widely distributed vertically are the copepods, with chaetognaths ranking next. Although the number of calanoid species is far greater than that of cyclopoids, the latter nearly equalled calanoids in total number of individuals, with the most numerous cyclopoids, *Farranula carinata* and *Oithona plumifera*, being more than twice as abundant as the top ranking catenoids, *Clausocalanus furcatus* and *Mormonilla minor*. Harpacticoida, the smallest group of planktonic copepods, includes the third most numerous form counted, *Microsetella rosea*. The total number of Copepoda collected at 48 stations in the Caribbean selected to compare abundance in major areas are shown in Table 40 and Figure 5. (Wichel, Foyo and Haagen, op. cit.

The Chaetognatha consists of 15 species prevalent in tropical oceans, five rare bathypelagic forms, *Bathyselos typhlops*, *Eukronia hamata*, *Leptochaelus proboscides*, *Sagittamegaton* and *Sagittella* and two neritic species water are sometimes swept into oceanic waters, *S. helenae* and *S. nisptda*. The total numbers of chaetognatha are given in Table 41 and Figure 56.

Michel and Foyo (1977) stated that Euphausiacea were inadequately sampled but they listed 15 new records for the Caribbean Sea, with *Euphausia americana*, "*E. brevis*", *E. tenera*, *E. gibboides*, *E. mutica*, *Nematocele*, *Stylochiron*, *Tongicorne*, *Stylochiron*, *Tongutua* and *Thysanopoda*. Bonacanth, among the most abundant of this group. The relative abundance of euphausiids is shown in Figure 57 and Table 40.

The most common Thecosomata (pteropods) encountered around Puerto Rico are listed in Table 38. They are:

Limacina inflata, *L. trochiformis*, *Creseis acicula*, *Stylocella subula*, *Diacra trispina*, *Cavolina inflexa* and *Betmoptera papilio*. The horizontal distribution of the Thecosomata for the Caribbean sea is shown in Figure 58.

The siphonophores *Abylopsis tetragona*, *A. eschscholtzii*, *Diphyes bojani*, *D. dispar*, *Eudoxoides mitra*, and *Chelophyes appendiculata* (Tables 37 and 38) were den-

tioned.

fied close to

juerto Rico. Total number of Siphonophora

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collected from the Caribbean are listed in Table 40 and
Shown graphically in Figure 59.

The salps, *Thalia democratica* and *Weelia cylindrica*,
found near Punta Tuna, are familiar inhabitants of the
upper two water masses of the area, the Tropical Surface
Water (TSH) and the Subtropical Underwater (SUK). These
two water masses comprise the upper 200 m of the Caribbean
Sea. The total numbers of salpidae collected from the
Caribbean Sea are listed in Table 40 shown in Figure 60.

Michel and Foyo (1977) calculated affinity indices

which show two groups with an index of 0.50. An epipelagic
Group consists of *Sagitta serratodentata*, *S. enflati*
Paracalanus sculeatug, *Clavosocata furcatus* Krohmitta
pactfica, *Diphyes Bojant*, *Acrocalanus Tongtornis* and
Ferranuta carinata species having affinity only with the
preceding are *Abylopsis eschscholtzii*, *Undinula vulgaris*,

S. hispida and *Euchaeta marina*. All these species are
Inhabitants of the TSW-and the SUN,

Bathypelagic species comprising the second group are

having affinity only with the preceding are

Eukrohnia fowleri and *E. bathypelagica*. The bathypelagic region is located between 1000 to 4000 m depth. In the Caribbean Sea this region corresponds with the Venezuela

Bottom Water (Wust, 1964; Sturges, 1965; Atwood et al., 1976).

3.2.2.3.3. Horizontal and Vertical Distribution

Michel and Foyo (1976) did not find a uniform distribution of abundance within any group or with all considered together. Instead, the greatest numbers of zooplankton were collected in the Central Caribbean and in the areas of upwelling in the Central American bight, very far from Puerto Rico. This is best illustrated by the distribution of copepods (Fig. 61, which also indicates a high level of productivity in the eastern Caribbean, suggested by earlier studies), as well as a massing of organisms in the far west, as waters approach the Yucatan Channel.

Michel and Foyo (1977) stat

Mormonilla minor, M. phasma, Rhincalanus cornutus, Conaea
gracilis, Sagitta pectinifera and: Kegisenos seuteates

?Species having a trinity: only when the preced:

"The vertical distribution of al? species except
very rare forms, e.g. Stylocheiron elongatum,
-Thysanopoda pectinata, and
heteropods, was diagrammed to show the relation-
ship of abundance to temperature and salinity.
Examples are given in Figures 62 and 63. Many
species were found over a great range, the

lower extremes of which cannot always be ascribed
to contamination because of the frequency of

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Figure 62. Temperature-salinity-plankton diagrams.

A. *Clausocalanus furcatus*; B. *Mormonilla minor*;

C. *Microsetella rosea*; D. *Farranula carina*

(Tiche and Foyo, 1977).

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records, and the efforts taken to wash nets and to eliminate desiccated specimens from consideration. However, the depths of major concentrations were usually clearly delimited. | Thus the copepods

rocalanus longicornis and *Clausocalanus furcatus* (Fig. 628) live primarily in TSW and SUW, but the former is far more numerous in surface waters than the latter. *Euchaeta marina*, *Paracalanus aculeatus*, *Scolecithrix danae* and *Undinula vulgaris* are also found mainly in the upper 100 m, and *Farranula carinata* (Fig. 620) and *F. gracilis* are SE rimerous in sub-surface. swarns. *Toptfus Jongicornis*. is concentrated between approximately 100 and 250 m day and night, occurring in lower TSW but most abundant in SUW and upper North Atlantic Central Water (NACH). *Lucicutia flavicornis* is distributed similarly, except that it is most numerous in TSW. *Rhincalanus cornutus* ϕ . *atlantica* was common over a broader range than the others, being rare at the surface, but numerous in TW and SUM, while the majority were living in NACH and Subantarctic Intermediate Water (SAIW). Others with similar extended distributions are *Macrosetella gracilis*, *Macrosetella roses* (Fig. 62C) *Oithona plumifera*, *Oncaea mediterranea* and *O. venusta*. In contrast, *Hornonitisa minor* (Fig. 628) was one of the few living in great abundance below SUM, common in SAIW and extending into North Atlantic Deep Water (NADM). The distribution of *M. phasma*, *Aegisthus aculeatus* and

Conaea graciis fs "similarly deep and the numbers

Fewer.

Distributional records of the more frequently caught euphaustid species indicate both migratory and non-migratory habits in that some occurred over a very broad vertical range in comparison with others. *Stylocheiron carinatum* and \$.

Submit were? collected only in Tai and SUDs Nenato-
Brachion boopis only in NACM and SAIW, and Nema

?celis tenella Tn NACW. Those found in TSk, SUW
ang HACK, DUE prinar ly tn HACK, are Euphaisia
hemigibba and Nematobranchion flexipes; those more
numerous in TSW vere E~ americana>E- brevis, E-

fenerg (2180, caught in? shiv), Stylo

ine, S. longicorne and Thysandpoda

aequatis; Brother group Tiving matniy- tn ACM,

Bit aTso' collected in SUM, consists of

seudogibba, Nenatoscelis megalops, N. microps/ -

?SeYantica, \$. abbrevistun ané-T~ ostusitrors.~

mutica,

chevron

?The vertical distribution of many chaetognath species is also extensive with however, the

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major concentrations clearly stratified. Most *Sagitta serratodentata* (Fig. 638), *S. enflata*

fig. 638), *S. bipunctata* and *krohntita pacifica*

Vive in ware surface waters of Mighty variable

salinity, while 5. hexaptera ond *Pterosagitta*

Graco are usuaTly associated with the OPE \$8) ine

SUM. The Teast numerous epipelagic species were

S. hispida, a natural inhabitant of inshore

waters, and *S. minima*, of shelf and slope areas.

Below these are four that span the greatest

vertical range among chaetognaths in the Caribbean

from SUM into SAIN and NADW: *S. decipiens*

(Fig. 630), *S. lyra* (Fig. 630) and *S. getes*

Krohnitta subtilis. The remaining four of the

more abundant species were largely restricted to

SAIW and NADH: *Sagitta macrocephala* (Fig. 63A),

Eurohnia bathyantartics, *E. bathypelegica*

(Fig. 638) and *E. fowleri*

Michel and Foyo, (op. cit.) also stated that

changes

in the distribution of some species, primarily

copepods and chaetognaths, indicate upwelling,

sinking, or advection of zooplankton with oceanic

waters. *Farranula gracilis* is a likely indicator

of warm, saline waters of the low equatorial
gyres found in the Caribbean and the
Tropical Straits. The presence of *Aegisthus*
aculeatus, which lives primarily in SAIW and NADW,
in the upper water masses, indicates upwelling as
does *Wormintta minor*, if numerous, in TSW.
Chaetognath species which mark an admixture of
coastal waters when found in the open sea are
Sagitta friderici and *S. tenuis*. (not collected
during the study), *S. helenae* and *S. hispida*.
The presence of deep water species in relatively
large numbers at unusually shallow depths,
indicates upwelling, e.g. *Ura*, & *macrocephala*
and *E. bathyantarctica* at 825 and 230 m,
respectively, at a station north of Panama. There
is also the possibility that chaetognath species,
rare in the Caribbean, may be indicators of waters
entering the Sea from the North Atlantic, 6-8.

rohnia hanata and *Sagitta planctonis*, known to
be established in the North Atlantic, *E. proboscidea*,
reported from southeast Africa, and *S. weeri*
thalma, from the Mediterranean and the Gulf of

Aden. Locations at which specimens were collected

are, in many cases, in or near the Windward and Anegada Passages and those between the Lesser Antilles. Intensive sampling in these areas might well show that there are biological labels to mark the influx of North Atlantic waters at various depths."

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3.2.2.4. Fishes

Historical information regarding the fishes near Punta Tuna is such that the conditions in the water column can be understood.

3.2.2.4.1. Epipelagic Region

The epipelagic region of the oceanic zone is really

a relatively thin, offshore extension of the neritic zone,

but it has permeable, water bottom, not a solid substrate,

This region is well-lighted at the surface, dimming

considerably towards its downward limit of about 200 m.

Seasonal variations are shown in certain parameters, such

as temperature, light, salinity, oxygen, nutrients, and

Plant and animal populations (Lagler, et al. 1962). Of

these parameters, light and temperature seem most important

in determining animal distribution. Fish inhabitants

include oceanward utilizers from the neritic zone, as

well as some sackerels and tunas, such as the following

species: *Thunnus albacares* (Yellowfin tuna), *T. albatunga*

(Albacore), *T. atlanticus* (Blackfin tuna), *T. thynnus*

(Bluefin tuna), *Euthynnus pelamis* (Skipjack tuna), *E.*

alletteratus (Little tuna), *Alopias thazard* (Frigate sackerel?)

Acanthocybium solanderi (Wahoo), *Scomberomorus cavalls*

(king mackerel), and *Seriola lalandi* (Cerrey RTT insee Fishes)

belong to the family Scombridae (Erdman, 1974).

Other fishes in this division are as follows: from the family Xiphiidae, Swordfish (*Xiphias gladius*); Istiophoridae, Sailfish (*Istiophorus platypterus*), Blue marlin (*Akaiira nigricans*) and White marlin *Cetrapectes aibidus*, ~ In the Coryphaenidae. Dolphin (Coryphaenidae) and Pompano dolphin (*C. equisetus*)-

In the Atherinidae family, Exocoetidae (Flying fishes) we have the Atlantic flyingfish (*Cypselurus heterurus*) and the Margined flyingfish (*C. cyanopterus*); and from the family Anguillidae, the American eel (*Anguilla rostrata*)?? Also? Triggerfish? and Filefishes of the family Balistidae (*Balistes vetula*, trigger fish) and needlefishes of the family Belontiidae (*Strognyira* spp.) could come from near-shore, In-addition to these fishes we may find drtocene Species of sharks of the following families: Rhincodontidae, Carcharhinidae, Lannidae and Sphyrnidae; also Mantas such as the Atlantic manta (*Manta birostri*)

3.2.2.4.2. Mesopelagic Region

Occupants of the mesopelagic region of the ocean (between 200 to 1000 m) depend for food on @ "rain" of Plankton, detritus, and droppings from the overlying epipelagic region and on predatory relationships. There

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is little seasonal variation of temperature; water temperature is virtually constant, ranging from 5-20 °C, depending on depth. The pressure is high and what little Light there is, is extremely dim, and in the blue and violet range. This region contains the uppermost aphotic waters of the oceans and is inhabited mainly by dark-adapted, or scotophilic, animals (Lagler et al., 1962). Many of the fishes in this zone are black or red and move upward to feed in the epipelagic region at night. The larval stages of these invaders also pass into epipelagic waters. An example of an inhabitant of this environment is the lanternfish (Myctophidae).

3.2.2.4.3. Bathypelagic Region

In the bathypelagic region of the oceanic zone most food gravitates downward from the waters above. There are no Seasonal variations in physical factors of the environment; the water is very cold (between 2° and 4°C at 2000 m), the water pressure is very great, and darkness prevails except for the bioluminescence arising from the light organs of some of the inhabitants. Fishes are greatly reduced in both number and kinds below those of the upper waters (Lagler et al., 1962). This division is also characterized by deep water species such as those of the families Zeidae (dories) and Scorpaenidae (scorpionfishes).

B.2.2.h8: thermocline and fishes

Laevastu and Hela (1970) explain in detail the interpretation and use of the ocean thermal structure in relation to the distribution of fish. They stated that there are pelagic fish which are found above the thermocline, and others which frequent the layers of the thermocline, and still others which are found mainly in deep water (Fig. 64). According to Shanley (1972) the seasonal thermocline near Punta Tuna lies between 50 to 125 m deep. Under these conditions yellowfin tuna (*Thunnus albacares*)

will remain above that depth, according to the seasonal ? changes. The bigeye tuna (*Thunnus obesus*) which is a species reported for the Atlantic and Pacific oceans could be found in the thermocline layers, and the Albacore (*T. alalunga*) would appear down to 50-125 m.

3.2.2.5. The Food Chain

The transfer of food energy from plants through a Series of organisms repeatedly eating and being eaten is referred to as the "food chain." Fishes are tied to other forms of life in their environment by food webs. Each food organism is a part of the chain of life in which a fish species is merely another link or, if one considers the relative positions of the eaters and the

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Figure 64. Schematic example of different depth and temperature

Preference by different species of tuna in tropical latitudes.

