"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, CEER-0-51.

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Executive Statement: As Puerto Rico is considered among the prime locations for operating OTEC plants, the U.S.

The Department of Energy is examining the oceanographic conditions around the island. The OTEC criteria apply to multiple locations around the island. While this report covers the general characteristics of the waters around Puerto Rico, the primary emphasis is on the Punta Tuna area, situated southeast of the main island. This document is a 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 include:

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 relevant 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 phases comprises two major requirements: a historical literature search and a historical data search. The literature search has yielded two comprehensive bibliographies. Each bibliography appears as a separate appendix in this report, one dealing with physical oceanography, and the other with biological citations.

The data search has reaffirmed to us that this area of the world's oceans has not been sufficiently studied to statistically determine, with any certainty, what the year-to-year and month-to-month variations in most 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, 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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The text appears to be corrected as follows:

The text is 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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Operating Ocean Thermal Energy Conversion (OTEC) power generating plants, the specific area of Puerto Rico 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 accessible 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, with a primary emphasis 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 on pertinent physical oceanography, and one on pertinent biological oceanography. After a review of the historical results and the fiscal 1979 data collection program, recommendations are made for increasing the effectiveness of future OTEC field data collection programs.

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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 a 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 is approximately halfway 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. Puerto Rico is at a latitude of about 18°N.

The Trade Wind Belt, which includes both winds and oceanic currents, generally moves east to west past the island. The main island of Puerto Rico is approximately rectangular in shape, about 180 km from east to west and about 60 km from north to south. The island is a mix 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 limited to the following parameters: Climate, Wind regime (including hurricanes), Waves regime, Oceanic and island shelf currents, and 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, which generate the water circulation patterns (currents) in the upper waters and affect and modify the mass distribution as determined by the distribution of temperature and salinity.

The available climatic and sea-state observations along the continental shelf of the South Coast indicate a winter trend and a summer trend. The hydrographic data, although sparse and probably insufficient, also reveal significant seasonal variations during the winter and summer months. These winter-summer variations are demonstrated by the existing reports and regional environmental data summaries that will be discussed in 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 formed.

The text develops the concept of winds moving landward from the sea, carrying moist sea air with them. This occurs as a result of convection cells that form during the day and reverse in the evening as the land cools, causing the winds to blow offshore. On the island of Puerto Rico, where there are numerous hills and mountains, the sea air is often cooled to saturation while still over the land. This leads to frequent, substantial rainfall, in some parts of the island, this occurs almost daily.

The Punta Tuna OTEC site, which is typical of much of the island, also has a tropical marine climate. General meteorological statistics can be gathered using data from the U.S. Weather Service Command (1974) and the U.S. Air Weather Service.

In summary, the meteorological conditions are as follows: For the north coast area, there is no distinct summer and winter season, but rather a transition from a wet season to a somewhat drier one. Air temperatures typically fluctuate within a range of 10 to 15 Fahrenheit degrees, with the lows in the 70's and the highs in the 80's from December through April, and temperatures ranging from the mid 70's to upper 80's from May through November. The lowest recorded temperature at San Juan Airport was 60.1°F.

Prolonged periods of either clear, sunny weather or completely overcast conditions are rare. The common condition is partly cloudy, where cumulus clouds cover between 40 to 60 percent of the sky. Throughout the year, relative humidity levels are high, usually between 65 and 85 percent, and rarely drop below 50 percent. Dense fog is an infrequent occurrence. Squalls and thunderstorms are common from May through November.

While the U.S. Coast Guard has maintained a light station at Punta Tuna for many years, no statistical compilation of the weather data observed at that station has been made. However, statistics do exist for San Juan, which is about 40 km northwest of Punta Tuna.

Some of these values are shown in Table 1. It includes the thirty-year (normal) values of temperature and rainfall, as well as the 23-year (normal) values of relative humidity.

The table shows values as a function of the month. It's likely that values from Punta Tuna would be similar. For tropical marine areas, changes in atmospheric pressure are usually very small. Changes of 5 mm of mercury (0.2 inches) over a couple of months are rare. However, severe tropical weather, such as tropical depressions, waves, storms, or hurricanes, could cause significant drops in atmospheric pressure. These pressure changes are key in controlling the local sea level. As the sea level changes due to such pressure disturbances, deep water is brought up towards, and in some instances, to the surface. This could bring cooler, denser water to the surface, potentially affecting the operation of an OTEC plant adversely.

Table 2 illustrates the expected minimum pressures as a function of frequency in years to return. Figures 3 and 4, reproduced from Atwood, et al. (1976), graphically represent the monthly maximum, minimum, and mean air temperature for the oceanic area south of Puerto Rico. The data suggests that the maximum temperatures usually occur in late summer, and the cooler temperatures 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 only be +10°F from the mean.

Figure 4 depicts the frequency of occurrence of relative humidity values for the same oceanic region south of Puerto Rico. Approximately 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.0. 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 amphidromic (nodal) point of the principal lunar tide is also present.

The 'senidturnal' (¥) tidal constituent lies near the site (Atwood et al., 1976; Dietrich, 1963; Defant, 1961). The proximity to the node implies minimal tidal motion. Additionally, as Punta Tuna is located on the somewhat exposed eastern side of the island, the tidal system affecting the North Atlantic may also influence our site. This could result in 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.

The next section of the text seems to be a mix of possibly coded or incomplete information, and may need further clarification or correction to be properly understood.

The amphidromic that lies east of Newfoundland may also affect our site. The result could be a moderately confused tidal current over our area of interest.

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 east trades, which generally blow fresh during the day. The center of the Bermuda High shifts a little north in summer and south in winter changing the direction of the winds over the island from NNE in winter to east in summer. Factors which interrupt the trade wind flow are frontal and east wave passages. As the cold front approaches, the wind shifts to a more southerly direction, and then as the front passes there is a gradual shift through the southwest and northwest quadrants back to northeast. The east wave passage normally does not bring a west wind but is usually characterized by an ENE wind ahead of the wave and a change to ESE following the passage."

Figure 8 shows the annual frequency distribution of wind in the area of Vieques.

Major disturbances to the normal

Trade wind circulation is caused by the passage of easterly waves, hurricanes, tropical storms, squalls, and thunderstorms. Hurricanes and tropical storms are the two most significant influences. During 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 with large heights and long wavelengths. 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, indicating 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 0.1% or approximately 9 hours a year.

Extreme wind speeds associated with hurricanes are given in Figure 10. The figure displays 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 principal 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, SE) account for 89.5% of the observed winds.

Atwood, et al. (1976), summarized wind regime data for the area taken from Publication H.0. 21, U.S. Dept. of Commerce (1958), and from the USNOO, Environmental Acoustic Atlas of the Caribbean Sea and Gulf of Mexico.

"In 1977, two waves passed near St. Croix, causing an increase in wind speeds (up to 15 m/s) and heavy rains. These tropical waves formed north of the inter-tropical convergence zone in the deep easterly flow that circulates 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 information 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.

(Wind Speed in Knots 29, 15 Winds, February 2, 20, 10, 15, WW, VS Use, E M, 19, 5, V SE 30 TOS. Percent as Great or Greater Than 10% of All Winds Have Speeds Greater Than 13 m/s)

(Wind Speed in Knots, ES MO, Winds, May 20, VE AU, 5, F OO 35. Percent as Great or Greater Than 10% of All Winds Have Speeds Greater Than 12.5 m/s)

(Wind Speed in Knots 25, 20 Winds, August 35. Percent as Great or Greater Than 10%)

(Wind Speed in Knots, SS 'Winds, November. Percent as Great or Greater Than 10% of All Winds Have Speeds Greater Than 25 m/s)

Some information about hurricanes affecting the study site can be determined from the U.S. Department of Commerce review of major hurricanes between the years 1873 and 1967. During these 94 years, there were 94 hurricanes reported, which is 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:"

The average, major, extreme, and great hurricanes are presented in Table 6. The average recurrence interval for hurricanes significantly impacting Vieques is around once every 3 years. However, these storms are not uniformly distributed throughout the years. As demonstrated in Figure 17, the hurricanes affecting Vieques have occurred in clusters. In certain years (1933 and 1955), two hurricanes occurred within the same year. During other periods, there were no hurricanes for many years. Atwood et al. (1976) and Lee et al. (1978) displayed the paths of some devastating North Atlantic hurricanes in their reports. These hurricanes likely affected the proposed Puerto Rico OTEC site. The map of these hurricane tracks is reproduced here as Figure 18. Figure 19 illustrates the graph for the occurrence of tropical cyclones within the five-degree square bounded by 15°-20°N, 65°-70°W, as presented by Atwood et al. (1976). The recurrence probability of tropical storms in the Puerto Rico area is approximately 70% annually. The average movement speed of these storms is about 12 knots towards the west-north-west (U.S. Naval Weather Service Command, 1974). Unsurprisingly, August and September are the most affected months, with a significant number occurring in July and October as well.

In Section 2.6, wave statistics for the study area were derived from the Summary of Synoptic Meteorological Observations (SMO), Area 23, which is near Vieques, P.R. Wave statistics for the SMO data are based on several years of visual observations. Additionally, one year of measured data reported by Deane (1974) was also used. The distribution of significant wave heights for the area of Vieques is shown in Figure 21. The most frequently occurring wave height falls within the range of 0.3-0.8m, occurring 41% of the year. The average significant wave height is 1m, with heights ranging from less than 0.3m to 1.4m occurring 79.3% of the year. Large wave heights greater than 2.3m occur rather infrequently, accounting for only 1.3% of the year.

Figure 16 shows the track of hurricanes affecting the study site.

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"NORTH ATLANTIC HURRICANES, ACER"

"FE OBOE"

"Occurrence of Tropical Cyclones"

"34"

The distribution of wave periods for Area 23 is given in Figure 22. The dominant wave period is less than 6 seconds, accounting for 78.7% of the year. The average wave period is 5.9 seconds. Wave periods indicative of swell (greater than 9.5 seconds) 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 meters 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 meters would recur on an average of once every 3 years. Wave heights of above 8 meters 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 .3-.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 ATM.

"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 0.6 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, 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

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"Figures 32 are reproductions of Figures 15 to 19, and 21 to 22 in the Atwood, et al. (1976) report. These figures show sea and swell 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 a 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 follows: “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 observed in the quadrant E 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 20m. 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 al. 1978), but for completeness they shall be mentioned again here in this report in order to consolidate the information. The cold water intake pipe of an OTEC plant would probably extend..."

From the surface to about 1000 m deep.

With the 43 wave, 10, SEA - FEBRUARY 25, 60 percent as great or greater than (10% of all seas are greater than 2.2 meters), 44 meters.

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Page 46 content is unintelligible and requires additional context to correct.

Sea height in feet, SEA - NOVEMBER 10, 30 percent as great or greater than (10% of all wave heights are greater than 2.1 meters).

Swell height in feet, SWELL - FEBRUARY 10, 100 percent as great or greater than (10% of all swell is greater than 3.4 meters).

Swell height in feet, SWELL - AUGUST 30, measurement unavailable.

