

CEERM157-4 ECOLOGICAL ANALYSIS OF SPATIAL AND TEMPORAL PATTERNS OF PELAGIC ECOSYSTEM COMPONENTS POTENTIALLY INTERACTING WITH AN OTEC PLANT NEAR PUNTA TUNA, PUERTO RICO PHYSICAL CHARACTERISTICS FINAL REPORT

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CENTER FOR ENERGY AND ENVIRONMENT RESEARCH

FINAL REPORT ON THE PHYSICAL OCEANOGRAPHY WORK ON OTEC AT PUNTA TUNA, PUERTO RICO

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FOREWORD

This document is part of the final report for the Department of Energy Project under Contract No. DE-ACOS-760R01833, which includes five main sections: Physical Characterization, Plankton, Primary Productivity, Chemical Characterization, and Summary and Synthesis. The document is primarily organized as a collection of preprints of articles being submitted for journal publication. Once all sections are completed, the entire series will be combined as a five-chapter volume dealing with the environmental aspects of the siting, construction, and operation of an Ocean Thermal Energy Conversion Plant based off the south coast of Puerto Rico. Of prime concern in these studies, as suggested by the title, is the relationship among the scale of distribution of natural phenomena, the scientific detectability of pattern, and the alterations of pattern likely to be caused by the hypothetical 100 MWe power plant adopted as the design unit.

ABSTRACT

The earliest studies of the Caribbean date from 1520. The intensity of research has been at a modest level. The upper 1000 m can be characterized as having small horizontal gradients in the conservative physical properties and relatively large vertical gradients when compared with more boreal seas. This is especially true of the salinity. In the thermocline and upper mixed layer, the flow is

Towards the west, the movements of the deeper layers remain problematic. The Center for Energy and Environment Research has conducted hydrographic studies designed to characterize the Punta Tuna, Puerto Rico area as a potential site for an OTEC power plant. Seven cruises were

conducted at approximately two-month intervals. Each cruise included at least 22 hydrocast stations, six of which were done as serial stations in a small area to reveal temporal and small-scale variability. Two long-term serial occupations of the Benchmark Station were conducted with 17 hydrocasts on the first and 364 bathythermograph drops on the second. The results of the analysis of these data so far indicate a bi-seasonality in the dynamics, Potential Energy Anomaly and Geostrophic Kinetic Energy. Mesoscale eddies and meanders are a common feature of the circulation pattern on Puerto Rico's southern coast. Our time series studies have shown the existence of a very energetic internal wave field with relatively large amplitude waves at the diurnal and semi-diurnal tidal frequencies. Our current meter work has shown the mean speed to be much larger than the mean flow, with no component of the flow accounting for more than 8% of the total signal.

INTRODUCTION

The Center for Energy and Environment Research has been conducting a study of the marine environment at Punta Tuna, Puerto Rico as part of the Department of Energy, Office of Health and Environment Research program for ocean thermal energy conversion. This report provides a brief background, an overview of the present state of the work, a description of the proposed further analysis, and an identification of expected papers to be submitted for publication.

Introduction to the Area

The earliest organized and scientifically based study of the physical oceanography of the Caribbean Sea was published in 1837 by the Spanish Direction of Hydrography. This report was confined to surface water movements and in many ways anticipated the U.S. Navy's Pilot Charts in its content. Wust (1964)

The text summarizes and significantly expands our understanding of the Caribbean. The main driving force behind the surface currents is believed to be the wind. The surface current charts, which are largely based on "set and drift" observations, show a westward drift on the southern side of Puerto Rico of approximately 0.1 statute miles per hour. Wust (1964) and Morrison & Nowlin (1982) also classified the various water masses in the Caribbean as follows:

0- 80/100 m Tropical Surface Water with a temperature of 22-25°C and a salinity of 33 to 36‰;

100-200 m Subtropical Underwater with a temperature less than 20°C and salinity of 36.800-37.200‰;

200-600 m Sargasso Sea Water with a temperature of 7-20°C and salinity of 35‰ to 36.8‰;

600-800 m Sub-Antarctic Intermediate Water with a temperature of 6°C and a salinity of 34.9‰;

and Atlantic Deep Water or Venezuelan Basin Water with a temperature less than 6°C and a salinity of 34.9‰.

The oxygen minimum is typically just above the Subantarctic Intermediate Water and the silicate and salinity maximum are in the Subantarctic Intermediate Water. The depths of the water mass boundaries tend to deepen as one moves north in the Caribbean, according to Gordon (1967).

Sturges (1965) performed a volumetric analysis of the Caribbean Sea waters and found more than half the water in the Caribbean Sea to be within 0.1°C and 0.02‰ of 3.9°C and 34.98‰. Sturges argued that the surface waters of the Caribbean Sea are formed by water flowing in through the eastern rim, the passages between the Lesser Antilles, and this dominance only extends to a depth

of 800 to 1000 m. Based on his water mass analysis of potential temperature and salinity relationships, Sturges argued that the water at and below the 800 to 1000 meter level entered through the Windward Passage between Hispaniola and Cuba. He concluded that a dynamic pressure gradient inhibited inward flow below this depth in the Anegada Passage.