(Laevastu and Hela, 1970)

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eaten, herbivores and carnivores are at different vertical positions (trophic levels) of a food pyramid. Usually the largest carnivore or top predator can be placed at the apex of the pyramid, e.g., sharks such as *Rhincodon typus* (whale shark) » *Carcharhinus fateitornis* (sitky shark) *C. longimanus*? (oceanic white tip shark). Also there are several species of fish of the families scombridae, Xiphidae, Istiophoridae, Coryphaenidae, Exocoetidae, and Anguillidae, which have been mentioned above. Furthermore, we should include some sea mammals such as the bottlenose dolphin (*Tursiops truncatus*), spinner dolphin (*Stenella Styptogaster*), spotted dolphin (*Stenella spp.*); common dolphin (*Delphinus delphis*), humpback whale (*Megaptera novaeangliae*), Fin whales; orcas, (*Balaenoptera*) Sperm whale (*Physeter catodon*), Cuvier's beaked whale (*Ziphius cavirostris*) and pilot whale (*Globicephala*

macrorhynchay. RTT these species of mammals have been
Gentoned by Erdman, et al., (1973) and Erdman (1970).
Some species of turtles such as leatherback (*Dermochelys*
SinGGTiPEER)Jongermend (*Caretta c: caretta*), green
?turtle (*Chelonia m. mydas*), and hawksBITT (*eretmochelys*
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4. *imbricata*], according to Rivero (1978), should also be
tentroned.?

The primary link or bottom trophic level is occupied
by green plants which bind the sun's energy for further
transfer through the living world. The phytoplanktons
mainly diatoms and flagellates are part of this bottom
level. Then comes an intermediate level composed of the
herbivores, and crustaceans such as copepods and euphausiids,
Chaetognaths, some mollusks, and fishes. Finally there is
the highest trophic level, occupied by carnivores, in which
there may be several tiers of fish and other big animals
Such as mammals and reptiles.

According to Erdman (1958, 1962) and Sudrez-Caabro

and Ouaré-Bello (1961), there are many species of marine animals which, even though they usually live their adult life in the neritic province and in the littoral and sublittoral zones, are present at least part of their lives

in the oceanic province as larvae. Among those fish and shellfish which are a part of the food chain are the

following: fishes such as *Acanthurus* spp. (Doctor fishes)»

Mulloidichthys martinicus (Goatfish), *Holocentrus ascensionis*

(Seutrrrettishy Teh] FER yeageg, (Glue runner)» *Weniramphus* »)

rasiliensis (Galtyhoo) and *Gempylus seroens* (snake weckerel)

crustaceans which include *Stomatopod* (Flat white shrimps)

larvae of several species of the family *Squillidae*;

Decapoda (larvae), zoea and megalops stages of different

species; *Phyllosoma* larvae of *Panulirus* spp. (Spiny

lobster}; some mollusks of the families *Loliginidae* and

Enoploteuthidae and *Onmastrephidae* (Squids) and *Octopus*

spp. (Octopuses}.

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Altering the deep water layers, at an OTEC plant site would produce some alterations in the distribution of the organisms in the trophic levels because some of them would move to other areas looking for their appropriate environment. Nevertheless, the deep, cold water that is discharged near the surface is rich in nutrients and contains zooplankton which could be used by fish or plants depending on the need. For this reason we can predict that the upwelling of this cold water, along with the shadows cast by the plants, will entice greater numbers of fish to the

are

3.3. FISHERIES RESOURCES

Juhl (1971) mentioned that the Caribbean fisher resources could be grouped in three mayor zones: island are and reefs, continental shelf, and pelagic, A fourth classification, midwater fishery, could be suggested but probably even today there is not enough information on this type of fishery.

In 1976, according to the Yearbook of Fishery Statistics FAO (1977), 47% of the regional product ton comes from island arc and reef resources. This includes the artisanal fisheries carried out by Puerto Rican local fishermen The continental shelf resources reached 48% of the total production of the Caribbean. It is important to note that the most productive area, owing mainly to good hydrographical conditions for fisheries, lies from the Guianas to the Panama region, very far from Puerto Rico. The pelagic resources are the least productive, both in volume and number of species composition, with only 4% of the total production in 1976

The most important Puerto Rico fishing centers close to Punta Tuna are located in the southern part of the island (Patillas, Maunabo, Yabucoa) and Vieques Island.

In 1978 there were a total of about 100 artisanal fisher-

men, 70 fishing boats, and 1,400 units of fishing gear in this region. Most of the fishing activities are carried out in the narrow shelf from Patillas to Yabucoa, and South of Vieques Island. Very few fishermen go beyond the 20m isobath. There are roughly 900 fishing pots, which represent 70% of the total fishing gear of the area. The total landings of fish and shellfish in these fishing centers in 1977 amounted to at least 225,000 Kg (Fig. 65).

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4.0. SUMMARY

This summary has for its basis, the literature and information that was discussed in this document, as well

as the very preliminary results of Puerto Rico's OTEC data-collection program for fiscal 1979. These latter results are not presented in this report, and shall only be referred to for confirmation or verification.

4.1. PHYSICAL ENVIRONMENT

The climate of Puerto Rico and its surrounding area is well documented as being typically tropical marine, with the superposition of predominant easterly winds.

As is frequently found in similar situations, the windward side of the island usually receives more rainfall, with precipitation varying from 70-500 cm/year, depending on location. Again, as is often the case in tropical and subtropical latitudes, hurricanes and severe storms are experienced in the area. There is an annual expectation of such a storm being sufficiently near the area to be felt, and statistically every 3-5 years, a severe storm or hurricane may be expected to affect the weather and sea conditions for an extended time.

Historical wave statistics indicate that 99% of the time the seas are less than 3m, and much of the time they range from 1-2 m.

The tidal excursion around the coast of Puerto Rico and her neighbors is small, ranging from virtually nothing to less than 1m. In spite of this low tidal range, the tidal currents are seen as being significant components in the coastal circulation patterns of some areas.

There have been few measurements or even attempts to measure the water currents in the area. Some surface results show a predominant westerly drift, with occasional reversals. The subsurface results are even less definitive, due to the few attempts. Usually a southwesterly drift is reported.

The salinity profile below the pycnocline (depth of most rapidly changing density-about 200 m maximum) along the south coast is documented fairly well. At and exceeding Such depths, the variations due to atmospheric fluctuations are seldom Seen. The upper waters are influenced by the atmosphere, the local weather and climate, and the degree of freshwater inflow from the major northeastern South American rivers. This relationship is now beginning to be understood. Typical upper water salinity may vary from

31-37 ‰, with 34-36 ‰, most common. A salinity maximum of about 37 ‰, is found immediately beneath the surface water mass (0-200 m). Below this salinity maximum, the salinity generally decreases to about 35 ‰ in the nearshore deep waters around the island.

Temperature values, and the resulting level of the thermal resource, are found frequently in the literature.

The surface water temperature usually ranges from 26°C to 29°C. A sharply defined seasonal thermocline exists during part of the year, but the permanent thermocline, although

Present, is not well defined. Typical values of the temperature at the 1000 m depth is 6°C, with some small variation. The thermal resource available to an OTEC Plant, using the surface and 1000 m depth values of temperature, is 20-23 C* throughout the year, except during severe weather conditions.

The Mixed Layer Depth, or isophycnic layer depth, varies from virtually zero to almost 150 m deep, with the usual range being 40-100 m, depending on the time of the year. These values are taken from various measurements made in the area over many years.

4.2, BIOLOGICAL ENVIRONMENT

The productivity of the Caribbean is known to be low due primarily to low available nutrient levels in the photic zone.

Not much has been reported about the phytoplankton, either nearshore, or in the open sea. The few exceptions include species lists (up to 450 species), and a brief description of the ecosystem near upwellings in the Caribbean.

Some zooplankton measurements have been taken both nearshore and in open water near Puerto Rico. Seasonal

changes are seen in the nearshore waters, with most of the variations caused by fluctuations of holoplankton. These Permanent plankton have accounted for 60-90% of the zoo-Plankton collected near shore, with copepods comprising most of the organisms. About 450 species of copepods have been reported throughout the Caribbean water column. The greatest number of zooplankton were collected in the Central Caribbean and near areas of upwelling.

Overall, the biological resource of the Caribbean fs scarcely being tapped, or understood, and therefore an accurate assessment of the ecosystem changes resulting from an OTEC plant being either present and/or operating can not necessarily be assessed at this time.

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4.3. CONCLUSTON

In conclusion, this survey shows that our present level of knowledge of the OTEC related oceanic parameters for the Puerto Rico area is low. Usually, the measurements, results, and citations used in this report were made with other purposes in mind. Therefore, the spatial and temporal scale of the measurements were not necessarily the most desirable for our purposes. It is hoped that during the next few years, this problem shall be corrected, with more OTEC-oriented measurement programs yielding more applicable and meaningful results.

5.0. RECOMMENDATIONS FOR FUTURE WORK

As there are few published and unpublished data available for the potential OTEC sites around the island of Puerto Rico, the results of this study lead to two recommendations; a more thorough historical data review, and future data collection.

5.1. HISTORICAL DATA REVIEW

Although the purpose of this study was to review the available physical and biological literature and unpublished information, there may still be more data as yet uncovered. One recommendation is to continue to be aware of any uncovered historical data sets that are pertinent to the area and to OTEC.

Most, if not all, of the available temperature and current data has been found for the Punta Tuna/Vieques area, but a more detailed study on salinity may be required. Furthermore, the geographical area of coverage should be expanded to include the remaining portion of

the south coast of Puerto Rico, as well as the entire

north and northwest coast. Although the physical differences measured at these locations should not vary considerably, they should be documented for the OJEC program.

This report does include a biological section, but the processing and reporting of biological results in the literature may lag behind the other data, due to longer processing and interpreting time. Therefore, an up-to-date interpretation of today's knowledge of the biota and their dynamics in this part of the world will probably not be available for some time. Continued literature monitoring will help minimize the time gap.

Chemical and geological reviews were not part of this study, but certainly should not be overlooked. These reviews should be started as quickly as possible, since any environmental effect on the biota might well come about as a result of chemicals used in the cleaning of heat exchangers, or by trace metal erosion. An understanding of the dynamical structural interrelationships between

the biota and their chemical environment might well predict or divert any future problems, or may suggest directions toward a more ecologically compatible design.

In summary, the following recommendations are being made with respect to the historical data:

1. Expand the geographical area of coverage of the literature review to include the entire south and north

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coasts of Puerto Rico, including both the Atlantic and the Caribbean.

2. Continue to monitor the biological literature for updating of existing information that is pertinent.

3. Monitor all environmental studies completed in this part of the world for any usable information.

4. Use any available satellite sea surface temperature data to enhance the existing data bank and to develop better predictive capabilities.

5.2. FUTURE DATA COLLECTION

As so little applicable information is available, the greatest thrust toward understanding the oceanic region near Puerto Rico shall have to lie in the realm of combining the sparse historical information with an intensive data collection effort. This program must be developed at the specific benchmark site of Punta Tuna (where the present work is being conducted), and also along the remainder of the south coast and the entire north coast. The program must address itself to the questions of,

"What effects will the ocean have on an OTEC power plant?"

and what effects will OTEC power plants have on the ocean??

Possible OTEC scenarios include using intake water of up to 3000 m/sec from both the near surface and the terminus of a deep water pipe, many tens of meters in diameters, located as much as 1000 m deep. These two water intakes may or may not be mixed during their exhaust cycle. Therefore, design and environment planners must understand the physical, chemical, and biological dynamics of the entire water column and the geology of the bottom. The upper waters must be studied for mooring and stress effects, safety, thermal resource, biofouling, entrainment, productivity, and contamination. The mid-depths must be studied for contamination, stress effects, and the movement of the deep scattering layer. The bottom depths must be studied for thermal resource, entrainment, nutrient levels, and mooring problems. Furthermore, predictive relationships for these and other parameters must be responsive to both real and temporal variations. These are

but a few of the considerations taken into account in the development of the recommendations which follow:

There is a need for further data collection at potential Puerto Rico OTEC sites to measure the following parameters + those considered most urgent are indicated by an asterisk (*):

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1. Temperature

ta) of the mixed layer, using thermometers, STD, or XBT (daily), when possible, for short term variations.

4b) to 200 m, using recorded monitoring equipment, for upper water thermal structure during severe weather events.

*c) in the water column to 1000 m, using thermometers, STD, or XBT (monthly), for ecological structuring and plant design purposes.

4) of the actual sea surface and the mixed layer, using thermometers, STD, XBT, and satellite (whenever the satellite data will be available) to correlate the Satellite sea surface temperature monitoring with the mixed layer temperature.

@) of the mixed layer, using thermometers, STD, and XBT (weekly), for ecological structuring.

2. Thermocline depth

*a) using XBT (daily, when possible, otherwise weekly), to anticipate discharge dynamics.

3. Salinity -

a) to 200 m depth downstream, at discrete depths

or with STD (biweekly), to assess the density structure for water discharge.

*b) in the water column, at discrete depths (monthly or bimonthly), for ecological structuring.

*c) to 200 m, using recording equipment, to determine vertical movement of water masses and salinity structure (during severe weather events).

4) in the mixed layer, at the benchmark site, at discrete depths, (weekly), to correlate with the rainfall in the surface water mass at its source area (the Amazon and Orinoco Rivers), for predictive purposes.

4. Mixed layer depth

*a) using STD or XBT (daily, if possible), for engineering design requirements.

+b) using recording equipment with thermistor strings, to monitor thermal resource variation during severe weather event:

5. Internal waves

*a) at one site in the Caribbean and one in the

Atlantic, measuring both amplitude and period, by monitoring the temperature profile with recording

thermistor strings, to determine the effect of the variation of the horizontal thermal structure (due to large amplitude long waves) on intake and outlet.

6. Wave spectra surface

+a) at one Caribbean and one Atlantic site, using @ recording wave rider, to determine the long-term wave spectra for plant and personnel safety,

7. Water currents

*a) using current profilers, (4 per day on a weekly basis), to supplement the recorded data with emphasis ~ during the tidal periods.

*b) using moored, recording current meters at discrete depths, to determine the stress to the plant mooring and deep water pipe, and to estimate the long and short-term eulerian movement of water past the site for intake and discharge.