Swell height in feet, SWELL - NOVEMBER, percent as great or greater than (10% of all swell is greater than 3.3 meters).

Page 50 content is unintelligible and requires additional context to correct.

At the 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

The 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. Its origin lies under the equatorial atmospheric trough (low), a tropical rain belt located northeast of South America. This water mass is influenced by precipitation in that area and by the rain and runoff from the drainage basins of the Amazon and Orinoco Rivers in the northeastern part of South America. The water mass is then driven by 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 have been further affected by the general and local climate of the area it traverses. Additional 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 assume a wedge shape along the northern Caribbean, due to geostrophic subsidence as the water moves westward. However, the actual depth of the water mass may be greatly influenced by atmospheric pressure and its variations. 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 rise, 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 event that the plant had not already been shut down. The water mass directly below the

The Subtropical Underwater, also known as Tropical Surface Water, 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. This, in turn, is related to the origin of the Subtropical Underwater mentioned above.

The air and climate under the Bermuda High are warm and dry. Due to the high relative humidity, evaporation is significant, and salinity is increased, making this water the most saline in 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°/oe to 37.2°/ee. Since the water rarely comes into contact with any diluting agent, its salinity remains consistently high. During low atmospheric pressure conditions, this water can push upward, resulting in very high salinity levels in the surface water.

The temperature range of this water mass is greater (20°C-24°C) than the water mass above. The temperature can vary as heat may be conducted upward or downward, unlike the salinity, which remains relatively stable. The density difference between the Subtropical Underwater and the Tropical Surface Water is large enough to keep the two water masses distinct.

The Subtropical Underwater generally moves south and westward into the Caribbean, beneath the faster-moving, more turbulent surface water mass. As this lower water mass moves westward into the Caribbean, it dilutes to about 36.5°/.0~36.6°/e in the Yucatan Strait. Near Puerto Rico, the water moves southward through both the Anegada and Nona Passages, then continues south and westward through the Caribbean. The core of this water mass is often observed to lie at about 150 m depth in the Puerto Rico area. Below this water mass lies...

"A transition zone of indistinct characteristics exists. The transition zone contains the lower portion of the thermocline and extends into the definite area of the cold water zone. This transitional water is a mixture of North Atlantic Central Water and diffused, diluted Mediterranean Water. The salinity ranges about 36.8°/oo, from the water mass above it, down to about 35°/oo. The temperature ranges from 20°C to about 7°C. This transition zone reaches from about 200m to 600m in 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, around 45°-55° latitude. The water tends to be low in salinity, as it is formed in an area where precipitation far exceeds evaporation.

This 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 comes into contact with higher saline water, increasing the salinity from its origin of about 34°/oo to 34.8°/oo off Puerto Rico. The temperature is from 6°C-7°C.

From 800m down to 1000m, between the Antarctic Intermediate Water and the North Atlantic Deep Water, lies another transition zone. From about 1000m 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 Sea."

The Caribbean is primarily accessed through the Windward and Anegada Passages. The water primarily moves westward from the Windward Passage, but it moves south and west from the Anegada Passage, filling all the deep basins in the Caribbean. This water, characterized by 4-5°C temperatures and a salinity of 35.0°/oo, moves into the Caribbean, where it is virtually trapped, with only a small passage out through the Yucatan Strait. This water remains in the Basin and differs slightly in silicate content from its source, the North Atlantic Deep Water, which is found outside the Caribbean Basin. Consequently, some people refer to this deep, cold water as the Venezuela Bottom Water. In some areas of the Caribbean Basin, this water mass is over 3000 m thick.

The general circulation of the Caribbean Sea has been described by various researchers including Must (1963), Worthington (1971), Gordon (1967), and Perlroth (1971). The Caribbean Current, a warm westward flow, is formed from the junction of the North Equatorial Current and the Guiana Current (Burns and Car, 1975), both of which are generated by the Northeast Trade Winds. Seasonal variations exist in the Caribbean Current. Surface velocities reach their maximum speed during the summer (June-August) and their minimum in October and November. Burns and Car (1975) reported maximum speeds along the north coast of Venezuela of about 43 cm/sec, peaking at 135 cm/sec.

Most of the water entering the Caribbean Sea passes through the straits north and south of St. Lucia. The main flow crosses the Jamaica Ridge southwest of Jamaica, moves west through the Cayman Basin, and then continues 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 provided by many researchers. Most of these summaries reference 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 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.

The current is measured 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, with the most frequent direction being towards the western quadrant (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 towards 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 a 240 m depth, 70% of the measured water direction was towards 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 240 m and 605 m.

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The speed was found to be 8.0 cm/sec (289°) and 5.4 cm/sec (061°) respectively. The direction was 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 the 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 directions, 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 drogue 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 were extracted from the SP169 IT publication. The closest location to the Punta Tuna site was station 41. The current profile at this station indicates water movement towards the northeast at a depth of about 600 m. However, above 500 m and below 800 m, the current direction is westward with speeds approaching 52 cm/sec (1 kt).

Station 42, located west of Punta Tuna, and station 40 to the north, show a steady westward flow along the water column to depths of approximately 900 m. Geostrophic velocities, 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 June 1972, between Lat. 17° and 16°N. Speeds reached above 20 cm/sec in the near-surface waters and 5 cm/sec at approximately 500 m depth. Further 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 conducted by Bretschneider (1977) for all the proposed OTEC sites. This comprehensive work includes calculations based on wind speeds, design wave heights, significant periods, and depth intervals down to about 150m. Bretschneider's calculations also indicate wind drift and 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), Just (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 and Freeman (1969), Ostericher (1967), and Wood, et al. (1975).

2.9.1. Salinity

Salinity profile 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 41 to 45. 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. 45), 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 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, which lowered the salinity in the fall, as observed by Wood et al. This is the peak of the rainy season, so the reduction is not unexpected. Ostericher (1976) conducted 7 hydrocasts in the Punta Tuna area in April 1967. During that time, he found the surface salinity to vary from 36.30°/oo to 36.35°/oo. 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°/oo to 34.81°/oo. 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 observed by Shanley and Duncan (1972) during 1971. The overall values range from 34.18°/oo in October to 36.00°/oo 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°/oo in August of 1967 to 36.45°/oo 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°/oo 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.

The salinity maximum and their observed depths are detailed here. The total range seen for all these measurements is from 36.88°/e to 37.14°/os. The salinity may not have actually 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 to the surface, exposing more of the higher salinity water to surface conditions.

Months: Jan, Feb, Mar, Apr, May, June, July, Aug, Sept, Oct, Nov, Dec.
Years: 1967, 1971, 1984, 1992.

Table 18: Summary of Surface and Maximum Salinity data Reported by Shanley and Duncan (1992)

Surface Salinity Range: 35.13-35.39°/eo, 37.0877, 35.73°, 35.84-36.00°/e6, 35.99°/e6, 35.17-35.90°/e0, 36.93°/6, etc.

Months: Feb, 1960, Mar, 1955, 1953, May, 1962, Avg, 1967, Sept, 1963, Oct, 1984, Nov, 1962, Dec, 1968.

Table 19 for Puerto Rico: Summary of NODC Nominal Cast Salinity Data (Monier, 1978).

Depth (m): 150, 4505, 2610, 100, 1986, 17, 3076, 150, 3936, 160, 4651, 192, 109, 1984.

Salinity (Sx): 35.72, 36.94, 34.97, 35.78, 34.99, 36.45, 37.01, 35.03, 35.98, 36.99, 35.4.

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 5-minute squares, in which the area was partitioned.

The composite temperature profiles are constructed in Appendix 8. An analysis of the surface temperature range from these profiles indicates that the minimum recorded value was 24.7°C, observed in February 1971 (Square 14), and the maximum recorded was 30.7°C, observed in September 1971 (Square 10). This implies that the surface temperature variation for that year was 6.0°C. Figure 48 shows the NODC data processed and averaged by O0s1 (1977). The average surface temperature typically varies, being slightly more than 26°C in October. This suggests an average annual variation of approximately 3°C.

Table 20, based on Craig et al. (1978), lists the observed temperature for each month of the year.

The data spans from 1953 to 1968. Again, the lowest value is observed in February, but the highest value is seen in September. An interesting observation from this table is that the temperature maximum does not always occur at the surface. It may actually be observed up to 50 m below the surface.

Table 21 shows typical temperatures reported by Shanley and Duncan (1972). Similar trends are observed, with the highest temperature seen in September and the lowest in March. The maximum temperature often occurs at the surface, but during the cooler winter months, the maximum can be 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 is typically located about 260 m below the surface. Atwood et al. (1976) indicate 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 the temperature of the water above 100 meters to as much as 29°C.

Month Feb. 1960

Depth is rather complex, but for the purposes of this discussion, it can be considered the depth to which a theoretical disturbance would have to extend in order to produce a given change in density.

Mar. 1955 Apr. 1953 May 1962 Aug. 1967 Sept. 1963 Oct. 1966 Nov. 1962 Dec. 1968

Table 20 Summary of NODC, Nansen Cast 1% for Puerto Rico Station PR PR-2 PR-3 PR-8 PRS PR-6 PR-7. Matter Craig et al. Depth (a) are 35 (as78) 82. Temperature data (degrees) (Surface-1000 m) 21.29 19.79 20.63 22.20 23.16 23.34 23.03 22.51. Salinity max. Max. max. max. Max. max. max.

Table 21 Typical Temperatures of the Caribbean Sea, South of Puerto Rico

Month: January, February, March, April, June, May, August, September, October, November, December. Data after Shanley and Duncan (1972)

Surface Temp. (degrees Celsius): 26.36, 25.91, 25.82, 26.20, 27.70, 27, 27.82, 28.21, 29.08, 28.17, 28.03, 27.40

Temp. at depth 1000m (degrees Celsius): 5.52, 5.59, 5.31, 5.44, 5.38, 5.38, 5.48, 5.51, 5.51, Surface-1000 m (degrees Celsius), 20.94, 20.32, 20.51, 20.76, 22.70, 23.51, 22.65, 21.87

2.9.3 Mixed Layer Depth

This parameter is important both to design engineers and environmentalists. The designers must use large volumes of water to run the power plant. The plant intake openings should have some non-zero vertical dimensions. The designers need to know the depth they can reach to maintain the same surface water characteristics, with little or no chance of intrusion of subsurface water, which can reduce the thermal efficiency or change the water chemistry. Environmentalists understand that the upper mixed layer is generally identified with the Tropical Surface Water, the upper water mass in the Caribbean Sea. This water has specific ranges of temperature, salinity, and light transmission. 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, it 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 is complex, but for this discussion, it can be considered the depth to which a theoretical disturbance would have to extend in order to produce a given change in density.

Depth (MLO) 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 specific 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 MLO 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 MLO. At that point, the temperature undergoes a great change within a small vertical distance, meeting 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 late summer and fall months are times of water mixing with severe storms occurring most frequently 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, 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 (Delta-T), in degrees Centigrade, between the surface water and the water at a depth of 1000 m. Many authors have directly discussed this parameter (Atwood, et al., 1976; Wolff, 1978; Sands, et al., 1978, and ODSI, 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 al. (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/m^2 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 biological information related to physical, chemical, and geological parameters, zooplankton, benthic invertebrates, 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 if an OTEC plant were to be located or operating in an area.