Morrison and Nowlin (1982) studied the formation of Caribbean Sea water masses using temperature, salinity, dissolved oxygen, phosphates, nitrates, and silicates as water mass indicators. They strongly... (text ends abruptly).

The work of Sturges (1965) has been amplified. Ingham and Mahnken (1966) also observed indications of surface inflow in the passages between the Lesser Antilles, and they saw evidence of turbulent vertical mixing in cyclonic eddies resulting from the surface flow around the island of St. Vincent.

Febres-Ortega et al. (1976) also observed an eddy in the lee of St. Vincent Island. Fett and Rabe (1976) saw evidence of eddies in the lee of Granada Island in satellite data. Gordon (1967) extended the earlier work of Wust (1969) and Sturges (1965) on the general circulation in the Caribbean. He based his study on baroclinic geostrophic current calculations using data from several transects across the Caribbean Sea and one across the Straits of Yucatan.

The westward flowing current has its axis in the southern third of the Caribbean, though the western flow was found all the way up to the Greater Antilles. Gordon found the level of zero-zonal velocity to vary from less than 100 meters to 1700 meters, with the shallowest levels being along the southern and eastern boundaries, north coast of South America and the Lesser Antilles.

Because the zero velocity level was found to be shallower than the sill depths for many of the inter-island passages, outflow into the Atlantic seemed possible. Just west of the Antilles, Gordon found local areas of eastward flow in his current calculations. These may have been similar to the eddies found by Ingham et al. (1966).

Gordon extended Wust's hypothesis of trade wind dominance of the surface currents by modeling the Ekman Mass Transport in the Caribbean Sea. His calculations resulted in a baroclinic field extending vertically to a depth of between 1000 and 1500 meters. This was sufficient to produce the westward moving current throughout the Caribbean, as persistently described.

The agreement between the model's predicted baroclinic field and the observed field was very good. Gordon's modeling efforts also predicted a deepening of isotherms and isohalines towards the northern boundary.

The agreement between observation and theory was once again reasonable. In 1970, Sturges conducted a five-day current meter study of the bottom flow through the Anegada-Jungfern Passage. The flow was found to be oscillatory, predominantly at a tidal frequency, and had a net inflow into the Caribbean of 6×10^2 m/s for brief periods of a few hours. This contradicted his earlier work from 1966.

In 1976, Metcalf used hydrographic sections on the Atlantic and Caribbean sides of the passages

between the Lesser Antilles to study water exchanges between the two bodies. Direct current meter measurements were also made. His results are summarized as follows:

- Inflow of water through Grenada Passage: 10 Sv
- St. Vincent Passage: 10 Sv
- St. Lucia Passage: 6 Sv
- Dominica Channel: less than 1 Sv

Metcalf moored two current meters near the bottom in the Anegada-Jungfern Passage. They confirmed the hydrographic data of approximately 1.39 Sv into the Caribbean above 700 m and approximately 0.7 Sv out of the Caribbean below 700 m. The direct measurement showed the flow to be unsteady, with reversals showing diurnal and semi-diurnal tidal frequencies, seiche frequencies, and storm surge effects.

The Marine Ecology Division of the Center for Energy and Environment Research has collected a large amount of physical oceanographic data in the Caribbean Sea, south of Puerto Rico and Vieques. This data set includes a large volume of data of many different forms:

1) 154 hydrographic stations, a 22 station grid occupied seven times at two month intervals for 13 months (Fig. 1). This is a larger hydrographic database than that used by Wust (1964), Sturges (1966), Gordon (1967), or Morrison and Nowlin (1982), and represents the first regional quasi-seasonal physical study of this part of the Caribbean Sea.

2) The data set also includes two 8-day and five 1-day studies of variability at one point.

The text beyond this point is unclear and requires further information for correction.

The text includes mechanical BTs (360). A single 8-day study was conducted with one drop every 30 minutes and 18 hydrocasts over an eight-day period at 12-hour intervals, with XBTs in between. A 131-day current meter record from Benchmark including speed, direction and temperature at 20m and 200m has also been compiled. Data reduction of the hydrographic and bathythermographic data to geophysical numbers has been completed. The results are not fully analyzed but preliminary work has shown that small eddy-like features are common. These eddies have a horizontal length scale on the order of tens of miles and appear to be island wake phenomena, unlike the small eddies recently reported from POLYMODE work (Dugan et al., 1962). Examples of these eddies and meanders are shown in Figures 2,3,4 and 5. La Fond's method for determining the reference level was used (in Newman and Pierson, 1966). Using this method, we found the 500 4B level to be the reference level.