B. Water trajectory - -

*a) using drogues above and below the thermocline, (bimonthly for 2-5 days), to determine the trajectory diffusion and plume dynamics of the plant discharge.

9. Zooplankton

*a) at the sites and downstream, using a net of 54 micron mesh at discrete depth intervals, (2 per day monthly), to determine the population structure of EmaTT and medium-sized zooplankton.

*b) at the sites and downstream, using a net of 330 micron mesh at discrete depth intervals, (2 per day monthly), to determine the population structure of

medTum zooplankton and meroplankton.

*c) at the sites and downstream, using a net of 1000 micron mesh at discrete depth intervals, (2 per day monthly), to determine some of the structure of the meroplankton and large zooplankton population.

d) at the benchmark site, using the above 3 nets with larger diameter openings and longer scope, through the entire water column, (hourly for 48 hours, twice

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er_year), to gather statistics describing the Datehiness of various sizes of plantton 4a the area.

e) using a very large multimesh net pulled through the water at various depths in the upper waters (bimonthly), for closer estimation of possible organism entrainment.

10. Chlorophyll

a) either at discrete depths or by pumping throughout the upper 200 m (bihourly for 48 hours, quarterly), to determine the normal short-term temporal variability.

*b) at the sites and downstream, at either discrete depths or by pumping throughout the upper 200 m (bimonthly), to determine the chlorophyll distribution for ecological structuring.

11. Phytoplankton

*a) at the sites and downstream, at discrete depths in the upper 200 m by net or bottle, (bimonthly), for Counting and identification to determine the spatial distribution and species present for ecological structuring.

*b) at discrete depths in the upper 200 m (bihourly, quarterly), for counting and identification to determine Statistics related to patchiness.

12. Nutrients

*2) downstream along the 200 m isobath, at discrete depths, (bimonthly), to determine if normal upwelling exists, for ecological structuring.

*b) downstream in the plume from the sites, at discrete depths throughout the water column (monthly), for ecological structuring.

Yc) at the benchmark site, at discrete depths (bihourly for 48 hours, quarterly) to determine temporal variations (quarterly)

13. Fish attraction

a) in upper waters from a moored structure, to

determine attraction effects of a floating pelagic structure.

APPENDIX A

SUMMARY OF COASTAL CURRENTS CHARACTERISTICS ALONG THE SOUTH COAST

Guayanilla - Punta Ventana Sector

- Guayama Sector

Gudnica Sector

Ponce Sector

La Parguera Sector

Summary of South Coast Nearshore Currents

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SUMMARY OF COASTAL CURRENTS CHARACTERISTICS

ALONG THE SOUTH COAST

The offshore surface currents of the south coast of Puerto Rico have been described by many investigators. Published reports from drift bottles studies, ship drift measurements and wind regime analyses and observations indicate that the main drift is in a west-northwesterly direction as shown in Figure A1. This is the north Equatorial current which dominates the entire Antilles. Figure A2 summarizes in vectorial and statistical methods the general distribution pattern of the currents on the South coast during winter and summer according to the data published in the Sea and swell Oceanographic Atlas of the North Atlantic (U.S. Naval Oceanographic Office, 1969). The figure also shows the wave regime statistical characteristics during the two most significant seasons.

Close to shore, however, this general current varies considerably, owing to the variations in depth. Surface and water column currents are deflected and influenced by submarine topography, tidal processes and shoreline morphology.

GUAYANILLA - PUNTA VENTANA SECTOR

Table AI shows the range of current speed at various depths as found in three previous studies on the area.

The variability of the currents at different times of the year is apparent. Minimum surface current speeds ranged from 7 to 22.6 cm/sec, both values having been measured in the May, 1969 study by Kamel and Hadjitheodorou, Maximum Surface current speeds are relatively more consistent, ranging from 22.5 to 38.7 cm/sec. Speed range at a depth of 5 meters is less variable, the greatest difference measured on June 10, 1971 and reported in the Oceanographic Baseline Data (1971-72) report. Maximum speed range at depths varies significantly in contrast to the current speed at the surface; there is a definite velocity gradient with depth.

Kamel and Hadjitheodorou (1969) concluded from their study that wind-drift and tidal currents are the predominant types in the Guayanilla Bay and Punta Verraco areas. The report of the "First Survey of the Guayanilla Disposal Site (Area G)* Oceanographic Baseline Data (1971-72) study indicates that wind-drift currents are predominant since the total rise and fall of the tide is well under a foot therefore, so not a great deal of tidal component to the current would be expected." Both studies conclude that

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Surface wind-drift current becomes insignificant at a depth of about 1 meter.

The results of investigations performed by the Department of Marine Sciences personnel (Herndndez-Avila and Morelock, 1975) suggest a third possible current~ generation process: a wave-induced surface and subsurface

Current affecting, mainly, the direction of flow. Table AZ of the original report (Caribtec Lab., 1975) shows results on current speeds at surface and intermediate layers as Measured by dye and drogues methods.

The Oceanographic Baseline Data (1971-72) reported Current speeds in the Guayanilla sector ranging from 9 cm/sec at a depth of 20 m to 28.7 cm/sec at 5 meters depth, as measured with an Ekman-Merz current meter.

Variability of current can be seen in Table F-1 (page 7-113). Range of speeds varied from 7.7 to 28.3 at a depth of 11 meters (Table F-3 of the report) as recorded by an in-situ current meter. Drogues measured a maximum surface Speed of approximately 35 cm/sec and a minimum of 2.1 cm/sec. (Table F-2))

GUAYAMA SECTOR

Current structure and patterns in the Guayama sector have been reported in the Oceanographic Baseline Data Project (1971-72). Mufioz (1967), a study carried out by PRASA (1967), and Heres (1971), reported data on currents made by employing drifting drogues and wood blocks. the general flow of water in all cases was found to be to the west at varying speeds, although variations to the east were encountered. These studies, according to the Oceano-

graphic Baseline Data Project reviewers, were not reported in proper form for more comprehensive analyses.

The current meter data reported by the Oceanographic Baseline Data Project study is listed in tabular form in Appendix F of their final report; graphs of the data are shown in Figures GH-2 through GM-7 of the same report. Speeds ranged from a maximum of 28.7 cm/sec at a depth of 5 meters to a minimum of 7.7 cm/sec at 20 meters depth as recorded with an Ekman-Merz meter, Recording meters at a depth of 11 meters showed current speeds from about 10 to 27 cm/sec. rogues gave velocities from 35 cm/sec at the Surface to a minimum of 1 cm/sec at a depth of 10 meters. Tables and figures of current meter data and drogues studies are given in pages 7.113 of Vol. II of the final report.

GUANICA SECTOR

The current patterns in the Guénica sector, as investigated by Herndndez-Avila (1977, unpublished), were similar to those at Punta Ventana, with the exception of the

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funneling effect of the canyon. Drifting drogues and dye traces indicated that surface currents are a function of the wind stresses from the east and southeast. The tidal

forces are observed to have an effect on the direction of the deeper drogues as shown in the 4, 6 and 7 meters drogue-tracks. Net mass transport in the water column was toward the west and west-north-west. Current velocity ranged from about 1 cm/sec to approximately 30 cm/sec at the surface.

Circulation at depths greater than 9 meters was determined to be a function of water reflection from the coast and the tidal excursion forces. Net mass transport was

in 9 south and southeastern direction. East flow was also dominant at intervals.

The reversal effect of the tides was observed in the Progressive vector diagrams. Velocity histograms indicated that the velocity ranged from 1.5 to a measured maximum of about 14 cm/sec. Mean velocities ranged from 2 to 7 cm/sec depending on the station's location.

The data shown from this study has not been fully analyzed as yet. Currents were monitored during the four Seasons of the year; wave refraction diagrams are in the Process of analysis, as are salinity, temperature, climatological, and other dynamic parameters that have been Measured periodically. Comparisons between the current Structure in the same station-during. two seasons of the

year will be made.

PONCE SECTOR

The available ocean current measurements in the Ponce area have been reported by Coldn (1971) of the Marine Resources Research Institute, University of Puerto Rico, Mayaguez Campus. Measurements were made at three different water depths employing Hydro-Products in-situ current meters, Model 502. The data has not been completely analyzed, at least with the methods usually employed.

Current roses are shown in Figures 1 to 4 of the aforementioned study. Figure 1 of the Colén study illustrates the frequency of direction of water flow at a depth of 1.5 meters in station 1. Dominant current direction was towards the north-east, east, and southeast quadrants. At station 2 (Figure 2) the dominant direction was shown to be towards the north-west quadrant at a depth of 1.5 meters, although reversals towards the east were also observed. The same pattern, but with stronger current speeds toward the east, were found at station 3, as illustrated in Figure 3 of the publication. Currents seemed to be dominant toward the southwest and east quadrants. Current velocities ranged from 0 to a maximum of about

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11 cm/sec (2 knots). Surface vectorial properties were Rot observed or measured in this investigation.

Colén (1971) made another study at Punta Cuchara in the Ponce area at a much deeper water depth. Variations of the current were immediately observed. Velocities at this depth, according to Colén, varied from .1 to .2 knots (5 to 10 cm/sec).

LA PARGUERA SECTOR

Surface and subsurface currents in La Parguera off-shore and nearshore areas have been monitored throughout the year by students and personnel of the Department of Marine Sciences. Directions and speed patterns in this area are similar to those found at Guanica, Guayanilla-Punta Ventana and at Ponce offshore-nearshore sectors. Current divergence by submarine morphological differences are evident. Surface speeds ranged from zero (at slack

time with no wind blowing) to a maximum of 30 cm/sec.

Surface resultant velocities vary according to the strength and variations of the wind patterns. At night the wind blows offshore, from the land, reducing the tidal current velocities if the flood tide is flowing.

Figure 13 in Roberts and Hernández (1976, unpublished) shows the results of a study performed with radiotracked current drogues offshore La Paraguera. Two radio drogues were tracked for an interval of four days. These drogues were later recovered in Mona Passage, one in the El Negro Reef complex, off Mayaguez, and the other in the vicinity of Desecheo island.

Colón (1971c) installed three in-situ current meters at different locations off the reefs near La Paraguera. Relative quantity of water and direction of flow were illustrated by means of current roses (Figures 1 to 3 of the report). Western directions of flow are dominant in the locations closer to land: Northeastern flow directions were found at a depth of 7.5 meters in the outer station. Velocities of the currents ranged from 5 to 20 cm/sec.

Circulation patterns around Laurel Reef, La Paraguera, Puerto Rico, have also been specifically determined by

Glynn (1973, pages 309 to 315).. Table 4 of this publication tabulates the current speeds and directions. The resultant vector diagrams are shown in Figure 12 of the published paper. Maximum velocities of around 10 cm/sec were measured.

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SUMMARY OF SOUTH COAST NEARSHORE CURRENTS

Conclusions (after Hernández-Avila, 1977, unpublished) from the general review of the available literature on nearshore-offshore currents of the south coast are as follows:

- A. Surface drift is a function of the relative strength of the wind, waves and tidal patterns. There are marked diurnal variations.

- B. During daylight hours the wind direction and speed are dominant, overpowering the ebb tidal flow or aiding the flood tide if these coincide. The land-sea breeze effect at night has the reverse effect: it opposes the flood

tides and aids the ebb tides.

C. Measured surface velocities during daylight hours

can reach a maximum of about 40 cm/sec toward the shore-

Vine owing to wind stress coupled with flood tidal condi-

tions and wave mass transport direction. Storm conditions

have not been monitored.

D. Current velocities usually decrease at night

during the flood tide to values below 5 cm/sec in an

offshore direction.

E. Surface current statistics:

1. Range: Minimum measured speed: 2.1 cm/sec

Maximum measured speed:

40 cm/sec

Approximate mean value: 18 cm/sec

2. Dominant direction: WNW

F. Tidal currents statistics:

1. Range: Mean Ebb: 6 cm/sec*

Mean Flood velocities: 10 cm/sec**

* = after wind stress has been cancelled out.

velocities vary as a function of sub-marine and coastal morphologic.

2. Direction of tidal flow:

Ebb tide: SSE

Flood tide: WNW

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completely negligible, but wave-induced stresses are still

@ dominant effect. The variability, owing to the revers-

ing tidal effect, will affect to a certain extent the

Speed distribution and flow direction towards shore on a

WW azimuth. Wave refraction effects are still present.

M. Current speed and direction at a depth of 45 meters, 5 meters above the bottom of Punta Ventana Canyon, a5 measured with an in-situ mechanical current meter.

1, Range: Minimum measured speed: 0 cm/sec (?)

Maximum measured speed: 19 cm/sec

mean speed: 3.6 ca/sec

2. Dominant Direction: ESE (mean direction) in

Punta Ventana; S and SE in La Parguera and

Guanica during the ebb tide cycle.

CONCLUDING REMARKS

1, General water mass movement at the surface and subsurface is in a western direction, at an angle to the shoreline. This circulation pattern minimizes any hydraulic back-flow from shore to the offshore areas, Mass transport at the shoreline will be along the shore in a western direction. Longshore current speeds ranging from 17 to

25 cm/sec have been measured at the Punta Ventana and Guénice shorelines. At La Parguera these currents are usually on the order of 5 to 10 cm/sec inside the reefs.

2. Surface circulation is expected to be nearly the same for long periods of time. This statement is supported by the location of the coast in a constant energy environment determined by steady trade wind incidence, mean wave regime, and meteorological data as shown in the tables of the text. Changes will occur during different seasons of the year, but the wind-driven, wave-induced mechanisms

from an almost constant direction will be dominating the surface circulation. Overall it can be concluded that parameter variations are mainly significant during the winter-summer seasons.

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APPENDIX B

LISTINGS AND CURVES OF NODC DATA FOR THE PUERTO RICO AREA

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Profiles dissolved oxygen, temperature,

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APPENDIX

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The present overview of studies of the effects of ocean thermal energy conversion (OTEC) plant operation on the physical environment of the ocean includes a review of the pertinent results of past and contemporary model efforts in terms of their implications for OTEC development and suggestions for future research consistent with OTEC timetables. Particular consideration is given to the areas of utilization of the thermal resource, effects of a single OTEC plant, and aggregate effects of many OTEC plants. These potential effects include modification of the local temperature, salinity, and nutrient distributions, induced changes in mixed-layer depths and sea-surface temperatures, and dispersal of biocides or working fluids (due to leaks).

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U.P.R., Dept. of Marine Sciences, Mayaguez, P.R. 104 p.