There is 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/n¢/year with a primary production of the order of 800 9 C/m@/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 (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 freshwater 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 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 9 C/m@/year. Cell counts fall mostly between 5 and 15 cells/mt (Hulburt, 1963, 1966, 1968), and pigment concentration between 0.05 and 0.3 mg chlorophyll a/m>. Phytoplankton extend to relatively major depths; diatoms are represented primarily by only those species associated with.

Ciliates, such as Chaetoceros coarctatus, are present. There are also sizeable populations of coccolithophorids, dinoflagellates, and blue-green Oscillatoria (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. Moreover, there are no specific data on marine productivity. However, considering some available information from the Punta Tuna site, we can speculate on the actual conditions in this area and the possible changes that would occur if an Ocean Thermal Energy Conversion (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 by 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 Western Mediterranean, such as the tintinnid species of the Stenosemella genus and other similar genera 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 pelagic 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 of phytoplankton should be found, among which are dinoflagellates like Noctiluca, which are carnivorous; Ceratium, which has a size varying from 200 to 500µ; and Peridinium, with a size of 200 to 250µ.

Furthermore, in this environment, genera such as Pyrocystis are common, which together with Noctiluca, are responsible for the

"Luminescence in tropical waters. The other important group of phytoplankton is composed of diatoms, with probably the most common being Coscinodiscus, Rhizosolenia, Bacillaria, Hemidiscus, Syrosigna, Biddutphia, Asterionelta, and Thalassiothrix. There is also the Trichodesmium, a blue-green, filamentous consistency, 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 like Acanthometra, about 200u in diameter; coccolithophorids of the Coccolithus genus; and finally the silicoflagellates, 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, larvaceans, veliger larvae, caridean larvae, brachyuran larvae, cirripede nauplii, number of fish eggs, holoplankton, and meroplankton were counted (number/ms). According to the above authors, seasonal changes in the abundance of the total zooplankton at any station (Fig. 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 accounted for, 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).

The following section appears to contain errors and is unclear:

Table 24 displays the total number of holoplankton and meroplankton in Nearshore Replicate Tows, Nearshore Tows, and Offshore Tows at different stations.

Fish eggs were abundant in this area, making up 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. However, it is not reported which groups of fish are represented by most of the eggs.

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 1974b). 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 provide a detailed examination of species abundance at all 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.

Table 26 shows the total number of larvaceans (number/100) for nearshore replicate tow nearshore tows stations. The data is not clear due to an error in the text.

Table 27 presents copepod populations observed at the Cabo Mala Pascua Site. Species usually most numerous (5 individuals /m) are Clausocalanus furcatus, Farranula gracilis, Dithona spp., and others. Species commonly present (observed on 5 or more sampling periods) include Corycaeus spp., Euchaeta marina, CandacTa pachydactyla, and others. Species occasionally present are Oncaea spp.

The text requires further clarification for an accurate interpretation.

I'm sorry, but the text you provided is too garbled and lacks sufficient context for me to accurately correct it. It appears to contain scientific terms, possibly related to species names, and perhaps page numbers or data entries. It also seems to have multiple page breaks, suggesting it's a portion of a larger document. However, without more context or clear sentences it's difficult to provide a precise correction. Please provide a clearer text or more context.

Observed at Station "Sei2" (Fig. 33) which are mentioned in Table 345 are Gaulerpa, Udotea, Alophila, and Halimeda. These were also observed at Stations "S-2" and "ESO". Between the 10 and 20 m isobaths at Station "S-10", a decrease of organisms typically associated with hard substrates was noted. This includes Montastrea cavernosa, a hard coral, and various species of sponges such as Callyspongia vaginalis, Haliclona rubens, Verongia longissina, and Treintastra bilinay.

Rise and changes in distribution could be observed among the fishes of this region (Tables 33-34), but they would not be as marked as in the case of the sedentary invertebrates and the aforementioned plants.

290° - vorr = 460" ett' sao" eatzt - - - gir = eet" att' eOT* beter 0" - 180° 080"/Lv0" 290° £90°/6S0" ¥60"/0S0° ¥60"/TE0" +pLe0zz Tor yao" £80" TOL" 190" 180" 0° eet" weve zt" 640" EO" _BEO"/EBO TLO" ¥hO"/6L0 9E0"/z80" ¥e0"/9B0" ¥HLZOEL ett Bot' $90" 960" 940" ot 460° Blo" ecg0Ez 90° e90" 860" s0" 040" £90" eyo" sho" e202 ' 5 & 2 1 22 @ @ a7e9 BuO; TS 'BuO TeaS SWF TeS smo} 240ys430 SMO] 940ys.0aN 'smo, aqe041day au0ysuven, ze tgp (gu/tm) worxue door 40 sseuoig 120) 12

113

Table 33 (from Wood, et al. 1975). Shoreline fishes of the Cabo Mala Pascua site

27 Feb 73 27 Feb 73, Seine Rotenone

FAMILY:

Muraenidae: Echidna catenata
Ophichthidae: Myrichthys acuminatus
Gobusocidae: Arcos macrophthalmus, Arcos Fubringenosus
Toniéodon: Fasctatus, Arcos artius
Scorpaenidae: Scorpaena plunieri
Gerreidae: Eucinostomus melanopterus
Ponacentridae: Abudefduf taurus, Abudefduf saxatilis
Mugitidae: Mugit ize
Labridae: Doratonotus megalepis
Watchoeres: Imuscurptina
Scaridae: Sparisoma rubripinne
Blenniidae: Entomacrodus nigricans
Clinidae: Enblemariopsis leptocirris
Tabrisoms: Gupi, Tabrisomus hatttensis, Labrisonus nuchipinnts

Table 33 (Cont.)

27 Feb 73 27 Feb 73 seine Rotenone

Gobiidae: Awgous taiasice, Sathyaobius soporator, PovenT ineatus, Goatholis.

"Thomsoni 7, Gonionellus baleosona. 1, Balistigne Aluterus schoepfi 1

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

Macroinvertebrates, algae, and fish observed at selected stations at Cabo Mala Pascua

22 Aug 74 2% Aug 74 22 Aug 74

PLANT KINGDOM,

Phylum Rhodophyta
Gracilaria sp.

Phylum Chlorophyta
Caulerpa mexicana, Ialineda sp. PenicTTus capitatus, Wastex consutina, Wastes fTabeton, Wotea spinutosa

Phylum Spermatophyta
Phila baillonis

ANIMAL KINGDOM

Phylum Porifera
Agelas, Athos ignelia varians, Cartyspongia vaginatus, Chondrilla nucula, Cinachyra cavernosa, Jeltiodes sp., Ratretona rubens, Trewa sp., Tetrochota birotulata, Igitosa Neoriularia massa

Table 34

Phylum Cnidaria
Class Anthozoa

Subclass Octocorallia
Briareum asbestinum, Exythoropodtum sp., Eunicea laxispica, Eunicea sp., Gorgonia, Maries' sp., Hurfesopsts sp., Plexaura homomalla, Pseudopterogorgia sp., Zoanthara Acropora cervicornis, Keropora palmata

Subclass Zoantharia
Igariels sp., Cotpophylita sp., Dichocoenia stokesii, Diploastrea heliopora, Eusmilia fastigiata, Favia fragum, Montastrea cavernosa, Palythoa sp., Porites astreoides, Siderastrea radians, Siderastrea siderea

Phylum Chordata

Subphylum Vertebrata

Class Pisces

Family Dasyatidae
Dasyatis sp.

Family Muraenidae
Gymnothorax moringa

Table 34 (Continued)

Phylum Chordata (continued)

Family Holocentridae
Holocentrus sp., H. Jacobus

Family Aulostomidae
Aulostomus maculatus

Family Sphyraenidae
Sphyraena barracuda

Family Serranidae
Epinephelus fulva, Unidentified serranid

Family Grammistidae
Rypticus sp.

Family Echeneidae
Echeneis naucrates

Family Carangidae
Unidentified species

Family Lutjanidae
Lutjanus sp.

Family Haemulidae
Haemulon flavolineatum

Family Sciaenidae
Cynoscion sp.

Family Sparidae
Calamus bajonado"

Page Break---

Table 4 (Cont.)

Family: Mullidae
Species: Pseudupeneus maculatus

Family: Chaetodontidae

Date: 8/22

Page Break---

Table 4 (Cont.)

Phylum: Chordata (cont.)

Family: Pomacentridae
Species: Chromis cyaneus, Pomacentrus partitus, Pomacentrus sp.

Family: Labridae
Species: Bodianus rufus, Thalassoma bifasciatum, Halichoeres sp., Labrid sp.

Family: Scaridae
Species: Sparisona sp., Scaridae sp.

Family: Acanthuridae
Species: Acanthurus sp.

Family: Balistidae
Species: Balistes sp.

Page Break---

Table 35 (from Wood, et al. 1975)

Cabo Mala Pascua shore collections
Station B1
Date: 22nd March 1973

Phylum: Chlorophyta
Species: Caulerpa racemosa, Enteromorpha sp.

Phylum: Phaeophyta
Species: Dictyota ciliolata, Sargassum hystrix

Phylum: Rhodophyta
Species: Bryothamnion triquetrum, Galaxaura sp.

Phylum: Spermatophyta
Species: Syringodium filiforme

Page Break---

Table 35 (cont.)

Station 81 and Station B2
Date: 22nd March 1973

Phylum: Mollusca (cont.)

Class: Gastropoda
Species: Acmaea antillarum, Columbella mercatoria, Fissurella barbadensis, Fissurella sp.

Phylum: Arthropoda

Order: Decapoda
Suborder: Brachyura
Species: Callinectes danae, Microphrys antillensis

Phylum: Echinodermata

Class: Echinoidea
Species: Tripneustes esculentus

Page Break---

Table 36

Species and individuals per species collected in 1/4 m² quadrat at Cabo Mala Pascua

Date: 2/22/73

Plant Kingdom

Phylum: Phaeophyta
Species: Dictyota sp.

Phylum: Rhodophyta
Species: Amphiroa sp.

Animal Kingdom

Phylum: Sipunculida

Phylum: Annelida

Class: Polychaeta

Polychaeta Arabella, Opatina Euntee, Fucata Eanes $55, Hermenta Verruculosa, Cactnontce Einberatt, Uopidonotae, Uiabrfaerets Sp., Tystatee Suteata, Wipes Fegatts, Rapes $5, Tenet Wfeafon Kingeratt, Eration Spe 5, Phyl Ioddce, Papttiosa, Family Sabellidae, Family Serpulidae Syltis Sp., Herberart Sp., Family Terebellidae, Und Polychaete 1 2 122.

Table 36 (cont.) s7 2/22/73

Phylum Mollusca:
Class Gastropoda: Columbella Mercatoria, Tucapina Sonerbiy
Class Pelecypoda: Rbatia Domingensis, Tora Tophaga Coral Iophaga, Toberus Castaneus, Tietoohags Igre, Unita Pelecypod

Phylum Arthropoda:
Order Stomatopoda: Unid. Stomatopoda,
Order Isopoda: Girolana Parva, Sphaeroma Walkeri,
Order Decapoda:
Suborder Natantia: Family Alphaeida, Tiete Rnfa Mexeana, Saar Spree Aprenden, Mectendont,
Suborder Brachyura: Mithrax Pleuracanthus

Phylum Echinodermata:
Class Echinoidea: Eucidarus Tribuloides,
Class Asteroidea: Asterinides Sp.,
Class Ophiuroides: Unid Ophiuroid.

Table 36 (cont.) 2/22/73

Family Amphiuridae: Amphiurid, UpntaclS Sartanyt, Spkionerets Savanvlosa, Li Oph Sp., Fopsila Sp., Bie Kar Ritse, Ophiothrix.

Phylum Chordata:
Class Ascidacea: Styela Partita.

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.

Tropical and subtropical regions maintain fairly steady levels of production. The overall production, when considered annually, may be considerably greater than it initially appears. This is likely due to the rapid recycling of nutrients at the higher sea temperatures of the tropical regions, which allows for several cycles to occur over the course of a year. However, the standing phytoplankton crop tends to be low at any one time in the tropical seas worldwide. As Riley (1939) 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 detailed studies on productivity in the Caribbean Sea have been conducted in the Gulf of Cariaco and adjacent regions, off northern Venezuela. In accordance with Margalef (1971), the primary production estimates, based on 14-C uptake (Fig. 51), range from 600 to 1000 mg C/m^2/day in the central productive area, decreasing to 50 to 200 mg C/m^2/day in more offshore or peripheral positions. These values represent a range between net and gross production (Ballester and Margalef, 1968) and align with the limited number of studies on inorganic carbon uptake in the Gulf of Mexico and the Caribbean.

3.2.2.2. Phytoplankton

The portion of the water column with sufficient sunlight for photosynthesis is called the euphotic zone (Duxbury, 1971). It extends to a depth of about 100m. At the OTEC plant site, the euphotic zone aligns closely with the Tropical Surface Water (TSH). This water mass may reach a thickness of up to 100m, and its characteristics are discussed in other sections of this report. Nearly all phytoplankton activity occurs within the first 100m of depth off Punta Tuna.

No less than 450 species of phytoplankton have been observed in the Caribbean and the Gulf of Mexico (Margalef, 1971). Undoubtedly, a catalogue of these species would have many flaws, especially in regard to the

Smaller and more delicate organisms are prevalent. The following species are more commonly found offshore in stable environmental situations. Their presence is likely more ecological than geographical: Amphidinium, Peridinium fatulipes, P. pentagonum latissimum, Ceratium betone, C. hirundinella, C. taiseni, C. trichoceros, C. vultur, Pyrocystis hamulus, Lauderia annulata, Rhizosolenia setigera, Tentaculifera cylindrus, Chaetoceros curvisetus, Neoceratium tridentium, and Hemiaulus membranaceus.

Margalef (op. cit.), studying the pelagic ecosystem of the Caribbean, stated that Chaetoceros curvisetus, Ch. socialis, Asterionella japonica, and Stephanopyxis turris are common species in the upwelled water. These species may be identified 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, only two stations, 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.

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

Page 126
Figure 54: Locations of stations at which hydrographic data and complete series of plankton samples were obtained (Michel, Foyo, and Hangensen, 1976).

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Table 37: Zooplankton species at Station 4, Cruise 6-6722, situated at 17° 52' N, 64° 49' W, with a bottom depth of 4026m and a fishing depth of 0-1520m on 1 December 1967 (Michel et al., 1976).

Phylum Coelenterate
Class Hydrozoa
Depth Estimated Order Siphonophora (n)
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 longicornis 335 165
5. Lucicutia flavicornis 0 250 55 150 Normonitla minor
335 cd 581 3 1040 2 1520
6. Mephasma 581 1 1520
7. Paracalanus aculeatus 0 500 55 250
9. Rhincalanus cornutus 335 5 581 3 1060 1 1520 3

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Table 37 (cont.)
10. Undinula vulgaris
Order Harpacticotda
11. Macrosetella gracilis
12. Microsetela rosea

Order Cyclopoida
13. Conaea gracilis
14. Farranula carinata
15. E. gracilis
16. Oithona plumifera

Phylum Arthropoda
Class Crustacea, Subclass Malacostraca
Order Euphausiacea
1. Euphausia americana
2. E. brevis
3. E. tenera
4. Stylocheiron longicorne

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Zooplankton species at Station 1, Cruise P-6911, situated at 00° 'N, 64° 49' W, with a bottom depth of 0-2337m on 26 October

Table 38
Class Hydrozoa
Order Siphonophore
1. Abylopsis eschscholtzis
2. A. tetragona
3. Chelophyes appendiculata
4. Dyphyes bojani
5. D. dispar
6. Eudoxoides mitra

Phylum Arthropoda
Class Crustacea, Subclass Copepoda
Order Calanoida
1. Acrocalanus longicornis
2. Clausocalanus furcatus
3. Ichaeta mari
4. Haloptilus longicornis
5. Lucicutia flavicomis
6. Normonilla minor

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Fishing 1969 (Michel et al., 1976) Estimated number: 120, 300, 570, 390, 60, 100, 8, 100

Table 38 (cont.)

72M. Phasma: 250, 150, 9, 2, 75, 27, 311, Bn, 6, 1835, 0, 2337, 3

8. Paracalanus aculeatus: 0, 90

9. Rhincalanus cornutus: 459, 49

Brincalanus cornutus: 459

Fa oil: 48, Ba, 1835, 5, 2337, 8

10. Undinula vulgaris: 150

Order Harpacticoida

1. Macrosetella gracilis: 0, 250, 250

12. Aegisthus aculeatus: 2, 137, 1835, 1

13. Microsetella rosea: 9, 390

Baresetella rosea: 6, 73, 250, 450, 459, 60

Order Cyclopoida

14. Conaea gracilis: 459, 160, 75, 155, 37, 137, 2, 1835, 2337

15. Farranula carinata: 270, 131

Table 38(cont.)

16. Githona plumifera: 180, 6, 760, 250, 2200, 459, 200

17. Oncaea media: 250, 300

18. O. venusta: 65, 200, 280, 50, 1835

Phylum Arthropoda, Class Crustacea, Subclass Malacostraca, Order Euphausiacea

1. Euphausia brevis: 65, 50, 5

2. Nematoscelis megalops: 250, 50

3. Thysanopoda sequallis: 6, 50

Phylum Chaetognatha

1. Eukrohnia bathyantarctica: 1371, 3, 1835, 1, 2337, 1

5. Pterosagitta draco: 65, 8

6. Sagitta decipiens: 250, 102

7. S. enflata: 55, 6, 165

8. S. hexaptera: 5

Table 38(cont.)

9. S. hispida: 20

10. S. lyra: 280

11. S. macrocephala

12. S. serratodentata: 20

13. S. zetesios

Phylum Chordata, Subphylum Urochordata, Class Thaliacea, Order Salpida, Family Salpiidae

1. Thalia democratica: 65, 800

2. Weelia cylindrica: 75

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

Mollusks Class Gastropoda, Subclass Opisthobranchia, Order Thecosomata

Suborder Euthecosomata, Family Limacinidae

1. Limacina inflata

2. Limacina trochiformis

Family Cavolinidae

3. Cavolinia trispinosa

4. Cavolinia inflexa

Suborder Pseudothecosomata, Family Desmopteridae

5. Desmopterus papilio

"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 planktonic 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 equaled calanoids in the total number of individuals. The most numerous cyclopoids, Farranula carinata and Oithona plumifera, were more than twice as abundant as the top-ranking calanoids, 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, Bathybelos typhlops, Eukronia hamata, E. proboscides, Sagittamegato, BihaTon, and S. planktonisy, and two neritic species that are sometimes swept into oceanic waters, S. helenae and S. nisptda. The total numbers of chaetognatha are given in Table 6d 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, Nemetocell, megeTops, Stytochetron, Tongicorne, S. elongutua, and Thyssnoposs Bonacanths being among the most abundant of this group. The relative abundance of euphausids 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."

The horizontal distribution of noted Thecofonates for the Caribbean Sea is shown in Figure S8. The siphonophores Abylopsis tetragona, A. eschscholtzii, Diphyes bojani, D. dispar, Eudoxoides mitra, and Chelophyes appendiculata (Tables S7 and S8) were identified close to Puerto Rico. The total number of Siphonophores is 134.

The organisms 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

(Note: The text between the page breaks appears to be scrambled or coded and therefore could not be corrected.)

Caribbean Sea. The total number 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. enflata, Paracalenus sculeatus, ClavsocaTams furcatus, Krohmitta pacifica, Diphyes Bojant, Acrocalanus Tongtcornis, 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 4000m 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) state that Mormonilla minor, M. phasma, Rhincalanus cornutus, Conaea gracilis, Sagitta pactocephala, and Kegisenos seuteates species have affinity only with the preceding.

The vertical distribution of all species except very rare forms, e.g. Stylocheiron elongatum, Thysanopoda pectinata, and heteropods, was diagramed to show the relationship 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 due to the frequency of 142 - 143 - 144 - 145. See Figure 62 for temperature-salinity-plankton diagrams.

A. Clausocalanus furcatus
B. Mormonilla minor
C. Microsetella rosea
D. Farranula carina (Mitchell and Foyo, 1977).

Efforts have been made to wash nets and eliminate desiccated specimens from consideration. However, the depths of major concentrations were usually clearly delineated.

The copepods Rocalanus longicornis and Clausocalanus furcatus primarily live in TSW and SUW, but the former is far more numerous in surface waters than the latter. Euchaeta marina, Paracal nus aculeatus, Scolectrix danae, and Undinula vulgaris are also found mainly in the upper 100m, and Farranula carinata and F. gracilis are numerous in sub-surface swarms.

Toptfus longicornis is concentrated between approximately 100 and 250m both day and night, occurring in lower TSW but most abundant in SUW and upper North Atlantic Central Water (NACW). Lucicutia flavi-cornis is distributed similarly, except that it is most numerous in TSW. Rhincalanus cormutus and C. Atlantica were 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 NACW and

Subantarctic Intermediate Water (SAIW).

Others with similar extended distributions are Macrosetella gracilis, Microsetella rosea, Oithona plumifera, Oncaea mediterranea, and O. venusta. In contrast, Mormonilla minor 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 gracilis is similarly deep and the numbers fewer. Distributional records of the more frequently caught euphausiid species indicate both migratory and resident species.

The non-migratory habits of some species occur over a very broad vertical range in comparison with others. Stylocheiron carinatum and S. Submit were collected only in Tai and SUds Nenato. Brachion boopis was only found in NACM and SAIW, and Nematoscelis tenella in NACW. Those found in TSk, SUW and HACK, primarily in HACK, are Euphausia hemigibba and Nematobrachion flexipes. The species more numerous in TSW were E. americana, E. brevis, E. fenberg (2180, caught in a ship), Stylocheiron ine, S. longicorne, and Thysanoessa aequatis. Another group, living mainly in ACM but also collected in SUM, consists of pseudogibba, Nematoscelis megalops, N. microps, Sergestes arcticus, S. abbreviatus, and T. ostracitrox. S. mutica and chevron were also included. The vertical distribution of many chaetognath species is also extensive, however, the major concentrations are clearly stratified.