This report was produced as a pre-environmental/assessment report for OTEC work off the southeastern Coast of Puerto Rico. The report evaluated present field data, as well as historical data, where available. The information analyzed concerned bathymetry, bottom quality, seismicity, climate, winds, hurricanes, tides, Sea and'swell, water masses, temperatures, salinity, currents, nutrients, and oxygen. This and other pertinent OTEC criteria are evaluated and compared to other sites in the world.

Atwood, O.K., C.P. Duncan, M.C. Stalcup, M.J. Barcelona. 1977. ?Resource assessment of a high potential OTEC site near Puerto Rico. In Proceedings of Fourth Annual Conference on Ocean Thermal Energy Conversion, 22-24 March 1977, New Orleans, University of New Orleans, pp Iv 74-78.

Environmental assessment of potential OTEC sites near Puerto Rico indicates that a high-potential site exists off the southeast coast. The a T to 1000

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meters can be as high as 24°C (43°F) and is never

9 less than 20°C (36°F). The insular slope at the site

is steep, and water depths of 1000 meters exist

(within 1°1/2 miles off shore. Geostrophic conditions

guarantee a warm, thick mixed layer with surface

Currents in the order of 1/3 of a knot. The supply of

cold water can be considered limitless. The site is

° protected from north and northeast swell, and a mild

sea state exists all year round (except during hurri-

canes). The salinity, temperature and nutrient dis-

tributions at the site are typical of open tropical

Seas, making the site ideal for a prototype OTEC

plant,

Bathen, K. 1977. A further evaluation of the oceanographic conditions found off Keahole Point, Hawaii, and the environmental impact of nearshore ocean Thermal Energy Conversion plant on the subtropical Hawaiian waters. In Proceedings of Fourth Annual Conference

on Ocean Thermal Energy Conversion, 22-24 March 1977, New Orleans, Univ. of New Orleans, pp IV 79-99.

Environmental analyses, as detailed in the previous 15-month NSF/RANN report, repeated for the case of a 100 MW and a 240 MW nearshore floating

power plant located 2 km off Keahole Point. Both

Summer and winter conditions were considered. The

intent was to evaluate just the approximate scale

of impact for each case. Based on the temperature

and discharge rate of cold water from the OTEC plant,

the local meteorological and oceanographic data estimates were made of changes in surface heat exchange, alteration in heat content of the mixed layer, and rates of spreading of the discharged work. Work was completed using the surface heat exchange equations and the two-dimensional heat conservation equation.

Given then an estimate of the plume outfall characteristics and local biological data, the degree of nutrient addition and the extent of possible bio-stimulation were estimated.

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Bretschneider, C.L. 1977. Operational sea state and design wave criteria: State-of-the-art of available data for U.S.A. coasts and the equatorial latitudes. in Proceedings of the Fourth Annual Conference on Ocean Thermal Conversion at New Orleans, 22-24 March 1977. Univ. of New Orleans, pp.IV 61-73.

This was a "state-of-the-art" investigation on the availability of published material on the subjects

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of winds, waves, and surface currents for possible use in the determination of operational and design criteria for potential OTEC sites. It included the offshore areas of the U.S. East Coast, the Gulf Coast and the West Coast, the Hawaiian Islands, and a1] the equatorial oceanic areas between 20°S and 20°N latitude. No additional measurements and no generation of new data were made for increasing the "state-of-the-art". The sources of data are referenced and classified into one of four classes according to a pre-determined set of rules and opinions.

° Brekhouskikh, L.M., K.N. Fedirov, L.M. Fomin, M.H.

Koshlyakov, & A.O. Yampolsky. 1971. Large Scale multi-buoy experiment in the Tropical Atlantic.

Deep Sea Res. 18(12):189-1206.

A large-scale hydrophysical experiment aimed

° at studying ocean currents variability was conducted

at a selected site (polygon) centred at 16°30'W in

the Tropical Atlantic. The experiment involved six

U.S.S.R. research vessels and a cross-shaped network

of buoy-stations laid out within a square 113 x 113

nautical miles. Currents and water temperature

° were continuously recorded by this network at various

depths. Each of the buoys was replaced every 25

days, Special arrangement being made to have over-

lapping records during each replacement operation

Additional research programmes were conducted from

participating ships.

Current records revealed an extremely high variability both in time and in space even after filtering out the inertial and tidal oscillations from these records. Density stratification seems to affect the mean current vector rotation with depth as well as the inertial and tidal currents which, as a result, have qualities of large-scale three-dimensional internal waves.

Among other studies measurements of small-scale

5 thermohaline structure deserve particular attention.

It is likely that the observed thermohaline micro-Structure is related to an intermittent mixing regime in which double-diffusivity convection interplays with larger scale turbulence of both convective and dynamical origin.

Bunker, A.F. & L.V. Worthington. 1976. Energy exchange charts of the North Atlantic Ocean. Bull. Amer. Meteor. Soc. 57(6):670-678.

Charts of calculated energy exchange across the the surface of the North Atlantic Ocean have been constructed. Wind and temperature observations obtained from 8 million ship weather reports were entered individually into the bulk aerodynamic equations with exchange coefficients that varied with wind speed and stability. The individual fluxes Were averaged to obtain monthiy and annual means of latent and sensible heat momentum. Net radiation fluxes were calculated using Budyko's (1963) formulas. Monthly and annual averages for 32 years have been formed for 500 subdivisions of the ocean. Averages for each month from 1941 through 1972 were computed for 66 10° squares to study the variations and anomalies of the fluxes, meteorological variables, and sea temperature. Charts giving annua) averages of the net heat gain by the ocean, evaporation,

sensible and radiational heat exchange, wind stress components, and meteorological variables are presented.

A graph of the monthly variations for Marsden Square 116 and an anomaly chart for January 1958 show the

- variability of the fluxes and the large-scale anomaly pattern.

Burns, D.A., M. Car. 1975. Current data report for the eastern part of the Caribbean Sea. Naval Oceanographic Office, Washington, D.C. Tech. Note, TN6110-6-75 146 pp.

Preliminary analysis of 36 current meter records, from 18 arrays in the eastern Caribbean Sea, showed wide variation in mean speed ranging from less than 1 cm/sec near St. Croix and Vieques, to a maximum of about 90 cm/sec between St. Lucia and St. Vincent at a depth of 45 meters. Ten of the records had significant tidal current signatures with maximum amplitude of the M2 constituent attaining approximately 24 cm/sec at 590 meters between St. Lucia and St. Vincent. Data were recorded during all

four seasons at depths ranging from 45 meters. to

1910 meters.

Chew, F., K.L. Drennan, & W.J. Demoran. 1962, Drift-

bottle return in the wake of Hurricane Carla, 1961.

J. Geoph. Res. 67(7):2773-2776.

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Most of the drift bottles released off the Mississippi delta three weeks before hurricane Carla entered the Gulf of Mexico were recovered from the vicinity where Carla crossed the Texas coast. The pattern of the recovered bottles is, presented together with a discussion of some possible interpretations.

Clarks, G.L, 1938. Light penetration in the Caribbean Sea and the Gulf of Mexico. J. Mar. Res. Vly

(2):84-94.

Measurements of light penetration using Photox rectifier cells were made at 8 stations in the Caribbean Sea region and in the Gulf of Mexico. At the stations in shallow water east of the Mississippi Delta, considerable turbidity was encountered in the surface layers. But at the offshore station in the Gulf and at all the other Stations the water was found to be highly uniform and extremely transparent. The value of the transmissive exponent from 95 to 185 at the Station in the Cayman Sea west of Jamaica was

$k = .038$, indicating the presence of the clearest ocean water ever measured.

Coton, J.A. 1963. Seasonal variations in heat flux from the sea surface to the atmosphere over the Caribbean Sea. *J. Geoph. Res.*, 68(5):1421-1430.

The annual variations in the heat flux to atmosphere over the Caribbean Sea are studied through a computation of the monthly heat balance

of the oceanic body. Various components of the heat balance are computed from available climatological information; the heat flux is obtained as a residual. A sample of bathythermograph observations accumulated through the years and compiled at the Woods Hole Oceanographic Institution was used in evaluating the rate of change of the heat content of the water body-the heat storage term. The results for this term indicate maximum cooling rates of about 141 ly day⁻¹ in December and maximum warming of 82 ly day⁻¹ in April and August. The warming from winter to summer is spread over a 7-month period. The cooling from summer to winter takes only 5 months. The divergence of heat transport by the ocean current is computed, but the Procedures are, of necessity, rather crude and

uncertain. There are indications that this term changes sign, with export of heat observed in Summer and import in winter, but the largest magnitudes are only of the order of 5 to 10 percent of the radiation absorption. The maximum heat flux to the atmosphere, about 369 ly day^{-1} , is observed in November; the minimum is 196 ly day^{-1} in August. The corresponding evaporation rates are 0.58 cm day^{-1} in December and 0.31 cm day^{-1} in August. The annual range and annual average are higher than previous estimates. A separate evaluation using turbulence transfer formulas with data for a section of the Caribbean Sea was also made; the results compared well with the heat balance computations.

Crease, J. 1962. Velocity measurements in the deep water of the western North Atlantic. *J. Geoph. Res.*, 67(8):3173-3176

Water velocity measurements are reported in the western North Atlantic using Swallow floats. The floats were moving at depths of 2000m and 400m. Typical speeds seen were of the order of 10 cm/sec.

Cuchrane, J.D. 1968. Currents and waters of the eastern ~ Gulf of Mexico and western Caribbean, of the western tropical Atlantic Ocean and of the eastern tropical Pacific Ocean. Texas A&M, Tech. Report 68-81 pp

Fisher, E.L. 1958. Hurricanes and the sea-surface temperature field. *J. of Meteor.*, 15(3):328-333.

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The behavior of hurricane tracks and the variations of the intensity of hurricanes are investigated in a study of the seasurface temperatures around eleven hurricanes. By the use of several methods of analysis, it is found that there is distinct, although not conclusive, evidence that hurricanes tend to form near relatively warm ocean areas, that they tend to follow tracks along the areas of warmest water, and that they tend to weaken when they move over pronouncedly colder water.

Forristall, G.Z. 1974. Three-dimensional structure of storm-generated currents. *J. Geoph. Res.*, 79(18): 2721-2728,

Previous studies of wind-driven currents have naturally concentrated on the prediction of destruc-

tive storm surges. However, the present and planned construction of large facilities in offshore waters makes study of the currents themselves equally important. Here we show that it is possible to model three dimensional time-dependent currents by numerical integration over a two-dimensional grid followed by an evaluation of convolution integrals over the sea slope and wind stress. Solutions for idealized cases are compared with analytical results, and a study of a hurricane in the Gulf of Mexico is presented.

Forristall, G.W., R.C. Hamilton, & V.d. Cardone. 1977.

Continental shelf currents in Tropical Storm Delia: Observations and theory. *J. Phys. Ocean.*, 7(4) 532-54

Storm currents are a significant part of the design hydrodynamic flow field in areas subject to tropical storms. In September 1973, Tropical Storm Delia passed over the instrumented Buccaneer platform located in 20 m of water 50 km south of Galveston, Tex. Current meter records from three depths show the, storm produced currents on the

order of 2 ms?! which persisted to near the bottom.

A mathematical model of wind-driven current generation was successful in hindcasting the observed current development after a linear slip condition bottom was incorporated in the model

Frassetto, R. & J. Northrop. 1957. Virgin Island

bathymetric survey. Deep Sea Res., 4:138-146.

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A bathymetric survey in the vicinity of the Virgin Islands showed that Anegada and Jungfern Passages, which connect the Atlantic Ocean with the Caribbean Sea between the Virgin Islands Platform and St. Croix Island, are the deepest charted passages

between the two seas. The 1,072-fathom sill depth of Jungfern Passage is the limiting factor in the exchange of deep water between the Atlantic Ocean and the Caribbean sea.

Furthermore, it was found that the Virgin Islands Basin, which lies between Aneгада and Jungfern Passages, has a flat floor 2,400 fathoms deep. It is bounded on the north and south by

Sea Scarps having apparent slopes of 9 to 43 degrees.

The eastern end of the basin is divided into two arms which embrace a 420-fathom sea knoll. Both these arms terminate at sills which separate them from Aneгада Passage and St. Croix Basin. The western end of the basin is connected with a smaller basin, 2,200 fathoms deep, which is bordered by Jungfern Passage on the south and by Grappler Bank on the west.

Froelich, P.N., D.K. Atwood. 1974. New evidence for

sporadic renewal of Venezuela Basin water. Deep-
Sea Res. 21(11):969-975.

Diagrams of silicate versus potential temperature
from two years of data at a hydrographic station on
the southern Puerto Rican insular slope 190 km west-
Southwest of Jungfern Passage sill indicate the
Presence of minor amounts of North Atlantic Deep
water (NADW) below 1600 m. Time-dependent sections
of silicate indicate that this water is present
only sporadically. Time-dependent sections of
salinity display no variation below 1600 m. These
observations are consistent with sporadic overflow
of NADW into the Venezuela Basin over Jungfern sill,
accompanied by mixing and geostrophic spreading at
intermediate depths westward along the Puerto Rico-
St. Croix ridge.

Froelich, P., D.A. Atwood, J. Polifka. Seasonal varia-
tions in the salinity-silicate structure of the
upper Venezuela Basin, Caribbean Sea. Trans. Amer.
Geop. Union, 55(4):303. 1974.

Recent temporal hydrographic studies in the
Venezuela Basin have yielded new information concern-

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Fry,

ing variations in the upper 400 meters. Seasonal
low-salinity surface water during October-November
is characterized by high silicates, indicative of
runoff, probably Anazonian. Linear regressions

of silicate versus salinity yield excellent correla-
tions ($r > .9$). STD traces during the Tow-salinity
Season display homogeneous low-salinity, high-
silicate water underlain by a steep thermocline, the
top of which shows a 2‰ increase in salinity and

22 ug-at/) decrease in Silicate within 15 m.

Salinity and silicate sections across the eastern Caribbean display temporal variations in the lateral Position and strength of the Subtropical Underwater (SUM) core. The SUN can be characterized by a weak silicate minimum as well as a strong salinity maximum.

D.J., J.F. Adams, G.H. Jirko. 1978. Evaluation of mixing and recirculation in generic OTEC discharge designs. In Proceedings of the Fifth Ocean Thermal Energy Conversion Conference, 20-22 Feb. 1978, Univ. of Miami, Clean Energy Research Institute. pp 104-116.