Most Sagitta serratodentata (Fig. 638), S. enflata (Fig. 638), S. bipunctata, and Krohnitta pacifica live in surface waters of highly variable salinity, while S. hexaptera and Pterosagitta Draco are usually associated with the OPE zone in the SUM. The least 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. 63), S. lyra (Fig. 630), S. cetos and Krohnitta subtilis. The remaining four of the more abundant species were largely restricted to SAIW and NADW: Sagitta macrocephala (Fig. 63A), Eukrohnia bathyantarctica, E. bathypelagica (Fig. 638) and E. fowler.

Michel and Foyo (op. cit.) also stated that changes in the distribution of some species, primarily copepods and chaetognaths, indicate upwelling, sinking, or a mixture of coastal with oceanic waters. Farranula gracilis is a likely indicator of warm, saline waters in shallow equatorial regions, and is found in the Caribbean and the Florida Straits. The presence of Aegisthus aculeatus, which lives primarily in SAIW and NADW, was also noted.

NADW, an indicator of water masses, signifies upwelling, as does Wormintta minor, if numerous, in TSW. Chaetognath species, such as Sagitta friderici and S. tenuis, mark an admixture of coastal waters when found in the open sea. Other species, S. helenae and S. hispida were not collected during this study. The presence of deep-water species in relatively large numbers at unusually shallow depths also indicates upwelling, e.g., Ura, macrocephala, and E. bathyantarctica at depths of 95.5, 82.5, and 230 meters, respectively, at a station north of Panama. There is also the possibility that rare chaetognath species in the Caribbean may indicate waters entering the sea from the North Atlantic, such as F. hanata, Sagitta planctonis, E. proboscidea, reported from southeast Africa, and S. werththalma, from the Mediterranean and the Gulf of Lez. Specimen collection locations were often in or near the Windward and Anegada Passages and those between the Lesser Antilles. Intensive sampling in these areas might show that there are biological markers to indicate the influx of North Atlantic waters at various depths.

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 a relatively thin, offshore extension of the neritic zone, but it has a permeable water bottom, not a solid substrate. This region is well-lit at the surface, dimming considerably towards its downward limit of about 200 meters. 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 mackerels and tunas, such as the following species: Thunnus.

Albacares (Yellowfin tuna), T. alatunga (Albacore), T. atlanticus (Blackfin tuna), T. thynnus (Bluefin tuna), Euthynnus pelamis (Skipjack tuna), E. alletteratus (Little tuna), Auxis thazard (Frigate mackerel), Acanthocybium solanderi (Wahoo), Scomberomorus cavalla (King mackerel), and S. regalis (Cero) all belong to the family Scombridae (Erdman, 1974). Other fishes in this division are as follows: from the family Xiphidae, Swordfish (Xiphias gladius); Istiophoridae, Sailfish (Istiophorus platypterus), Blue marlin (Makaira nigricans) and White marlin (Tetrapterus albidus). In the Coryphaenidae family, Dolphin (Coryphaena hippurus) and Pompano dolphin (C. equisetus). In the Exocoetidae family, (Flying fishes) we have the Atlantic flying fish (Cypselurus heterurus) and the Margined flying fish (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 Belonidae (Strongylura spp.) could come from near-shore. In addition to these fishes we may find marine species of sharks of the following families: Rhincodontidae, Carcharhinidae, Lamnidae and Sphyrnidae; also Mantas such as the Atlantic manta (Manta birostris).

3.2.2.4.2. Mesopelagic Region

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

See Figure 64. Schematic example of different depth and temperature preferences by different species of tuna in tropical latitudes. (Laevastu and Hela, 1970) 152

Herbivores and carnivores occupy different vertical positions (trophic levels) in a food pyramid. The largest carnivore or top predator, such as sharks like Rhincodon typus (whale shark), Carcharhinus falciformis (silky shark), and C. longimanus (oceanic white tip shark), can typically be placed at the apex of the pyramid.

There are several species of fish from the families Scombridae, Xiphidae, Istiophoridae, Coryphaenidae, Exocoetidae, and Anguillidae that have been mentioned above. Furthermore, we should include some sea mammals such as the bottlenose dolphin (Tursiops truncatus), spinner dolphin (Stenella longirostris), spotted dolphin (Stenella spp.), common dolphin (Delphinus delphis), humpback whale (Megaptera novaeangliae), fin whales, rorquals (Balaenoptera spp.), sperm whale (Physeter macrocephalus), Cuvier's beaked whale (Ziphius cavirostris), and pilot whale (Globicephala macrorhynchus). All these species of mammals have been mentioned by Erdman et al., (1973) and Erdman (1970).

Some species of turtles such as the leatherback (Dermochelys coriacea), loggerhead (Caretta

caretta), green turtle (Chelonia mydas), and hawksbill (Eretmochelys imbricata), according to Rivero (1978), should also be mentioned.

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. Phytoplankton, mainly diatoms and flagellates, are part of this bottom level. Then comes an intermediate level composed of herbivores and crustaceans such as copepods and euphausiids, chaetognaths, some mollusks, and fishes. Finally, there is the highest trophic level, occupied by carnivores, where there may be several tiers of fish and other large animals such as mammals and reptiles. According to Erdman (1958, 1962) and

Sudrez-Caabro and Ouarte-Bello (1961) noted that many species of marine animals, even though they usually live their adult lives in the neritic province and in the littoral and sub-littoral zones, are present at least part of their lives in the oceanic province as larvae. Among those fish and shellfish that are part of the food chain are the following: fishes such as Acanthurus spp. (Doctor fishes), Mulloidichthys martinicus (Goatfish), Holocentrus ascensionis (Squirrelfish), Caranx lugubris (Black jack), Hemiramphus brasiliensis (Ballyhoo), and Gempylus serpens (Snake mackerel).

Crustaceans 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, Enoploteuthidae, and Ommastrephidae (Squids), and Octopus spp. (Octopuses) are also included.

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 area.

3.3. FISHERIES RESOURCES

Juhl (1971) mentioned that the Caribbean fishery resources could be grouped into three major zones: island arc 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

The fisheries carried out by local fishermen in Puerto Rico accounted for 48% of the total production of the Caribbean's continental shelf resources. It's worth noting that the most productive area, largely due to favorable hydrographical conditions for fisheries, is found from the Guianas to the Panama region, which is quite a distance from Puerto Rico. The pelagic resources are the least productive in both volume and species composition, contributing only 4% to the total production in 1976.

The most significant fishing centers in Puerto Rico, located near Punta Tuna, can be found in the southern part of the island (Patillas, Maunabo, Yabucoa) and on Vieques Island. In 1978, the region had a total of around 100 artisanal fishermen, 70 fishing boats, and 1,400 units of fishing gear.

Most of the fishing activities are conducted on the narrow shelf from Patillas to Yabucoa and south of Vieques Island. Very few fishermen venture beyond the 20m isobath.

There are approximately 900 fishing pots in use, which constitute 70% of the total fishing gear in 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 is based on the literature and information discussed in this document, as well as the preliminary results from Puerto Rico's OTEC data-collection program for fiscal 1979. These latter results are not presented in this report and will be referred to only for confirmation or verification.

4.1 PHYSICAL ENVIRONMENT

The climate of Puerto Rico and its surrounding area is typically tropical marine, influenced by predominant easterly winds. The windward side of the island usually receives more rainfall, with precipitation varying from 70-500 cm per year, depending on the location.

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 a storm being close enough to the area to be felt, and statistically every 3-5 years, a severe storm or hurricane may significantly 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 often they range from 1-2 m. The tidal excursion around the coast of Puerto Rico and its neighboring islands is small, ranging from virtually nothing to less than 1m. Despite this low tidal range, tidal currents are significant components in the coastal circulation patterns in some areas.

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

The salinity profile below the pycnocline (the depth of most rapid density change-about 200 m maximum) along the south coast is fairly well documented. At and exceeding such depths, the variations due to atmospheric conditions are minimal.

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

Temperature values, and the resulting level of the thermal resource, are frequently found 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 are 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 isopycnal 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 zooplankton collected near shore, copepods comprised most of the organisms. Approximately 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 is scarcely being tapped or understood, therefore, an accurate assessment of the ecosystem changes resulting from an OTEC plant being either present and/or operating cannot necessarily be assessed at this time.

4.3. CONCLUSION

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 will 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 areas.

This text discusses a 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 shouldn't vary considerably, they should still be documented for the project program. This report does include a biological section. However, the processing and reporting of biological results in the literature may lag behind the other data, due to the longer time required for processing and interpreting. Therefore, an up-to-date interpretation of our current understanding of the biota and their dynamics in this part of the world may not be available for a while. Continual monitoring of literature will help to minimize this time gap.

Chemical and geological reviews were not part of this study, but they should certainly not be overlooked. These reviews should be initiated as quickly as possible, since any environmental impact on the biota could potentially come from chemicals used in heat exchanger cleaning or trace metal erosion. An understanding of the dynamic structural interrelationships between the biota and their chemical environment could potentially predict or divert any future problems, or suggest directions towards a more ecologically compatible design.

In summary, the following recommendations are being made in regard to the historical data:

1. Expand the geographical area of coverage of the literature review to include the entire south and north coasts of Puerto Rico, including both the Atlantic and Caribbean coasts.
2. Continue to monitor the biological literature to update existing information that is relevant.
3. Keep track of all environmental studies completed in this part of the world for any useful information.
4. Use any available satellite sea surface temperature data to enhance the existing data bank and to develop better predictive capabilities.

FUTURE DATA COLLECTION: As there is so little applicable information available, the greatest effort towards understanding the oceanic region near Puerto Rico will have to lie in the

The realm combines sparse historical information with an intensive data collection effort. This program must be developed at the specific benchmark site of Punta Tuna (where the current work is being conducted), and also along the remainder of the south coast and the entire north coast. The program must address 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 diameter, located as deep as 1000 m. 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 just a few of the considerations taken into account in the development of the following recommendations: 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 (*):

1. Temperature
   a) of the mixed layer, using thermometers, STD, or XBT (daily), when possible, for short term variations.
   b) up 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.

1. Monthly monitoring for ecological structuring and plant design purposes.

2. Measurement of the actual sea surface and the mixed layer using thermometers, STD, XBT, and satellite (when available) to correlate the satellite sea surface temperature monitoring with the mixed layer temperature.

3. Weekly monitoring of the mixed layer using thermometers, STD, and XBT for ecological structuring.

4. Daily, when possible, otherwise weekly, measurement of the thermocline depth using XBT to anticipate discharge dynamics.

5. Biweekly monitoring of salinity up to 200m depth downstream, at discrete depths or with STD, to assess the density structure for water discharge.

6. Monthly or bimonthly monitoring of salinity in the water column, at discrete depths for ecological structuring.

7. Monitoring of salinity up to 200m using recording equipment during severe weather events to determine vertical movement of water masses and salinity structure.

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

9. Daily, if possible, measurement of mixed layer depth using STD or XBT for engineering design requirements.

10. Monitoring of thermal resource variation during severe weather events using recording equipment with thermistor strings.

11. Measurement of internal waves at one site in the Caribbean and one site in the Atlantic, 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.

12. Measurement of wave spectra surface at one Caribbean site and one Atlantic site using a recording wave rider, to determine the long-term wave spectra for plant and personnel safety.

13. Four times daily on a weekly basis, measurement of water currents using current profilers, to supplement the moored data with emphasis during the tidal periods.

14. Use of moored, recording current meters at discrete depths to monitor water currents.

depths, to determine the stress on 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 small 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 medium 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 per year), to gather statistics describing the patchiness of various sizes of plankton in the area.
*e) Using a very large multi-mesh 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 (bi-hourly 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 (bi-hourly, quarterly), for counting and identification to determine statistics related to patchiness.

12. Nutrients
*a) downstream along the 200 m isobath, at discrete depths, (bi-monthly), 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.
*c) at the benchmark site, at discrete depths (bi-hourly 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.

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 A1 shows the

The range of current speed at various depths has been reported in three previous studies of 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, with both values 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. The speed range at a depth of 5 meters is less variable, with the greatest difference measured on June 10, 1971, and reported in the Oceanographic Baseline Data (1971-72) report. The maximum speed range at depths varies significantly in contrast to the current speed at the surface, indicating 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 "First Survey of the Guayanilla Disposal Site (Area

G)" from the Oceanographic Baseline Data (1971-72) study indicates that wind-drift currents are predominant, as "the total rise and fall of the tide is well under a foot; therefore, not a great deal of tidal component to the current would be expected." Both studies conclude that the surface wind-drift current becomes insignificant at a depth of about 1 meter. Investigations performed by the Department of Marine Sciences personnel (Hernandez-Avila and Morelock, 1975) suggest a third possible current generation process: a wave-induced surface and subsurface current mainly affecting 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. The variability of the current can...

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As seen in Table F-1 (page 7-113), the 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).

In the Guayama sector, current structure and patterns have been reported in the Oceanographic Baseline Data Project (1971-72). Studies carried out by Muñoz (1967), 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 Oceanographic 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. Drogues 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 drogue studies are given on pages 7-113 of Vol. II of the final report.

In the Guánica sector, the current patterns, as investigated by Hernández-Avila (1977, unpublished), were similar to those at Punta Ventana, with the exception of the funneling effect of the canyon. Drifting drogues and dye traces indicated that surface currents are a function of...

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The wind stresses originate from the east and southeast. The tidal forces seem to influence the direction of the deeper drogues, as evidenced by the tracks of the 4, 6, and 7-meter drogues. The net mass transport in the water column was directed towards the west and west-north-west. Current velocities varied from about 1 cm/sec to approximately 30 cm/sec at the surface. Circulation at depths exceeding 9 meters was determined to be a result of water reflection from the coast and the effects of tidal excursion forces. Net mass transport moved in a south and southeastern direction. Eastward flow was also dominant at intervals. The tide's reversal effect was observed in the progressive vector diagrams. Velocity histograms indicated velocities ranging from 1.5 to a maximum of about 14 cm/sec. Mean velocities varied from 2 to 7 cm/sec, depending on the location of the station. The data from this study has not yet been fully analyzed. Currents were monitored throughout the four seasons of the year; wave refraction diagrams, salinity, temperature, climatological, and other dynamic parameters are being analyzed. Comparisons between the current structure in the same station during two different seasons will be made.

In the Ponce sector, the available ocean current measurements have been reported by Colon (1971) from the Water Resources Research Institute, University of Puerto Rico, Mayaguez Campus. Measurements were made at three different water depths using Hydro-Products in-situ current meters, Model 502. The data has not been completely analyzed, at least not with the methods typically used. Current roses are shown in Figures 1 to 4 of the aforementioned study. Figure 1 of the Colon study illustrates the frequency of water flow direction at a depth of 1.5 meters in station 1, with the dominant current direction being towards the north-east, east, and southeast quadrants. At station 2 (Figure 2), the dominant direction was shown to be towards the north-west.

The quadrant was 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, was 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 173 -

11 cm/sec (2 knots). Surface vectorial properties were not observed or measured in this investigation. Colén (1971) conducted another study at Punta Cuchara in the Ponce area at a much deeper water depth. Variations in the current were immediately observed. Velocities at this depth, according to Colén, ranged from .1 to .2 knots (5 to 10 cm/sec).

LA PARGUERA SECTOR

Surface and subsurface currents in La Parguera offshore 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 Hernéndez (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.

Colén (1971c) installed three in-situ current meters at different locations off the reefs near La Parguera. The relative quantity of water and direction of flow were illustrated by means of current roses (Figures 1 to 3 of the).

Report: Western flow directions are dominant in locations closer to land. Northeastern flow directions were found at a depth of 7.5 meters in the outer station. Current velocities ranged from 5 to 20 cm/sec. Circulation patterns around Laurel Reef, La Parguera, Puerto Rico, were 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.

Page Break

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, due to wind stress coupled with flood tidal conditions 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 submarine and coastal morphology.
2. Direction of tidal flow:
- Ebb tide: SSE
- Flood tide: WNW

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Negligible, but wave-induced stresses are still the dominant effect. The variability, owing to the reversing tidal effect, will affect to a certain extent the speed distribution and flow direction towards the 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, are 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 cm/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 the 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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Figure 8-4. Vertical Profiles of dissolved oxygen, temperature, salinity, and silicates for Puerto Rico: September 1963.

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2 Allender, J.N., J.D. Ditmars, R.A. Paddock, K.D. Saunders. 1978. “OTEC physical and climatic environmental impacts: An overview of modeling efforts and needs. In Proceedings of Fifth Ocean Thermal Energy Conference, 20-22 Feb. 1978, Miami. Clean Energy Research Institute, Univ. of Miami. pp 165-185. 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 multiple OTEC plants.

"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).

Atwood, O.P., P. Duncan, M. Stalcup & M. Barcelona. 1976. "Ocean Thermal Energy Conversion: Resource Assessment and Environmental Impact for Proposed Puerto Rico Site." Final Report - NSF Grant #AER7S-00145, 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 temperature difference up to 1000 meters can be as high as 24°C (43°F) and is never less than 20°C (36°F). The insular slope at the site is steep, and water depths of 1000 meters exist within 1.5 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 hurricanes). The salinity, temperature and nutrient distributions at the site are typical.

"Of Open Tropical Seas" makes 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 a nearshore Ocean Thermal Energy Conversion plant on the subtropical Hawaiian waters. This was documented in the Proceedings of the Fourth Annual Conference on Ocean Thermal Energy Conversion, 22-24 March 1977, New Orleans, University of New Orleans, pp IV 79-99.

Environmental analyses, as detailed in the previous 15-month NSF/RANN report, were 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 the approximate scale of impact for each case.

Based on the temperature and discharge rate of cold water from the OTEC plant, 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 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. 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. University of New Orleans, pp.IV 61-73. This was a "state-of-the-art" investigation on the availability of published material on the subjects 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, the West Coast, the Hawaiian Islands, and all the equatorial oceanic areas.

The text is located between 20°S and 20°N latitude. No additional measurements were made nor was new data generated to increase the "state-of-the-art". The data sources are referenced and categorized into one of four classes based on a predetermined set of rules and opinions. Brekhouskikh, L.M., K.N. Fedirov, L.M. Fomin, M.H. Koshlyakov, and A.0. Yampolsky conducted a large-scale hydrophysical experiment in 1971. This experiment, titled "Large Scale multi-buoy experiment in the Tropical Atlantic", was published in Deep Sea Research, volume 18, issue 12, pages 189-1206.

The experiment, aimed at studying ocean current variability, was conducted at a specific site (polygon) centered at 16°30°W in the Tropical Atlantic. It involved six U.S.S.R. research vessels and a cross-shaped network of buoy-stations arranged within a square 113 x 113 nautical miles. Currents and water temperatures were continuously recorded at various depths by this network. Each buoy was replaced every 25 days, with arrangements made for overlapping records during each replacement operation. Additional research programs were conducted from participating ships.

Current records revealed high variability both in time and 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 thermohaline structure deserve particular attention. It is likely that the observed thermohaline microstructure is related to an intermittent mixing regime in which double-diffusivity convection interacts with larger scale turbulence of both convective and dynamical origin.

In 1976, Bunker, A.F. & L.V. Worthington published "Energy exchange charts of the North Atlantic Ocean," in the Bulletin of the American Meteorological Society, volume 57, issue 6, pages 670-678. The publication contains charts of calculated energy exchange across the surface of the North Atlantic Ocean.

The text was constructed using wind and temperature observations obtained from 8 million ship weather reports. Each report was individually entered into the bulk aerodynamic equations, with exchange coefficients that varied with wind speed and stability. The individual fluxes were averaged to obtain monthly and annual means of latent and sensible heat momentum. Net radiation fluxes were calculated using Budyko's (1963) formulas.

Monthly and annual averages for a period of 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 annual 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 was produced by the Naval Oceanographic Office, Washington, D.C. Tech. Note, TN6110-6-75 consists of 146 pages.

A preliminary analysis of 36 current meter records, from 18 arrays in the eastern Caribbean Sea, showed a wide variation in mean speed. Speeds ranged 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 the 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, documented drift-bottle return in the wake of Hurricane Carla, 1961 in their work titled, J. Geoph. Res. 67(7):2773-2776.

Most of the drift bottles released off the Mississippi delta three weeks before Hurricane Carla entered the Gulf of Mexico.

The following items were recovered from the vicinity where Carla crossed the Texas coast. The pattern of these recovered items is presented, along with a discussion of some possible interpretations.

Clark, G.L. (1938). Light penetration in the Caribbean Sea and the Gulf of Mexico. J. Mar. Res. VI (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. However, at the offshore station in the Gulf and at all other stations, the water was found to be highly uniform and extremely transparent. The value of the transmissive exponent from 95 to 185 m 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 the 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 over 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 --Page Break-- uncertain.

Facilities in offshore waters make the study of the currents themselves equally important. Here, we show that it's possible to model three-dimensional time-dependent currents through numerical integration over a two-dimensional grid. This is 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.Z., 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, Texas. Current meter records from three depths show that the storm produced currents on the order of 2 ms^-1, which persisted to near the bottom. A mathematical model of wind-driven current generation successfully hindcasted the observed current development after a linear slip condition bottom was incorporated into the model.

Frassetto, R. & J. Northrop. (1957). Virgin Island bathymetric survey. Deep Sea Res., 4:138-146, 244. 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 Anegada and Jungfern Passages, has a flat floor 2,400 fathoms deep. It is bounded on the north and south by sea scarps with 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 of these arms terminate at sills which separate them from Anegada 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., and D.K. Atwood published new evidence in 1974 for sporadic renewal of Venezuela Basin water in Deep-Sea Research, 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 suggest 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.