This paper has two parts. The first summarizes the results of an experimental and analytical study of the external fluid mechanics of generic OTEC designs, which was conducted at M.I.T.'s R.M. Parsons Laboratory for Water Resources and Hydrodynamics from March 1976 to July 1977, In this study it was concluded that plants of 100-200 MW, utilizing mixed evaporator and condenser discharges, could be designed

to operate with no recirculation under typical ocean conditions. The primary design variables affecting recirculation were identified and recommendations

for future research were made. The second half of the paper outlines a continuing research effort.

This effort consists of further study of near-field mixing processes currently underway at M.I.T. and Study of the intermediate field disturbances of the ambient ocean now underway at Cornell University.

Fukaoke, J.A., A. Ballester & F. Cervigon. 1964. An analysis of hydrographical conditions in the Caribbean Sea-III-Especially about upwelling and sinking. Studies on Oceanography. Hidaka Commemoration, Univ. of Washington Press, Seattle. pp. 145-149.

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Gordon, A.L. 1967. Circulation of the Caribbean Sea.

9! Geoph. Res. 72,(24) 26207-6223.

The geostrophic method was applied to six north-south hydrographic profiles across the Caribbean

Sea and one across the Yucatan Strait. An access

of flow exists in the southern third of the Caribbean Sea. It flows directly over the steep slope in the reference layer found by DEFANT's method. This condition is similar to that of the Gulf Stream.

The baroclinic mass distribution extends to approximately 1200 meters. Below this, the flow is weak

(5 cm/sec) except in the depths of the Ceyman and Yucatan basins, where currents of over 10 cm/sec

occur. The deep and bottom flow may fluctuate in phase with overflow through the Windward and Anegada Passageways. The main axis of flow corresponds closely with the main axis of spreading found by the core method in both the salinity maximum and the salinity minimum layers. The volume transport across the meridional section in the Caribbean is about 31×10^8 m³/sec toward the west. The northern passageways contribute only a small part of this water. The major outlet is the Yucatan Strait, where the calculated geostrophic volume transport corresponds to the transport through the Strait of Florida. The surface flow is directly affected by the wind. The upper baroclinic field mass is produced by the Ekman transport of the light surface water toward the northern boundary. It is expected that divergences occur to the south of the main flow, and convergences occur to the north. This is supported by salinity and temperature sections. The upwelling, in the south is calculated to be of the order of 10^6 cm/sec at the bottom of the Ekman layer.

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Gould, W.J., W. J. Schmitz, & C. Wunsch. 1974. Preliminary

field results for a Mid-Ocean Dynamics Experiment,
(WODE-0).? Deep-Sea Res. 21(11):911-931.

Three arrays of moored instruments were placed
in the western part of the Sargasso Sea in 1971-1972

to provide pilot data for a Mid-Ocean Dynamics Experiment (MODE-I). Current, current-temperature, temperature-pressure, and acoustic positioning sensors were deployed on these moorings. The acoustic positioning instrumentation, in combination with conductivity, temperature, and pressure sensors, was also used in free-fall mode to obtain 12 vertical profiles of

temperature and horizontal currents with a vertical resolution of 20 m over a 36-h period during deployment of the first array. These observations were collectively designed to provide estimates of energy levels and space and time scales for mesoscale motions. For frequencies less than 1 cycle day⁻¹, velocity and temperature records are dominated by 50-100 day fluctuations, with apparent horizontal spatial scales of the order of 100 km. The vertical structure of

the mesoscale motions appears to be dominated by the barotropic and first few baroclinic modes. Estimates of kinetic energy from current meter records were found to depend upon the type of mooring used. Records from moorings with surface buoyancy yield kinetic energies that are higher than those from moorings with subsurface buoyancy. This effect occurs over the entire frequency spectrum. A special purpose experiment, with current meters at the same depths on the two different mooring types and separated horizontally by only a few hundred meters, yielded the same type

of result. The vertical and horizontal displacements of a mooring with subsurface buoyancy at 500-m depth (water depth of about 5400 m) observed over a 4-day duration during the retrieval of the third array

were ± 1 and ± 50 m, respectively. Pressure measurements at other depths on this mooring yielded the

same ± 1 m bound on the magnitude of vertical excursions.

The vertical displacements obtained from a 4 1/2 - month pressure record at 2000-m depth for a similar mooring configuration were ± 6 m.

Hastenrath, S.L. 1966. On general circulation and

energy budget in the area of the Central American Seas. *J. Atmosph. Sci.* 23:694-711.

The field of large-scale vertical motion and the atmospheric oceanic energy budget in the areas of

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the Caribbean Sea and the Gulf of Mexico are studied with ?emphasis on seasonal and regional variations, Using the available radiosonde data of the entire year 1960. The atmosphere over the Caribbean Sea exports latent heat during the winter half of the year, changing to import during summer, while divergence of the latent heat flux prevails over the Gulf of Mexico during most of the year with the exception of midsummer. The troposphere as a whole imports geopotential energy and sensible heat during winter in the Caribbean, and during most of the year in the Gulf area, this being effected by the upper-tropospheric westerly current originating over the equatorial regions of the eastern Pacific. During the summer half of the year, an export of geopotential energy and sensible heat takes place over the

Caribbean Sea, being concentrated in the upper-tropospheric easterlies, this pattern also including the area of the Gulf of Mexico in midsummer. Regarding the total energy budget, the troposphere over the Caribbean Sea acts as an exporter of energy to other parts of the globe throughout the year, while import is indicated for the Gulf of Mexico during some winter months. Ocean currents export heat from the Caribbean Sea during the summer half of the year while conspicuous import is indicated for the Gulf of Mexico throughout the year, with the exception of midsummer. The tropospheric energetics are discussed with respect to their role in the general circulation

Hastenrath, S.I. 1968. Estimates of the latent and

sensible heat flux for the Caribbean Sea and the Gulf of Mexico. *Limn. & Ocean.* 13(2):322-331.

Monthly mean values of the latent and sensible heat flux at the sea-air interface (Q_{+0}) are derived for the areas of the Caribbean Sea and the Gulf of Mexico, separately: 1) from the multiannual mean of the oceanic heat budget; 2) from the atmospheric energy budget, on the basis of the available radiosonde data for the entire year 1960; and 3) by the bulk-serodynamic method, using 1960 ship observations.

The annual average of the latent and sensible heat transfer in the area of the Central American Seas is of the order of 270 ly/day. Making allowance for the propagation of errors and the different time periods used, the results of the three independent approaches are in fair agreement. The shortcomings

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o inherent in all the procedures make various independent approaches desirable wherever possible.

Hazelworth, J.8. 1968. Water temperature variation resulting from hurricanes. J. Geoph. Res. 73(16) :5105-5123.

Daily variations in sea surface temperature at

several coastal and lightship stations and the Nomad

buoy during the passages of ten hurricanes are pre-

sented. The temperature variations are given for

the coastal stations and Nomad buoy for a period

from 10 days before to 36 days after the hurricane

° passed. Generally, marked cooling of the sea surface

Occurred during the passage of a hurricane. However,

examples are noted where a rise in temperature occurred.

A comparison was made of the daily temperature variation due to hurricanes as recorded at the coastal and deep water sites. The mean temperatures decrease for the eleven coastal examples and for the thirteen Vightsnip examples was 3.1°F , and for the three Nomad samples was 6.4°F . The extent of cooling of the surface water appears to be related to storm density and orientation with respect to the recording station.

The temperature decreases at the Nomad buoy during the passage of hurricanes were quite large compared with the changes at other times during the 47-day periods, but factors other than hurricanes appear to cause larger temperature variations at the coastal sites. The length of time for the water temperature to return to normal after passage of a hurricane

was computed for all stations. For the coastal and lightship stations the temperature returned to normal in less than one month with mean time of 13 and 10 days, respectively. At the Nomad buoy, near prehurricane surface temperature conditions were recorded

° within 19 days. These observations indicate the rapidity with which hurricane effects are modified

by subsequent environmental events

Hidaka, K. & A. Yoshio. 1955. Upwelling induced by a circular wind system. *Records of Oceano.* 2:7-18.

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Jirkas G.H., D.J. Fry, R.P. Johnson, D.R.F. Harleman.

1977. "Investigations of mixing and recirculation

in the vicinity of an Ocean Thermal Energy Conversion plant. In Proceedings of the Fourth Annual Conference on Ocean? Thermal Energy Conversion, 22-24 March 1977, University of New Orleans, pp IV 35-4)

Experimental and analytical studies on the external fluid mechanics in the vicinity of an

Ocean Thermal Energy Conversion (OTEC) plant are conducted. Schematic OTEC conditions defined by

a mixed discharge model and a discreetly stratified Ocean are assumed. The interaction of several fluid mechanical regions, a jet entrainment zone, an intermediate buoyant layer and an intake flow zone, is simulated in a shallow laboratory basin representing the upper layer of the stratified ocean. A

Concurrent analytical model development gives satisfactory agreement with the experiments and allows to define an approximate criterion for the existence of recirculation of discharge water back into the plant intake.

Jordon, C.L. 1964. On the influence of tropical cyclones

on the sea surface temperature field. Proc. Symp.

Trop. Meteor. New Zealand Meteor. Vol. 7, Service

Wellington, pp. 614-622.

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Kinard, W.F., D. Atwood and G.S. Giese. 1974. Dissolved

Oxygen as Evidence for 18°C Sargasso Sea Water in

the Eastern Caribbean Sea. Deep-Sea Res. 21(1):

71-82.

Dissolved oxygen measurements at a serial hydro-
graphic station in the eastern Caribbean and along

@ hydrographic transect between La Parguera, Puerto

Rico and La Guaira, Venezuela (67°M) indicate an

intermediate oxygen maximum at about 300 m in the

north gradually rising to 175 min the south. The water at the oxygen maximum has a temperature of about 18°C and a salinity of about 36.5‰, indicating it is 18°Sargasso Sea Water.

Korgen, J. Bodvarsson, and L.D. Kulm. 1970. Current speeds near the ocean floor west of Oregon. Deep-Sea Res. 17(2):353-357.

Near-bottom current speeds were measured at distances of from 1-3 meters above the ocean floor west of Oregon. The instrument used was a temperature-current probe designed to measure temperatures at 8 levels and current speeds at either 1 or 2 levels near the sea floor.

Sampling was carried out at six selected positions. A distribution of recorded current speed versus water depth (from 725 to 2900m) reveals a systematic and significant increase in current speed with decreasing depth.

Mean current speeds for depths from 2700 to 2900 meters were approximately 2 cm/sec with maxima of

up to 6 cm/sec. Mean current speeds for continental Slope stations, with depths from 725 to 1700 meters, range from 5 to 20 cm/sec with maxima of 20-40 cm/sec depending on water depth.

LaFond E.C. 1962. Temperature structure of the upper layer of the sea and its variation with time. Temperature, its measurement and control in science and industry, Vol. I. Reinhold, N.Y. pp. 751-762.

Description of equipment necessary to measure the temperature structure versus time is discussed.

Also, factors controlling the sea temperature are described, as well as cycles in sea temperatures.

Short period temperature fluctuations are also described.

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° Lee, T.N., R.S.C. Munier, S. Chin. 1978. Mater mass

structure and variability north of St. Croix, U.S.

Virgin Islands, as observed during the summer of 1977, for OTEC? assessment. UM-RSHAS #78004, Univ. of Miami, Rosentiel School of Marine and Atmos. Sci. 80 pp.

Variability of the water mass structure north of St. Croix in the Virgin Islands Basin was observed during a 2.5 month study of corrosion and biofouling on OTEC heat exchanger performance in the summer of 1977. Daily STD profiles and weekly hydrocasts

} were taken of the upper 1500 m from Tracor Marine barge moored 15 km north of St. Croix in 3600 m water depth. The largest temporal fluctuation in water properties occurred in the Tropical Surface Waters of the upper 100 m due primarily to advection of this spatially inhomogeneous water mass past the

3 moor. Currents in the upper layer were also highly variable with speeds ranging from 0 to 50 cm/sec and numerous direction reversals. Subsurface currents appeared to be more steady and toward the west at 10 to 15 cm/sec.

° The water used in the heat exchanger test was pumped continuously from the Tropical Surface Waters at a depth of 20 m, which is within the Surface mixed layer defined by temperature, but at the base of the surface salinity mixed layer. Intake salinity variations of 1.7‰ over a one-month

9 period were coherent with similar changes in the upper 60 m of TSW. Variation in water properties below the Tropical Surface Water was small. The mean and ranges of temperature and salinity at 1000 m were only $5.4 \pm 0.5^{\circ}\text{C}$ and $35.0 \pm 0.06 \text{‰}$, respectively. Temperature of the surface mixed waters

° was also quite steady with a total range of only 0.9°C from 27.8 to 28.7°C during the experiment.

The thermal resource available for OTEC power plants defined as the vertical temperature difference ΔT between the surface mixed waters and subsurface water averaged 23°C at a depth of 1000 m with a

o standard deviation of $+ 0.2^{\circ}\text{C}$. The depth to reach $2 \Delta T$ of 20°C varied from a minimum of 660 m to a Maximum of 740 m. Historical data indicate that the maximum depth to reach a ΔT of 20°C would

occur in the winter and would not exceed 956 m.

Thus, from thermal resource considerations, the

o waters north of St. Croix are considered an excellent
Location for an OTEC site.

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Leipper, D.F. 1967. Observed ocean conditions and
Hurricane Hilda, 1964. J. Atmos. Sci. 24:182-196,

Hurricane Hilda crossed the Gut of Mexico in
the period 30 September to 4 October 1964 develop-
ing into a very severe hurricane in the central
Gul."Sea temperature data available prior to the
storm indicated what was probably a typical late
Summer situation with some surface temperatures
running above 30C Beginning 5 October 1964, a 7-
day cruise was conducted over the area where hurri-

cane winds had been observed. Using the GUS II]

of the Galveston Biological Laboratory of the Bureau of Commercial Fisheries, four crossings of the hurricane path were made, Bathythermograph observations were taken regularly to 270 and hydrographic casts to 125 m. The data on all four crossings indicated similar patterns. The observed temperature-depth structures after the storm indicated that the warm ocean surface layers were transported outward from the hurricane center, cooling and mixing as they moved; that these waters converged outside of the central storm area with the result that downwelling to some 80 to 100 m in depth took place there; and that cold waters upwelled along

the hurricane path from depths of approximately

60 m. Sea surface temperatures decreased by more than 5°C over an area of some 70 to 200 mi. A cyclonic current system was observed around the area of greatest hurricane intensity. It is estimated that the total heat loss from the ocean to the atmosphere in the area of hurricane force winds was 10.8×10^{18} cal with the transfer per unit area being 4500 cal cm^{-2} . The data collected on the GUS III

cruise are the first systematic observations available
immediately after @ severe hurricane in deep water.