In another paper by Froelich, P., D.A. Atwood, and J. Polifka published in 1974, "Seasonal variations in the salinity-silicate structure of the upper Venezuela Basin, Caribbean Sea" (Trans. Amer. Geop. Union, 55(4):303), recent temporal hydrographic studies in the Venezuela Basin have yielded new information concerning variations in the upper 400 meters. Seasonal low-salinity surface water during October-November is characterized by high silicates, indicative of runoff, probably Amazonian. Linear regressions of silicate versus salinity yield excellent correlations (r > .9). STD traces during the low-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/p 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 (STU) core. The STU

In the depths of the Cayman and Yucatan basins, 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 x 108 m/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 cm/sec at the bottom of the Ekman layer.

Gould, W.J., Schmitz, W.J., & Wunsch, C. (1974). Preliminary field results for a Mid-Ocean Dynamics Experiment (MODE-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-hour period during the deployment of the first array. These observations were collectively designed to provide estimates of energy levels and space and time scales for mesoscale motions.

Frequencies less than 1 cycle per day, 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 approximately 1 m and 50 m, respectively. Pressure measurements at other depths on this mooring yielded the same approximate 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 approximately 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 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... [Page Break]

Winter occurs in the Caribbean, and for most of the year in the Gulf area. This is influenced by the upper-tropospheric westerly current originating from the equatorial regions of the eastern Pacific. During the summer half of the year, there's an export of geopotential energy and sensible heat over the Caribbean Sea. This is concentrated in the upper tropospheric easterlies, which also includes the Gulf of Mexico area in midsummer.

In terms of the total energy budget, the troposphere over the Caribbean Sea acts as an energy exporter to other parts of the globe throughout the year. However, energy import is observed in the Gulf of Mexico during some winter months. Ocean currents export heat from the Caribbean Sea during the summer half of the year, while a substantial amount of heat import is observed in the Gulf of Mexico throughout the year, except in midsummer. The tropospheric energetics are discussed with respect to their role in general circulation (Hastenrath, S.I., 1968).

Estimates of the latent and sensible heat flux for the Caribbean Sea and the Gulf of Mexico are derived from the multiannual mean of the oceanic heat budget, the atmospheric energy budget (based on the available radiosonde data for the entire year of 1960), and the bulk-aerodynamic method using 1960 ship observations. The annual average of latent and sensible heat transfer in the Central American Seas is roughly 270 ly/day.

Accounting for error propagation and different time periods used, the results of these three independent approaches are fairly consistent. However, due to the inherent shortcomings in all the procedures, multiple independent approaches are desirable where possible (Hazelworth, J.B., 1968).

The variations in water temperature resulting from hurricanes are also discussed.

"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 presented. 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, a 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 temperature decrease for the eleven coastal examples and for the thirteen lightship examples was 3.1°F, and for the three Nomad samples, it 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 the 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 a mean time of 13 and 10 days, respectively. At the Nomad buoy, near pre-hurricane 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.

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 discretely 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 defining 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. 251

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 hydrographic station in the eastern Caribbean and along a 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 175m in 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, B.J, G. 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..."

The 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. The 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.

Lee, T.N., R.S.C. Munier, S. Chin. 1978. Water 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. The 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 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 are within the surface mixed layer defined by temperature, but at the base of the surface salinity mixed layer. There were intake salinity variations of 1.7 per mil over a one-month period that were coherent with similar changes in the upper 60 m of Tropical Surface Water (TSW). Variations in water properties below the TSW were minimal. The mean and ranges of temperature and salinity at 1000 m were only 5.4 ± 0.5°C and 35.0 ± 0.06 per mil, respectively. The temperature of the surface mixed waters was 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 Ocean Thermal Energy Conversion (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 standard deviation of ± 0.2°C. The depth to reach a ΔT of 20°C ranged from a minimum of 660 m to a maximum of 740 m. Historical data indicates that the maximum depth to reach a ΔT of 20°C would occur in the winter and would not exceed 956 m. Therefore, from thermal resource considerations, the 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 Gulf of Mexico from 30 September to 4 October 1964, developing into a very severe hurricane in the central Gulf. Sea temperature data available prior to the storm indicated what was probably a typical late summer situation with some surface temperatures above 30°C. Beginning 5 October 1964, a 7-day cruise was conducted over the area where hurricane 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 m and hydrographic casts to 125 m. The data from 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. These waters converged outside of the central storm area resulting in downwelling to some 80 to 100m in depth there; cold waters upwelled along the hurricane path from depths of approximately 60m. Sea surface temperatures decreased by more than 5°C over an area of some 70 to 200 miles. 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 x 10^78 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 a 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.

Marine Sciences Department. 1976. Oceanographic data of the University of Puerto Rico; January 1971-June 1973, Vol. I. 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; 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 was collected by the Department of Marine Science, University of Puerto Rico, Mayaguez. The research was funded by the National Science Foundation and the Commonwealth of Puerto Rico. The Marine Sciences Department in 1976 conducted oceanographic data collection at the University of Puerto Rico from July 1973 to November 1975, which resulted in Volumes I and II. These documents are maintained at the Hall of Puerto Rico Documents, General Library, University of Puerto Rico, Mayaguez. The tables included show depth, temperature, salinity, density, dynamic height, oxygen, phosphate, silicate, and potential temperature for both observed and interpolated data.

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Martin, P.D., and Roberts, G.O., in 1977, estimated the impact of OTEC operation on the vertical distribution of heat in the Gulf of Mexico. This was presented at the Fourth Annual Conference on Ocean Thermal Energy Conversion, held from 22-24 March 1977 at the University of New Orleans. The effect of OTEC operation on the thermal structure of the Gulf of Mexico was estimated by using a one-dimensional heat conservation equation to predict the horizontal mean temperature. The surface heat fluxes were parameterized in terms of the observed air-sea temperature difference and the predicted sea surface temperature (SST). The advection of heat into the Gulf by the Yucatan Current was treated as a heat source for the surface layer of the Gulf. A constant mean upwelling was calculated to balance the overall heat budget. Within the mixed layer, the vertical diffusivity was calculated using the Mellor-Yamada Level 2 turbulent diffusion model. Below the mixed layer, a constant diffusivity was determined from a balance between vertical advection and diffusion to yield a realistic mean temperature profile. The operation of 1000 OTEC plants in the Gulf is under consideration.

The model is parameterized by the addition of a mean vertical velocity profile to the model. This profile is 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 sea surface temperature (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 deep warming rate 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. The impact is correspondingly reduced for the operation of only 100 OTEC plants. After 30 years, the model predicts a drop in SST of 0.05°C and a 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. Page Break. The current pattern associated with the origin of the Equatorial undercurrent is examined. The temperature/oxygen relationship 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 over 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 around 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 #£6-77-S-02-4283, DOO. 56 pp.

The examination of data from the water areas surrounding the Hawaiian Islands leads to the conclusion 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 temperatures, 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, 258.

Univ. of Miami, Clean Energy Research Inst. pp. IIT 214-230. Analyses of surface temperature averages and anomalies focusing on the 25-year period from 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. University of Miami, Clean Energy Research Institute, 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 plant's impact 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 exceedance 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 variability in the smaller regions. Finally, a method to obtain crude estimates of the distribution of surface speeds is presented. Molinari, R.L., and J.F. Festa. 1978. Ocean thermal and velocity characteristics of the Gulf of Mexico relative to the placement of a moored OTEC plant. NOAA Tech Memo ERL AOML-33. NOAA Atlantic Oceanographic and Meteorological Lab., Miami 105 pp. This report presents the results of the second stage of a four-stage effort designed to provide ocean 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 (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..."

A longshore current was recorded. During the storm, bottom current speeds ranged up to 160 cm/sec, and their direction rotated from alongshore, parallel to the wind, to seaward against the wind. Oser, R.K. and L.J. Freeman, in 1969, summarized an oceanographic cruise to Vieques Island, Puerto Rico area from December 1968 to March 1969 in an informal report for the Naval Oceanographic Office, Washington, D.C., titled Informal Report IR#69-66. This 16-page 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. The survey included Nansen casts, bathymetry, sub-bottom profiling, current measurements, marine fouling studies, bottom photography, geomagnetic measurements, and sediment sampling.

In 1967, Ostericher, C. released an oceanographic cruise summary titled "Atlantic Fleet Tactical Underwater Range; Southeast Puerto Rico- 1967." This was also an informal report for the Naval Oceanographic Office, Washington, D.C., specifically Informal Report IR#67-76. The 44-page report covers an oceanographic survey of a proposed Fleet Tactical Underwater Range off the southeast coast of Puerto Rico, conducted during March - April 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. The report also includes the ocean station 3 data listings and the calculations used in the analysis of the moorings.

Parr, A.E., in 1937, made a contribution to the hydrography of the Caribbean and Cayman Seas, which was published in Bull. Bingham Oceanography Coll. 5(4):1-110. In 1938, he made further observations on the hydrography of the Eastern Caribbean and adjacent Atlantic waters, also published in Bull. Bingham Oceanography Coll. 6(4):1-29.

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 objective 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 show that a depression of the sea surface temperature by 0.1 °C leads to an increased heat flow from air to sea of 9.6 cal/cm²/day. This serves 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 interaction 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 OTPP 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.P.R., Mayaguez, PRIC 162, 464 in 2 volumes. 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, foraminifera, algae, turtle grass, mangrove root community, coral reef ecology, fish, and birds.

Puerto Rico Nuclear Center. June 1975. Aguirre Environmental 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.

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 each 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 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 indicate a strong cooling of the air above the tropopause, computed to be as much as five times that of the troposphere. The day-to-day fluctuation of net radiation from the troposphere was large, as was the range of observed fluxes. Statistical analysis suggests that the control of the net radiation from the troposphere lies primarily 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 potential 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. University 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 OTPP design. A rectangular domain of depth 500ft has three horizontal slots of height 72ft on its left boundary, centered respectively at depths of 75, 150 and 315ft, to represent the inflow and outflows. Four separate computations assume statistical uniformity across widths of 50ft, 100ft, 200ft and 400ft. It is believed that the results for widths of 100ft and 200ft essentially bracket the results for the three-dimensional prototype flow.

The ambient temperature profile assumes a surface temperature of 80°F, and a thermocline at depth 300ft where the temperature is 61.5°F. The temperature at 500ft is 44.4°F. The temperature at the cold inflow, at depth 1550ft, 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 either leaves or enters the computational domain horizontally, with a 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. This contributes to the reduced inflow temperatures. In all cases, the OTPP-generated turbulence is negligible at distances greater than 380 ft from the inflow and outflows. Ross, C.K., and C.R. Mann, in 1971, made oceanographic observations in the Dungfern Passage and over the sill into the Venezuela Basin, in February 1968. This was published by SIRCSAR, UNESCO, Paris, on pages 171-174.

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 a 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 0. Webb. In 1971, wrote about the four-month drift of a Swallow float in Deep-Sea Research, 18(10): 1035-1039. The Swallow float, at a depth of 1100 m, was tracked by SOFAR in the region between Bermuda, Bahamas, and Puerto Rico. During the four-month lifespan of the float, it drifted 300 km to the west. This corresponds to an average drift rate of 2.8 cm/sec, which 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 x 108 m3/sec. The trajectory 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 water temperature dropped 0.5°C, there was a sudden change in the

An observation was made on the oscillation phase and frequency, a transition that is consistent with the float moving from one relatively well-mixed layer to another. Sands, M.D. 1978. A progress report for the environmental impact assessment program for the 1-MWe early OTEC test platform was presented at the Fifth Ocean Thermal Energy Conversion Conference, 20-22 Feb. 1978. The University of Miami, Clean Energy Research Institute, hosted this event. The report is detailed between pages 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 environmental impact assessment, thereby bringing 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 the 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. 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.

In addition, the international, federal, state, and local legal implications of siting will be considered. While the socioeconomic impacts of OTEC-1 currently 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.

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. University of Miami, Clean Energy Research Institute, pp. 83-103. Bio-ecologic measurements were initiated in July 1977 and November 1977 for environmental assessment of the impact of an operating Ocean Thermal Energy Conversion Plant at the proposed Gulf of Mexico site off the coasts of Louisiana, Mississippi, Alabama, and Florida. This was done 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 site and two 1c 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 (AOML). They included 4 hydrocasts, 7 net tows for zooplankton (samples analyzed by Gulf Coast Research Laboratory), 1 STD trace, 20 XBT's and one 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 the Caribbean Sea and Pesca Serial Station at 17°38'N, 67°00'N for 1971. Dept. of Marine Science, U.P.R., Mayaguez #72-1.

Shanley, G.E., Reviewed by C.P. Duncan. 1972. Hydrographic data for the Caribbean Sea and for

Pesca Serial Station at 17°38'N, 67°00'N for 1971. Dept. of Marine Science, U.P.R. Mayaguez #72-1 (REV).

Smith, N.P. 1978. Longshore currents on the fringe.

"Hurricane Anita: J. Geoph. Res. 83(C12): 6087-6051. Subsurface current data from a two-week period in August and September 1977 are compared with coastal wind stress and water level data to describe long-shore 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 made landfall.

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 x 108 m3 sec-1. This transport is divided between the Grenada, St. Vincent, and St. Lucia passages with, respectively, 10, 10 and 6 x 106 m3 sec-1 flowing to the west. The transport through Dominica passage was less than 2 x 100 m3 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.

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 Passage sill is 1818 m. As described by the 1800 m isobaths, it is 3 km wide and 10 km long and contains a central depression with depths exceeding 1970 m. In agreement with earlier data, the Jungfern Passage (Virgin Passage) sill is shown to be the deepest or controlling one between the Venezuela and Virgin Islands basins. The Anegada Passage sill, found during recent surveys, is not that found by Frassetto and Northrup (1957). The one described here is located near Barracuda Bank and, with a depth of 1915 m, is 300 m shallower than the one previously described.

Stevenson, R.E. 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. 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 x 10^7 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, is consistent, but sporadic inflow may occur through Windward Passage into the western basins. It appears that there is no inflow of water at mid-depth above either sill.

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. Proceedings from the Fourth Thermal Conference on Ocean Thermal Energy Conversion, held on March 22-24, 1977, at the University of New Orleans, pp IV'42-49.

As an essential part of its operation, an OTEC plant withdraws significant amounts of water (typically 6 x 10^4 gpm per MW of capacity) from both the surface and deeper layers of the ocean, discharging them at intermediate levels. The circulations induced in the ambient ocean from these withdrawals and discharges are of paramount importance, as any adverse changes in the ambient stratification will directly affect the operational efficiency of the plant. Specifically, any "short circuit" between the outflows and the inflows could lead directly to a decrease in power production. Due to this direct "feedback" effect, the external flow induced by an OTEC plant must be considered an essential part of its operation.

This paper presents the interim results from an ongoing experimental study assessing 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 types of problems: the first involves an ambient current without ambient stratification, and the second involves the opposite. 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 included."

The text given provides detailed measurements that are relevant to the "tuning" of mathematical models (turbulence) of the flow field. The similitude parameters that govern the problem are identified, and the way 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 depths of 2000 m and 4000 m in the western North Atlantic Ocean. The observed speeds were on the order of 10 cm/sec.

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, held on 22-24 March 1977 at the University of New Orleans, pages IV 50-56 were discussed.

In the absence of actual operations, the complex interactions of OTPP's and the environment can only be assessed using numerical ocean models and laboratory experiments. The best strategy for OTPP far-field modeling of the ocean is to select a single, well-observed ocean basin with well-defined boundary and surface input data. The conditions in the basin should be 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 range of numerical models of the Gulf of Mexico for use in studies of OTPP operations. The first model is nonlinear, time-dependent, and retains both barotropic and first baroclinic modes. The model uses primitive equations on an S-plane, and both external and internal gravity waves are treated implicitly. The model uses a uniform rectangular grid with ax = ay = 16 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.

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.

This information was presented by H.E. Wurtburt and P.D. Marint in 1978. Results were obtained from the Gulf of Mexico - OTEC far-field numerical model, which was featured in the Proceedings of the Fifth Ocean Thermal Energy Conversion Conference, held from February 20-22, 1978. The conference was hosted by the University of Miami's Clean Energy Research Institute, and the findings were published on pages 141-164.

One reasonable strategy for predicting the complex interactions between OTEC and the far-field environment is to develop a numerical model of a 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.

The integration to statistical equilibrium was performed with both wind and Loop-Current forcing included. The circulation characteristics for a mid-Gulf site, a 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 are 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 the area. The current data was predominantly tidal with a nearly constant phase relationship between maximum flood and ebb and predicted high and low tides. Observed currents 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. 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 was collected from moored current meters.

The text is corrected as follows:

At a single site (Site D) in the western North Atlantic, vertical profiles of steady and time-dependent horizontal ocean currents are defined. The mean velocity profile shows currents systematically flowing towards the west, with an amplitude that decreases with depth. Time-dependent currents have a vertical profile of kinetic energy, which is proportional to the vertical profile of the 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 one 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 anisotropy may be due to the interaction between low-frequency processes and the nearby continental shelf. Eddy momentum fluxes have a profile that reverses sign at the approximate depth of the continental shelf.

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 the 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. This was observed by Wolff, P.M. in 1978 in his paper "Temperature Difference Resource," which was presented at the Fifth Ocean Thermal Energy Conversion Conference, 20-22 Feb 1978 at the University of Miami's Clean Energy Research Institute. The paper discusses the continuous operation of OTEC plants and their requirement for a consistent temperature difference resource. He also examines and relates the requirements of such a consistent OTEC temperature resource to other parameters.

Ocean Data Systems, Inc. has studied 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 the most probable monthly soundings for each of 60 one-degree latitude and longitude squares. The Hawaiian and Puerto Rican areas are characterized by homogeneous temperature conditions and small variability at all depths. However, in the Eastern Gulf of Mexico and off Key West and Miami, there are stronger currents and greater spatial and temporal variability.

The Loop Current in the Eastern Gulf of Mexico poses additional analytical difficulties due to the possibility of a bi-modal temperature structure. Wolff, P.M. and L. Lewis in 1977 also discussed plans for additional resource analysis in their paper "Monthly Assessment of Temperature Resource for Three Potential OTEC Sites," which was presented at the Fourth Annual Conference on Ocean Thermal Energy Conversion, 22-24 March 1977 at the University of New Orleans.

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 temperature 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, they also determined the existence of a temperature of 20°C at a depth less than the given value.

Passage. The second section ran from the Grenada Basin into the Caribbean Sea through the Windward Passage. Findings from these sections showed that there was a change in the deep water's characteristics from 1963 to 1966.

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 presents an environmental study of the area just south of Cabo Mala Pascua, Puerto Rico. It does not include any conclusions or results, but rather data collected and presented. The data collected includes 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 a decline in the oxygen values of the Caribbean deep water by 0.3 ml/l over the last twenty years. This loss closely corresponds to that in the North Atlantic deep water. The surrounding Atlantic water suggests that there has been no renewal of the Caribbean deep water since the end of the eighteenth century, coinciding with a cold climatic variation at high latitudes in the North Atlantic. It is further deduced that the Windward Passage was the original source of this water 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-Sea Res. 3(3): 234-235. Observations of the temperature of the deep Caribbean water are made from 1500m to 3000m. The dates discussed are 1933 and 1954. An estimation of the temperature increase is used in an attempt 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 section ran from the Atlantic Ocean into the Venezuela Basin through the Anegada Passage, and the other from the Grenada Basin into the Caribbean Sea through the Windward Passage. The findings showed a change in the characteristics of the deep water from 1963 to 1966.

The text seems to discuss two oceanographic sections: one running from the Cayman Basin to the Atlantic through the Windward Passage, the other through the Virgin Islands Passage. These sections are different from those in MUST's research (1963, 1964), as there's presently no evidence indicating that bottom water is entering the Caribbean. The bottom water in the Cayman Basin appears to have warmed approximately 0.03°C since the studies conducted by PARR in 1933 and 1937.

Worthington, L. V., in 1971, explored water circulation in the Caribbean Sea and its relation to North Atlantic Circulation. Data from both oceanographic sections were used to determine the origin of the Caribbean's bottom water. Potential temperature profiles through both the Windward Passage and the Virgin Islands Passage indicate no recent renewal. Also, the dissolved silicate is distinct from the Atlantic basin to the basin. Currently, there's no evidence of bottom water renewal. The main circulation in the Caribbean was also examined, with most of it being towards the south. However, other studies on water mass distribution suggest that the circulation maximum is to the north.

Wright, W. R., in 1970, studied the northward transport of Antarctic bottom water in the western Atlantic Ocean. The volume transport of Antarctic Bottom Water in the western basin of the Atlantic Ocean was calculated dynamically 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 observed in both temperature-depth and salinity-depth traces, marking the transition from North Atlantic Deep Water to Antarctic Bottom Water. The northward transport decreased from 5-6 x 10^6 m^3/sec in the southern sections to about 10^6 m^3/sec in the northern sections. The results are consistent with those obtained previously.

By solving a set of conservation equations, a simple box model of the deep circulation in the western Atlantic is formed. Wust, G. (1963). On the stratification and circulation in the cold water sphere of the Antillian-Caribbean Basins. Deep-Sea Res, 10, 165-187. The cold water circulation within the Antillean-Caribbean Basins is discussed. The three water masses investigated are the Subantarctic Intermediate Water, the North Atlantic Intermediate Water, and the Caribbean Bottom Water. The Subantarctic Intermediate Water, formed at the southern polar front with a salinity minimum, extends throughout the entire breadth of the Atlantic at depths of 700-900 m. This water finds its way into the Antillean Caribbean Basin, maintaining its identity. The North Atlantic Deep Water is formed near southern Greenland. This water reaches the 2000-2500 m level and is characterized by an oxygen maximum. This water eventually spills over the sills into the Caribbean, changing its character enough to develop a slightly separate identity as the Caribbean Bottom Water.

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Appendix D: Bibliography of Marine Biology References for Puerto Rico and Other Tropical Waters

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