Leming, T.D. & .C. Ingham. Oceanic conditions in the
eastern Caribbean Sea and Adjacent Atlantic,
6 August to 6 October 1965.

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Marine Sciences Department. 1976. Oceanographic data of the
University of Puerto Rico; January 1971-June 1973, Vol.
I. University of Puerto Rico, Nayaguez, Puerto Rico.

Collection maintained at the Hall of Puerto Rico Documents, General Library, University of Puerto Rico, Mayaguez.

Tables showing depth, temperature, salinity, density, dynamic height, oxygen, phosphate, silicate, and potential temperature for both observed and interpolated data collected by the Department of Marine Science, University of Puerto Rico, Mayaguez, and funded by the National Science Foundation and the Commonwealth of Puerto Rico.

Marine Sciences Department. 1976. Oceanographic data of the University of Puerto Rico; January 1971-June 1973, Vol.

II. University of Puerto Rico, Mayaguez, Puerto Rico.

Collection maintained at the Hall of Puerto Rico Documents, General Library, University of Puerto Rico, Mayaguez.

Tables showing depth, temperature, salinity, density, dynamic height, oxygen, phosphate, silicate, and potential temperature for both observed and? interpolated data collected by the Department of Marine Science,. University of Puerto Rico, Mayaguez, and funded by the National Science Foundation and the Commonwealth ?of Puerto Rico.

Marine Sciences Department. 1976. Oceanographic data of the

University of Puerto Rico; July 1973-November 1975,
Volumes I and II. University of Puerto Rico, Mayaguez,
Puerto Rico. Collection maintained at the Hall of Puerto
Rico Documents, General Library, University of Puerto
Rico, Mayaguez.

Tables showing depth, temperature, salinity, density,
dynamic height, oxygen, phosphate, silicate, and potential
temperature for both observed and interpolated data col-
lected by the Department of Marine Science, University of
Puerto Rico, Mayaguez, and funded by the National Science
Foundation and the Commonwealth of Puerto Rico.

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o Martin, P.d., 6.0. Roberts. 1977, An estimate of the
impact of OTEC operating on the vertical distribution
heat in the Gulf of Mexico. In Proceedings of the
Fourth Annual Conference on Ocean Thermal Energy
Conversion, 22-24 March 1977, Univ. of New Orleans.

The effect of OTEC operation on the thermal structure of the Gulf of Mexico is estimated by using a one-dimensional 2-t heat conservation equation to predict the horizontal mean temperature.

The surface heat fluxes are parameterized in terms of the observed air-sea temperature difference and the predicted sea surface temperature (SST).

Advection of heat into the Gulf by the Yucatan Current is treated as a heat source for the surface layer of the Gulf. A constant mean upwelling is, ° calculated to balance the overall heat budget.

Within the mixed layer, the vertical diffusivity is calculated using the Mellor-Yamada Level 2 turbulent diffusion model. Below the mixed layer, a constant diffusivity f_s determined from a balance between vertical advection and diffusion to yield a realistic θ mean temperature profile.

The operation of 1000 OTEC plants in the Gulf,

is parameterized by the addition to? the model of a

mean vertical velocity profile required to complete

?the circulation between the near-plant intake and

° discharge flows. The result is a surface cooling and a warming at depth. The SST drops about 0.3°C during the first two years and then remains fairly constant. However, the deep water in the region above the cold water intake warms continuously at the rate of about 0.3°C per year. This rate of

° deep warming is about the worst that could be expected since the model does not allow the removal of this heat from the Gulf by the currents. For the operation of only 100 OTEC plants, the impact is correspondingly reduced. After 30 years, the model predicts a drop in SST of 0.05°C and

Q warming in the region above the cold water intake of 0.8°C .

McFadden, J.D.. 1967. Sea-surface temperatures in the

wake of Hurricane Betsy (1965). Monthly Weather Review, 95(5):299-302.

Following the passage of Hurricane Betsy (1965) through the Gulf of Mexico two flights were made

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the current pattern associated with the origin of the Equatorial undercurrent. The temperature/oxygen

ationship indicates that most of the Undercurrent water comes from the South Atlantic by way of the North Brazilian Coastal Current and that the contribution of North Atlantic water is very minor.

Metcalf, W.G., M.C. Stalcup. 1974. Drift bottle returns

Miller, ALR. 1978

from the eastern Caribbean. Bulletin of Marine
Science, 24(2):393-395,

On oceanographic cruises to the eastern Caribbean
Sea in the spring of 1970 and again in 1972, 1750
drift bottles were released. A total of 65 returns
(3.7 per cent) were recorded. During the 1972 cruise,
a small but distinct shift in the drift pattern with
time was observed in a group of bottles released in

a period of 1 1/2 months in a relatively small area
near St. Croix island. It is inferred from the
results that the major part of the surface water
crossing the Caribbean Sea from east to west enters
that sea through the southeastern and not the north-
eastern passages.

Ranges and extremes of the natural

environment in and about the Hawaiian Archipelago ~

(related to design criteria for Ocean Thermal

Energy Conversion plants). Report #C00-4293-5

(WHOI-78-74). Woods Hole Oceanographic Inst. for

U.S. Dept. of Energy. Contract #E6-77-S-02-4283,

DOO. 56 pp.

Examination of data from the water areas

Surrounding the Hawaiian Islands leads to the con-

clusion that Hawaii is suitably situated for ocean

thermal energy conversion. Historical records of

Surface temperature for the Hawaiian area and the

tropical and sub-tropical Pacific suggest that the

Proposed site may be vulnerable to significant

epochal changes and yearly shifts in base tempera-

tures but the site should still remain within the

limits of operational parameters. Annual and

monthly charts have been prepared for sea surface

temperature, surface windspeeds and directions.

and reported storm severities.

Willer, A.R. 1978. A preliminary comparative study of historical sea surface temperatures at potential OTEC sites. In Proceedings of the Fifth Conference on Ocean Thermal Energy Conversion, 20-22 Feb. 1978,

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° Univ. of Miami, Clean Energy Research Inst. pp. IIT 214-230.

Analyses of surface temperature averages and anomalies focusing on the 25-year period 1945-1969 show long-term systematic fluctuations varying on a hemispherical scale. A 180-degree phase correspondence seems to exist between the fluctuations of temperature in the Gulf of Mexico and the Caribbean Sea. Another time-connected coincidence, based on

a 50-year record, suggests a relationship between Hawaiian temperatures and Japanese surface temperature phenomena. A breakdown of annual surface temperatures into their monthly anomalous components identified cold seasons from warm seasons and warrants further study.

Molinari, R.I., and J.F. Festa. 1978. Ocean thermal and ° velocity characteristics of the eastern Gulf of Mexico relative to the placement of an OTEC plant: A progress report. In the Proceedings of the Fifth Ocean Thermal Energy Conversion Conference, 20-22 Feb. 1978. Univ. of Miami, Clean Energy Research ° Inst. pp 11 64-83,

Historical temperature and current data collected in the Gulf of Mexico are reviewed to produce data representations needed in the design and placement of an OTEC plant and the evaluation of the impact

° of the plant on the environment. Specific products include horizontal plots of mean monthly vertical temperature differences and mixed layer depths. Regions selected by the Department of Energy as potential OTEC sites are subdivided into smaller regions, for which annual and seasonal exceedence

° diagrams of these thermal properties are computed. Synoptic cruise data are reviewed to ascertain those regions which warrant further study, and to determine the cause of the variability in the smaller regions.

Finally, a method to obtain crude estimates of the distribution of surface speeds is presented.

o Molinari, R.L., and J.F. Festa. 1978. Ocean thermal and? velocity characteristics of the Gulf of Mexico relative to the placement of ® moored OTEC plant. NOAA Tech Nemo ERL AOML-33. NOAA Atlantic Oceanographic and Meteorological Lab., Miami 105 pp-

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This report presents the results of the second stage of a four stage effort designed to provide ocean

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thermal and velocity data in the Gulf of Mexico for OTEC. The four stages are!

(1) define ocean thermal and velocity data requirements for OTEC design and impact studies,

(2) review the historical data-set and literature for relevant information,

(3) design a measurement and/or data reanalysis Program, and

9 (4) conduct the measurement and/or reanalysis program.

Murray, S.P. 1970. Bottom currents near the coast during Hurricane Camille. *J. Geoph. Res.* 75(24):4579-4582.

A ducted current meter, which was mounted on the bottom in 6.3 meters of water off the coast of the Florida panhandle, was operative during much of the activity of Hurricane Camille. Before the arrival of the storm an unexpected outward extension of the wave-driven longshore current was recorded. During the storm bottom current speeds ranged up to 160 cm/sec, and their direction rotated from along shore parallel to the wind to seaward against the wind.

Oser, R.K. and L.J. Freeman, 1969, Oceanographic cruise summary Vieques Island, Puerto Rico area December 1968 to March 1969. Naval Oceanographic Office, Washington, D.C. Informal Report IR#69-66. 16 pp.

This informal report is a summary of an oceanographic and geophysical survey in the proposed Deep Oceanographic Survey Vehicles (DOSV) Test and Evaluation (TEV) Site southwest of Vieques Island. Puerto

Rico. Included in the survey were Nansen casts, bathymetry, sub-bottom profiling, current measurements, marine fouling studies, bottom photography, geomagnetic Measurements, and sediment sampling.

Ostericher, C. 1967. Oceanographic cruise summary Atlantic fleet Tactical Underwater Range; Southeast Puerto Rico-1967." Naval Oceanographic Office, Washington, O.C. Informal Report IR#67-76 44 pp.

An oceanographic survey of a proposed Fleet Tactical Underwater Range off the southeast coast of

2 260

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. Puerto Rico was conducted during March - April 9 1967. Data collected included: temperature and salinity, surface currents, moored current meter Measurements, bottom sediments, bottom stereo Photographs, and ambient noise. Preliminary analysis Of the data? indicates that the distribution of physical

properties is as expected for this time of the year,
but current speeds may be somewhat higher than
anticipated. The bottom was revealed to be exceedingly
flat in the basin, which is an area of ponded sediments.

Included in the report are the ocean station
3 data listings and the calculations used in the
analysis of the moorings.

Parr, A.E. 1937. A contribution to the hydrography
of the Caribbean and Cayman Seas, Bull. Bingham
Oceano. Coll. 5(4):1-110.

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Parr, AE. 1938. Further observations on the hydrography
of the Eastern Caribbean and adjacent Atlantic waters.
oO Bull. Bingham Oceano. Coll. 6(4):1-29.

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Perlroth, I. 1971. Distribution of mass in the near

surface waters of the Caribbean. SIRCSAR, UNESCO,
Paris. pp 147-152.

Historical oceanographic data have been used
in this study to achieve a better understanding
of the physical processes in the near surface
waters of the Caribbean. It is believed that
Climatological studies of this type may lead toward
a deeper understanding of the complexities in
the oceanographic media.

The advantage of setting up a historical model
to depict average physical environmental conditions
in the ocean are manifold. Surveys of water mass
structure and transport could be planned more

intelligently; a more complete procedure for quality control and processing of data could be established and, consequently, a better understanding of the air-sea interaction would result. Furthermore, the historical mode? would enable the synoptic oceanographer to review vast ocean areas.

Piacsek, S.A., P.J. Martin, J. Toomre and G.O. Roberts.

1976. Recirculation and thermocline perturbations from ocean thermal power plants. NRL, NRL-GFD/OTEC 2-76, ERDA contract £(49-26)1003 to NAL.

Numerical experiments were performed on the fluid motions resulting from the pumping action of ocean thermal power plants. In particular, the resulting thermocline distortions, sea surface temperature decrease and corresponding heat flow change were investigated. The object was to find engine discharge configurations and pumping rates that would minimize these alterations. This would result in both a minimal environmental impact and

Preservation of the temperature gradient across the engine, i.e. the energy resource.

The results obtained to date use 2-D turbulent flow calculations. Near the engine, the sea surface temperature reduction ranges from 0.01°F to 3°F, depending on design, flow rate, season and location.

The mean temperature of the warm inflow water is reduced by up to 4°F from the mean temperature at the depth, for certain designs and flow rates, due to recirculation and turbulence. The far-field

Surface heat calculations applied to the Puerto

Rico area shows that a depression of the sea surface

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temperature by 0.1 °C leads to an increased heat flow from air to sea of 9.6 cal/cm²/day, serving to replenish the heat removed from the surface layers by the plant. Accepting 0.1 °C as a permissible environmental perturbation, the area requirement

for a typical 100 MW plant is 2500 km², with a radius of 28 km. The corresponding estimates for Hawaii are 4 cal/cm²/day, an area of 6000 km², and a radius of 44 km.

Piacsek, S.A. and A.C. Warn-Varnas. 1977. Air-sea inter-

action perturbations by plant operations. In Proceedings of the Fourth Annual Conference on Ocean Thermal Energy Conversion, 22-24 March 1977, University of New Orleans. pp iv 3-6.

The readjustment in the air-sea heat flow and the air-sea temperature contrast following a possible sea surface temperature lowering by OTEC Operations has been calculated in the areas of Puerto Rico, Gulf of Mexico, and Hawaii. The net heat and the perturbations due to OTEC operations are found to be 96, 81 and 67 cal/cm²-day-°C.

Puerto Rico Nuclear Center. March 1973. Aguirre power

Project environmental studies 1972, Annual Report
and Appendix, Puerto Rico Nuclear Center, U.PcR.,
Mayaguez, PRIC 162, 464 in 2 Vols.

This report of two volumes is an environmental
report of Jobos Bay on the south coast of Puerto
Rico. Many types of data were taken, with no
Conclusions indicated. Some of the data taken and
discussed are: plankton, foraminifers, algae,
turtle grass, mangrove root community, coral reef
ecology, fish and birds.

Puerto Rico Nuclear Center. June 1975. Aguirre environ-

mental studies Jobos Bay, Puerto Rico Final Report,
Puerto Rico Nuclear Center, U.P.R. Mayaguez, Puerto
Rico. PRNC 196 VI (95 p), VII (184 p).

This report of two volumes is an environmental
report of the Jobos Bay on the south coast of Puerto
Rico. Many types of data were taken, with conclusions

mentioned for some of them. The data taken include:
microzooplankton, zooplankton, seagrasses, mangrove
community, fish, fish egg entrainment, and foraminifera.

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Richards, F.A. and R.F. Vaccaro. 1956, The Cariaco
Trench, an anaerobic basin in the Caribbean Sea.
Deep-Sea Res. 3:214-228.

The Cariaco Trench is a basin in the Caribbean
Sea which is anaerobic below depths of about 375
meters to the bottom at 1,400 meters. Below ea
250 meters the water is essentially isothermal at
about 16.9 C and has practically uniform salinity
and density. Hydrogen sulphide reaches maximum
concentrations of .03 mgA sulphide S per litre, which
is about 10% of the concentration found in the depths

of the Black Sea. Inorganic phosphate is linearly related to the oxygen and sulphate consumption in a ratio equivalent to 235 atoms of oxygen utilized for the production of 1 atom of phosphate. The anaerobic zone is free of nitrate and nitrite, but some ammonia is present. It is suggested that most of the nitrogen arising from decomposition of organic matter is present as elementary K_0 in solution. The age of the water is estimated to be between 100 and 2,000 years. The physical properties of the trench are compared with those of other isolated basins.

Riehl, H. 1962, Radiation measurements over the Caribbean during the autumn of 1960. J. Geoph. Res. 67(10): 3935-3942.

Observations made over the Caribbean Sea with the Suomi-Kuhn infrared radiometer during 1960 are analyzed. About 120 soundings released at five stations ascended to the 100-mb level or beyond. Compared with Elsasser's results they show greater cooling below 800 mb and much smaller cooling higher up. In the high troposphere a radiational

heat source due to long-wave radiation alone is found. It follows that vertical heat transport requirements from the surface by convective means, for heat balance, are much less than was previously estimated. Fragmentary observations above 100 mb indicate that the outward radiative flux increases above the tropopause and gradually approaches the values obtained from Explorer 7 measurements. Strong cooling of the air above the tropopause is computed, as much as 5 times that of the troposphere. Day-to-day fluctuation of net radiation from the troposphere was large, as was the range of observed fluxes. Statistical analysis indicated that the control of the net radiation from the troposphere lies mainly in the high troposphere, in the layer of maximum wind. It is

shown that a cirrus hypothesis of this control is

at least plausible and that differential radiation

can be sufficiently strong to be of considerable possible

importance in the growth and evolution of daily

weather systems.

Roberts, G.O. 1977. Stratified turbulence modeling for
new field external flow. In Proceedings of the Fourth
Annual Conference on Ocean Thermal Energy Conversion,
22-24 March 1977. Univ. of New Orleans, pp IV 7-25.

A simplified two dimensional model is used to
calculate the turbulent flow near the two outflows
and the warm inflow associated with one power module
of the Lockheed baseline OTEC design. A rectangular
domain of depth 500 ft has three horizontal slots

of height 72 ft on its left boundary, centered respectively at depths of 75, 150 and 315 ft, to represent the inflow and outflows. Four separate computations assume statistical uniformity across widths of 50 ft, 100 ft, 200 ft and 400 ft; we believe that the results for widths of 100 ft and 200 ft essentially bracket the results for the three-dimensional prototype flow. The assumed ambient temperature profile has a surface temperature of 80°F, and a thermocline at depth 300 ft where the temperature is 61.5°F. The temperature at 500 ft is 44.4°F. The assumed temperature at the cold inflow, at depth 1550 ft, is 42.6°F; this water is warmed by 2.4°F in the condenser and leaves the cold outflow at 45°F.

The numerical results for the average warm inflow temperature are 75.7°F, 77.2°F, 77.9°F and 78.6°F in the four cases. This inflow water is cooled by 3°F in the condenser before leaving the warm outflow. In all four cases, the far-field flow leaves or enters the computational domain horizontally, with temperature equal to the ambient profile. In the 50 ft and 100 ft computations, there is significant recirculation (4000 cu ft/sec and 1300 cu ft/sec, respectively) from the warm outflow back into the

warm inflow, contributing to the reduced inflow temperatures. In all cases, the OTHP-generated turbulence is negligible at distances greater than 380 ft from the inflow and outflows.

Ross, C.K. and C.R. Mann. 1971. Oceanographic observations in the Jungfern Passage and over the sill into the Venezuela Basin, February 1968. SIRCSAR, UNESCO, Paris. pp 171-174.

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According to previous work, the 3.84°C isotherm lies at a depth of 3000 m in the Venezuela Basin. These results show the same isotherm at a depth of only 1700 m in the Jungfern Passage, and at the bottom in the basin. As no water with potential temperature less than the above was found at stations within the basin, it is not certain to infer that the Venezuela

Basin bottom water is continually being renewed through the Jungfern Passage. Possibly the cold dense water is prevented from moving down into the basin by the dynamics of deep water near the sill.

Rossby, T., and O. Webb. 1971. The four month drift of a Swallow float. Deep-Sea Res. 18(10):1035-1039.

A Swallow float at 1100 m depth was tracked by SOFAR in the region between Bermuda, Bahamas and Puerto Rico. During the four month life of the float it drifted 300 km to the west, a displacement which corresponds to an average drift rate of 2.8 cm/sec. This is consistent with previous studies and suggests that the transport to the west between Bermuda and the West Indies is well in excess of $100 \times 10^8 \text{ m}^3/\text{sec}$. The shape of the trajectory is such that it may have been governed by planetary wave dynamics. -

Inertial oscillations were observed with unexpected clarity. It is evident that they can remain stable for weeks, but on one occasion when the temperature of the water dropped 0.5°C , a sudden change in the oscillation phase and frequency was observed, a transition that is consistent with

the float moving from one relatively well-mixed layer to another.

Sands, M.D. 1978. Progress report for the environmental impact assessment program for the 1-MWe early OTEC test platform. In Proceedings of the Fifth Ocean Thermal Energy Conversion Conference, 20-22 Feb. 1978. Univ. of Miami, Clean Energy Res. Inst. pp lit 186-202,

The 1-MWe Ocean Thermal Energy Conversion Early Testing Platform (EOTP) has a projected test date

in mid-1979 in the Gulf of Mexico, Hawaii or Puerto Rico. With the implementation of the National Environmental Policy Act of 1969, all government funded activities must consider potential environmental consequences of the activity and prepare an environ-

mental impact assessment and bring environmental considerations into the decision making process.

This presentation summarizes the progress to date for the environmental impact assessment program for OTEC-1, the Early Ocean Testing Platform.

The considerations in assessing impact for OTEC-1 first require a detailed description of the physical system design. Included in the design description are the depth of intake and discharge Pipes, volumes discharged, and applicable safety regulations and procedures. The detailed site descriptive information including the biological, chemical, physical, oceanographic, and meteorological data must be gathered from all available sources.

Particular study areas include the effects of impingement and entrainment, biocide effectiveness and toxicity to non-target biota, working fluid release effects, climatological impacts, and worker safety.

Also, the International, Federal, State, and local legal implications of siting will be considered,

While socioeconomic impacts of OTEC-1 now appear to be minimal, there is potential later for substantial benefits to the resident community serviced. When all relevant data is at hand the predictive process for assessing environmental impact is underway.

Sandusky, J. and P. Wilde. 1978. Preliminary bio-ecologic investigations at the OTEC Gulf of Mexico site - 29°N 88°W. In Proceedings of the Fifth Ocean Thermal Energy Conversion Conference, 20-22 Feb. 1978. Univ. of Miami, Clean Energy Res. Inst. pp 83-103.

Bio-ecologic measurements important for environmental assessment of the impact of an operating Ocean Thermal Energy Conversion Plant have been initiated in July 1977 and November 1978 at the proposed Gulf of Mexico site off the coasts of Louisiana, Mississippi, Alabama, and Florida with physical oceanographic measurements on the OSS Researcher in

a joint effort with the Atlantic Ocean Marine Laboratory (AOML) of the National Oceanic and Atmospheric Administration (NOAA). The measurements in July included 16 formal hydrocast stations of various

depths of 1000 meters. Water was analyzed for trace metals, nutrients, and phytoplankton biomass as estimated by chlorophyll and ATP. Physical data were supplied by NOAA-AOML. In addition, two surface net casts were taken to obtain zooplankton at the

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site and two bioassays were made to measure productivity. The Deep Scattering Layer (DSL) was monitored at the site by a continuously recording 12 KHZ depth sounder. Measurements in November were made from the RV Virginia Key (AQML). They included 4 hydrocasts, 7 net tows for zooplankton

(samples analyzed by Gulf Coast Research Laboratory),

1 STD trace, 20 XBT's and one 14¢ phytoplankton

bioassay.

Seiwell, H.R. Application of the distribution of oxygen to? the physical oceanography of the Caribbean Sea region. Pap. Phys. Oceanog. Meteorol. 6(1):1-60.

Shanley, G. 1972. Hydrographic data for Caribbean Sea and Pesca Serial Station at 17°38'N, 67°00'N for 1971. Dept. Mar. Sci., U.P.R., Mayaguez #72-1.

Shanley, G.£., Rev. by C.P. Ouncan. 1972. Hydrographic data for Caribbean Sea and for Pesca Serial Station at 17°38'N, 67°00'N for 171. Dept. of Marine Sci. U.P.R. Mayaguez #72-1 (REV).

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Smith, NP. 1978. Longshore currents on the fringe

° Sivilurricane Anita: J. Geoph. Res. 83(C12) :6087-6051.

Subsurface current data from a 2-week period in August and September 1977 are compared with coastal

° wind stress and water level data to describe longshore motion in response to the passage of Hurricane Anita across the northern Gulf of Mexico. Current meters 2 and 10 m above the bottom 21.5 km off the central Texas Gulf coast indicate strongest speeds of approximately 70 and 80 cm/s, respectively

° coinciding closely with the time of maximum wind stress.

A qualitative comparison of the variations in sea surface slope and wind stress with the recorded longshore current suggests that both wind stress and the longshore pressure gradient combined to produce the strong flow recorded during the storm but

° that the pressure gradient was primarily responsible for decelerating the current after the storm and fall

Stalcup, M.C. and W.G. Metcalf. 1972. Current measurements in the passages of the Lesser Antilles, J.

° Geoph. Res. 77:1031-1049.

Direct-current measurements during March and April 1970, in the four major passages through the Lesser Antilles show a westward transport of about $26 \times 10^8 \text{ m}^3 \text{ sec}^{-1}$. This transport is divided between

° the Grenada, St. Vincent, and St. Lucia passages with, respectively, 10 , 10 and $62 \times 10^6 \text{ m}^3 \text{ sec}^{-1}$!

Flowing to the west. The transport through Dominica passage was less than $2 \times 10^6 \text{ m}^3 \text{ sec}^{-1}$ during these measurements. This flow pattern is consistent with the distribution of variables as shown by data from

° hydrographic stations to the east and west of each passage. On the basis of the temperature-oxygen relationship, water that enters the Caribbean with a temperature between 16° - 23°C comes from a broad band of water found east of the area.

9 Stalcup, H.C. and W.G. Metcalf. 1973. Bathymetry of the sills for the Venezuela and Virgin Islands Basin, Deep-Sea Res. (20(8)):739-742.

Recent bathymetric surveys using a precision radar ranging navigation system in the Anegada-Jungfern

° Passage reveal that the depth of the Jungfern Passsge
sills fs 1818 m. As described by the 1800 m isobeth

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it is 3 km wide and 10 km Jong and contains a central
depression with depths exceeding 1970 m. In agree-
ment with earlier data the Jungfern Passage (Virgin
Passage) sill is shown to be the deepest or controll-
ing one between the Venezuela and Virgin Islands
basins.

The Anegada Passage sil] found during the

recent surveys, is not that found by FRASSETTO and
NORTHRUP (1957). The one described here is located
Rear Barracuda Bank and, with a depth of 1915 m, is
300 m shallower than the one previously described.

Stevensen, R.£. and R.S. Armstrong. 1965. Heat loss

from the waters of the northwest Gulf of Mexico during Hurricane Carla. *Geofisica International*, 5249-57,

The temperature and salinity of an area off Galveston and Corpus Christi, Texas was measured about one month after Hurricane Carla passed. by

In general, surface water was seen to be cooler along the hurricane's path, and warmer elsewhere. Heat was lost from up to 100 meters depth. An estimate of the heat loss at each station yields about 2.5×10^{17} cal/day. This value seems to compare with those determined for Hurricane Daisy in 1961

Sturges, W. 1965. Water characteristics of the

Caribbean Sea. *J. Mar. Res.* 23(2):147-162

The volume of Caribbean Sea water in bivariate Classes of potential temperatures vs. salinity has been estimated from 76 hydrographic stations. The resulting statistics are presented on a pair of

characteristic diagrams. The outstanding feature of the diagrams is the strong mode; nearly half of all Caribbean water lies within 0.1°C and 0.02 per mil of the mode, and 3.9°C and 34.98 per mil. An envelope of all samples has been determined. The waters below 2900 m in each of the four large basins are compared by using only data from a single CRANFORD cruise. In each basin the deep water is remarkably homogeneous, but the deep waters are different in the eastern (Yucatan and Cayman) and western (Colombia and Venezuela) basins. There appears to be no inflow of deep water through Jungfern Passage, the deepest connection with the Atlantic Ocean, but there may be sporadic inflow through Windward Passage into the western basins. There appears to be no inflow of water at mid-depth above either sill,

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Sundai

Swall

+ T.R. E. Sambuco, A.M. Sinnarwalla and S.K.

Kapur. 1977. The external flow induced by an

Ocean Thermal Energy Conversion (OTEC) power plant.

In Proceedings of the Fourth Thermal Conference

on Ocean Thermal Energy Conversion, 22-24 March

1977, Univ. of New Orleans. pp IV'42-49.

As an essential part of its operation, the

OTEC plant withdraws large amounts of water (typically

6×10^4 gpm per MW of capacity) from both the surface

layers and the deeper layers of the ocean and dis-

charges them at intermediate levels. The circulations

induced in the ambient ocean of these large withdrawals

and discharges are of paramount importance, since

any adverse changes in the ambient stratification

will directly influence the operational efficiency

of the plant itself. Specifically, any "short

circuit" between the outflows and the inflows will

directly lead to a decrease in power production.

Because of this direct "feedback" effect, the external

Flow induced by an OTEC plant has to be considered

as an essential part of its operation. The present Paper describes the interim results from an on-going experimental study to assess the recirculation potential under various design and environmental conditions.

The method used is a "building block" approach in which "dissected" parts of the overall problem are isolated and studied experimentally. Specifically, experiments are described on two classes of problems, the first in which an ambient current is present

but not ambient stratification, and the second in which the opposite is true. Recirculation is measured directly by introducing dye into the discharges and by measuring the dye concentration in the intake

flow. Maps of the distributions in the jet flow of the mean and turbulent quantities are also given

such detailed measurements being of relevance to

the "tuning" mathematical (turbulence) models of

the flow field.

The similitude parameters governing the problem are identified and the manner in which the results of the "dissected" studies can be used to construct results for the overall problem is discussed,

ow, M. 1961. Deep currents in the open ocean.

Oceanus, VII(3):2-8.

Water currents were measured at 2000 m and 4000 »

in the western North Atlantic Ocean. Speeds seen were on the order of 10 cm/sec.

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Thompson, J.P., H.E. Hurlburt,

Thompson, J.D

and L.B. Lin, 1977.

Development of a numerical ocean model of the Gulf of Mexico for OTEC environmental impact and resource availability studies. In Proceedings of the Fourth Annual Conference on Ocean Thermal Energy Conversion, 22-24 March 1977, Univ. of New Orleans. pp IV 50-56.

Short of actual operations the complex interactions of OTEC's and the environment can only be assessed using numerical ocean models and laboratory experiments. The best strategy for OTEC far-field modeling of the ocean is the selection of a single, well-observed ocean basin with well-defined boundary and surface input data with conditions in the basin representative of those to be encountered in the tropical and subtropical oceans. The basin should be large enough to represent open ocean conditions, but small enough for economical computer modeling. The Gulf of Mexico is therefore appropriate for initial model studies.

We are developing a hierarchy of numerical models of the Gulf of Mexico for use in studies of OTHP operations. The first model is nonlinear, time-dependent, and retains both barotropic and first baroclinic modes. The model uses primitive equations on a S-plane and the external and internal gravity waves are treated implicitly. The model uses uniform rectangular grid with $\Delta x = \Delta y = 16 \frac{2}{3}$ km and Δt up to $1/7$ day. The numerical model was driven for five years by an idealized wind field consistent with observational data presented by Franceschini and by Hellerman. The statistically steady-state model results show periods of upwelling along all the boundaries and downwelling in the interior. Baroclinic boundary currents of varying strength are found along all the boundaries, but are strongest along the western and northern boundaries. Eddies associated with nonlinear recirculation are found in the northwest and southwest corners with additional eddies representing baroclinic Rossby waves found throughout the model basin. A significant result of the model is the existence of strong baroclinic eddies in the Gulf even in the absence of the Loop Current.

HE. Wurtburt, and P.d. Marint. 1978.

Results from the Gulf of Mexico - OTEC far-field
numerical model, In Proceedings of the Fifth Ocean

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Thermal Energy Conversion Conference, 20-22 Feb.
1978. Univ. of Miami, Clean Energy Research Inst.
pp. iti 141-164.

One reasonable strategy for predicting the
complex interactions between OTEC and the far-
field environment is to develop a numerical mode}
of 9 single well-observed ocean basin and reproduce
observed aspects of its physical oceanography.

Then OTEC can be inserted as a perturbing influence
on the basin. The impact of OTEC operations on the
circulation and thermal structure of the basin can
then be assessed.

The Gulf of Mexico was chosen for initial model studies by virtue of its potential for OTEC utilization, its size, and relatively well-defined boundary conditions and well-observed features. The second model in the hierarchy of increasingly complex models of the Gulf of Mexico has now been developed, Simplified but realistic bottom topography and wind-forcing have been incorporated in a two-layer primitive equation model. The model is 900 km x 1600 km with a grid resolution of 20 km and a time step as large as 1/12 day. The model retains a free-surface and treats internal and external gravity waves implicitly. Forced inflow through the Yucatan Straits and outflow through the Florida Straits has been included.

A nine-year integration to statistical equilibrium was performed with both wind and Loop-Current forcing included. The circulation characteristics for a mid-Gulf site, site just south of New Orleans, and

a site corresponding to the OTEC Gulf test-site

are described, based on model results. Near-surface and sub-surface scalar discharges from each plant

are traced for ten months and concentration maps presented. The relevance of these model predictions to OTEC siting in the Gulf is discussed in detail.

Underwood, J.W. 1967. Oceanographic cruise summary SALVOPS Vieques, U.S.S. Hoist (ARS~40). Naval Oceanographic Office, Washington, D.C. Informal Report IR#67-16, 44? pp.

An oceanographic survey was conducted off the eastern tip of Vieques Island during August 1966. The purpose of the survey was to obtain current, bottom sediment, and underwater photographic data for immediate use by U.S. Navy divers working in

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the area. Only current data were predominantly tidal with a nearly constant phase relationship between maximum flood and ebb and predicted high and low tides. Observed currents also were significantly stronger than predicted currents and times of maximum flood and ebb occurred later than predicted.

Vukovich, F.M. 1978. Analysis of sea-surface temperature variations in the Gulf of Mexico using satellite data for OTEC siting. In Proceedings of the Fifth Ocean Thermal Energy Conversion Conference, 20-22 Feb. 1978. Univ. of Miami, Clean Energy Res. Ins. pp ili 38-63.

Sea-surface temperature variations were investigated using NOAA infrared data in the northern portions of the eastern Gulf of Mexico. The region was characterized by sea-surface temperature variations produced by cold intrusions of warm Loop Current water. The central portion of this region was most affected, but the results of the analysis suggested that this entire region was a difficult place to site OTEC.

Webster, F. 1969. Vertical profiles of horizontal ocean currents. Deep-Sea Res. 16(1

?Data collected from moored current meters at

a single site (Site D) in the western North Atlantic

are used to define vertical profiles of steady and time-dependent horizontal ocean currents. The mean velocity profile shows currents systematically flowing towards the west, with amplitude which decreases with depth. Time-dependent currents have a vertical profile of kinetic energy which is proportional to the vertical profile of Brunt Vaisala Frequency, N^2 . Since the mean speed is dominated by time-dependent components, its profile is approximately proportional to $N^{1/2}$.

At frequencies lower than 1 cycle per day, the time-dependent motion is not horizontally isotropic at all depths. In the surface layer, north-south (v) components have a larger variance than east-west (u) components; at mid-depths, the u -variance is greater; at great depths the variances are approximately equal. At frequencies higher than one cycle per day, the motions are horizontally isotropic. The pattern of an isotropy may be due to the interaction between low-frequency processes and the nearby continental shelf.

Eddy momentum fluxes have a profile which reverses sign at the approximate depth of the continental shelf.

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Webster, F. 1971. On the intensity of horizontal ocean currents. *Deep-Sea Res.* 18(9):885-893.

Ocean currents on both the east and west sides

of the Atlantic, near Bermuda, and in the Mediterranean Sea show similar mean kinetic energy and mean speeds from long-term current measurements. At a given depth, there is less than a factor of two in the range of speeds and a factor of four in kinetic energy.

In spite of intermittency in time and location in Space there is remarkable uniformity in the intensity of the currents. A notable exception is a set of

high values of speed and kinetic energy NNE of Bermuda that are possibly associated with a Gulf Stream meander.

Both moored current meters and neutrally buoyant (Swallow) floats have been used for measurement of

Currents. Speed and total kinetic energy are similar with the two methods, but estimates of the kinetic energy of the fluctuating component of motion are generally lower when Swallow floats are used.

Wolff, P.M. 1978. Temperature difference resource. in Proceedings of the Fifth Ocean Thermal Energy Conversion Conference, 20-22 Feb, 1978. Univ. of Miami, Clean Energy Res. Inst. pp III 11-37.

The continuous operation of OTEC plants requires the availability of a consistent temperature difference resource. The requirements of such a consistent OTEC T resource are examined and related to other parameters,

Ocean Data Systems, Inc. has examined all temperature soundings in the archive for possible OTEC sites in the following areas: Hawaii, Puerto Rico, Gulf of Mexico, Florida Straits, and Florida East Coast. This investigation produced most probable monthly soundings for each of 60 one-degree latitude and longitude squares.

The Hawaiian and Puerto Rico areas are characterized by homogeneous temperature conditions and small variability at all depths. In the Eastern Gulf of Mexico and off Key West and Niani there are stronger currents and greater space and temporal variability. The Loop Current in the Eastern Gulf of Mexico causes additional difficulties in analysis. A bi-modal temperature structure can exist.

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Plans for additional resource analysis are discussed.

Wolff, P.M. and L. Lewis. 1977. Monthly assessment of temperature resource for three potential OTEC sites. In Proceedings of the Fourth Annual Conference on Ocean Thermal Energy Conversion, 22-24 March, 1977. Univ. of New Orleans, pp iV 57-60.

During 1975 Ocean Data Systems, Inc. assembled an ocean temperature data set for OTEC purposes from available soundings in Navy and NOAA files.

In this study the OTEC data file was summarized monthly for three possible sites, The depth necessary to achieve a T of 18°C, 20°C and 22°C was determined for each area for the most probable monthly temperature structure,

The data are presented in plan view and in

tabular form. For each site the existence of a

T of 20°C at a depth less than 1500 meters was

demonstrated for each month of the year.

Some information was provided on plans for expanded investigation of this type.

Wood, E., M.O. Youngbluth, P. Yoshioka, M. Canoy.

1975. ?Cabo Mala Pascua Environmental Studies

Puerto Rico Nuclear Center, U.P.R., Mayaguez, PRNC-

188. 95 p.

This report is an environmental study of the area just south of Cabo Mala Pascua, Puerto Rico, with no conclusions or results, only data collected and presented, These data collected were: currents, temperature, salinity, dissolved oxygen, nutrients. sediments, Zooplankton, benthos, and terrestrial vegetation.

Worthington, L.V. 1955. A new theory of Caribbean bottom-water formation. *Deep-Sea Res*, 3:82-87.

A recent section across the Caribbean Sea shows that in the Caribbean deep water oxygen values have dropped 0.3 ml/l in the last twenty years, a loss closely corresponding to that in the North Atlantic deep water. Study of the surrounding Atlantic water suggests that the Caribbean deep water has not been

renewed since the end of the eighteenth century,
coincident with a cold climatic variation at high
latitudes in the North Atlantic, It is further
deduced that the Windward Passage was the sill over
which this water originally came from the Atlantic,
and that both the Jungfern and Windward Passage
sills must be considerably shallower than
Dietrich's(1939) estimates.

Worthington, L. V. 1956. The temperature increase in

the Caribbean deep water since 1933. Deep

3. (3): 234-235,

Observations of temperature of the deep

Caribbean water are made from 1500m to 3000m. The

dates discussed are 1933 and 1954. Using some

estimation of the temperature increase, an attempt

is made to date the deep water in the Caribbean.

Worthington, L. V. 1966. Recent oceanographic measurements in the Caribbean Sea. *Deep-Sea Res.* 13: 731-739,

Two oceanographic sections were made across the two deepest sills of the Caribbean Sea in September 1963. One ran from the Atlantic Ocean into the Venezuela Basin through the Anegada and Virgin Islands Passages; the second ran from the Cayman Basin into the Atlantic through the Windward Passage. These sections differ from MUST's (1963, 1964) sections in that there is no evidence that bottom water is entering the Caribbean at the present time. The Cayman Basin bottom water appears to have been warmed about 0.03°C since the surveys made by PARR in 1933 and 1937.

Worthington, L. V. 1971. Water circulation in the

Caribbean Sea and its relationship to North Atlantic Circulation. SIRSCAR, UNESCO Paris. pp 181-191.

Using data from two oceanographic sections, one from the Cayman Basin to the Atlantic, through the Windward Passage, and the other through the Virgin Islands Passage, tests were made to determine the origin of the bottom water in the Caribbean. Potential temperature profiles through the Windward Passage and the Virgin Islands Passage both indicate no renewal. Also, the dissolved silicate is different from the basin to the Atlantic. There is no evidence for renewal of the bottom water taking place

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at present.

The question of the main circulation in the Caribbean was also studied. The present work indicates that most of the circulation is to the south, while water mass distribution studies of

others indicate the circulation maximum is to the north

Wright, W. R. 1970. Northward transport of antarctic bottom water in the western Atlantic Ocean. Deep-Sea Res., 17: (2) 367-371.

The volume transport of Antarctic Bottom Water in the western basin of the Atlantic Ocean has been determined by dynamic calculations for seven Oceanographic sections made during the International Geophysical Year between 32°S and 16°N. The reference level was based on the sharp bend, seen in both temperature-depth and salinity-depth traces, that marks the transition from North Atlantic Deep Water to Antarctic Bottom Water. The northward transport decreases from 5-6 x 10 m³/sec in the southern sections to about 10 m³/sec in the northern sections. The results are consistent with those obtained by solving a set of conservation equations -

for a simple box model of the deep circulation in

the western Atlantic.

Wüst, G. 1963. On the stratification and circulation in the cold water sphere of the Antillean-Caribbean Basins. *Deep-Sea Res.* 10: 165-187.

The cold water circulation is discussed for the Antillean-Caribbean Basins. The three water

masses investigated were the Subantarctic Intermediate Water, the North Atlantic Intermediate Water, and the Caribbean Bottom Water. The Subantarctic Intermediate Water is formed at the southern polar front, having a salinity minimum, and extends throughout the whole breadth of the Atlantic at depths of 700-900 m. This water finds its way into the Antillean Caribbean Basin, retaining its identity.

The North Atlantic Deep Water is formed near south Greenland. This water makes its way to the 2000-2500 m level, and is characterized by an oxygen maximum. This water ultimately spills over the sills into the Caribbean, and changes character enough to

have a slightly separate identity, the Caribbean
Bottom Water,

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Antillean-Caribbean Basins. Part 1. Columbia
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The Caribbean and Antillean Basins are described
as of the available information for this data. The
Circulation and stratification for all depths are
discussed, and are related to the surrounding waters.

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APPENDIX D

BIBLIOGRAPHY OF MARINE BIOLOGY REFERENCES FOR PUERTO RICO
AND OTHER TROPICAL WATERS

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