The hydrography results from the January cruise showed the surface baroclinic currents to be weak and variable with an average speed of 8 cm/sec. Below 100m, the flow was well organized to the west. A 10 to 15 cm per second maximum was found at 200m. The March cruise results again showed weak and disorganized surface baroclinic currents with maxima of 5 to 10 m/sec occurring below 100m and a well-organized westward current. South of Guayanilla Bay, there was a small anticyclonic eddy extending to at least 400m with a radius of about 10 nmi.

The May cruise results show two eddies embedded in the mean westward flow. One of these eddies, south of Punta Tuna, was anticyclonic and extended to a depth of 400m. The other, south

of Jobos Bay, was cyclonic and extended to a depth of more than 600m when referenced to the 1000 4B level.

In July, a well-organized eastward flow dominated the surface flow but became westward below 200m. September's results showed what appears to be a strong, but small, anticyclonic eddy south of Vieques. This meander or eddy extends to at least 400m.

The November cruise results once again indicated a westward flow below 200m with a weak, poorly organized surface pattern. In February 1961, there were signs of a subsurface anticyclonic eddy south of Vieques with maximum currents at 200m and a vertical range extending from 100 to 400m depth. The eddies observed in the results from the seven cruises are either subsurface or extend well below the Ekman layer depth; therefore, they are likely not wind-generated. They are not associated with water mass anomalies as in the case of POLYMODE eddies (Dugan, et al., 1982). Their length scale, 108 of nmi, is the same order of magnitude as the Windward Islands located upstream to the east of our survey area. Thus, it appears that they are an island wake phenomenon physically analogous to a Von Karmen vortex street. Such eddies have not been previously reported in the northeastern Caribbean Sea. This survey is the first with a station spacing on a grid scale precise enough in space and time to adequately define these mesoscale features. The surface dynamic height fields for May, July, September 1980, and February 1981 are shown in Figures 2-6.

Unfortunately, the text from this point becomes unclear, likely due to errors in transcription or scanning. The document appears to contain a series of page breaks and nonsensical sequences of numbers and letters.

The last paragraph suggests that another feature was observed for the first time. There seems to be a significant seasonality in the northeastern Caribbean. The mean dynamic height anomaly increases by 5 to 10 cm relative to the 500 dB level. This increase is such that the range of dynamic heights within cruises does not overlap (see Fig. 7). The observed increase in dynamic heights results in an increase in the potential energy anomaly. However, the final sentence of the text is incomplete, making it impossible to determine what change was observed.

The following text was recorded in July, September, and November of 1981 and was limited to the upper 500m. There was an increase in mean dynamic height and potential energy anomaly which was associated with increased salinities and elevated temperatures in the upper ocean during this time.

Time Series Studies were conducted on each of the seven cruises at one station, named Benchmark (Figure 1). This station was occupied for a period of 24 to 48 hours, during which hydrocasts were conducted to 1000m and XBT drops to 750m. In addition, two of the stations in the small-scale grid were also occupied.

This sampling scheme was designed to reveal temporal and spatial variability on a time scale of less than one day and a length scale of less than ten kilometers. The results of four of these surveys are shown in Figures 8-10. The results show internal waves with an amplitude of 50 to 80m at 700m and a period approximating an M2 tide.

To more precisely study the internal wave field, a study employing hydrocasts to 150m at 12-hour

intervals was conducted. Internal waves were again observed in the upper ocean isotherms and isohalines (Figures 11 and 12). These internal waves have a diurnal periodicity, M2, and appear to be superimposed on a general deepening of the isotherms and isohalines.

The apparent deviation in the main internal wave periodicity from an M2 to an M4 tide period may be an artifact of the sampling interval and the fortnightly variability of the tidal cycle. Observing the tides in San Juan on the north side of the island, one sees the fortnightly tidal cycle varying from no semi-diurnal inequality to a very pronounced one.

Semi-diurnal inequality (Fig. 13). If this tide were sampled on a 12-hour basis for eight days, it would be difficult to discern the true semi-diurnal nature over much of the cycle. Similar variations are possible in the internal tidal waves at Punta Tuna (Benchmark Station) on the south coast. If the internal tides develop a strong inequality in amplitude during the fortnightly cycle, a twelve-hour sampling interval for only eight days could miss the presence of the minor semi-diurnal component. The deepening of the isotherms and isohalines may be related to the advection of an eddy through the survey area. The February 1981 cruise in the seven-cruise sequence was conducted three weeks after the 8-day serial occupation. As can be seen in Figure 6, we see the surface dynamic height field at the time of the cruise. In the upper 200 m, the flow through Benchmark was eastward. South of Vieques, there was a cyclonic eddy between 100 and 400 m. If this eddy had been advected through the Benchmark site, this would have produced the observed deepening of the isotherms and isohalines. The Benchmark station was again occupied between July 11 and July 18, 1981. On this occasion, mechanical BTs were dropped at 30-minute intervals for eight days. The results of this sampling effort showed an internal wave field with peaks in the spectrum at 0.08 CPH and 0.6 CPH (Figure 14). The semi-diurnal variation in the thermocline was between 30 and 40 m at the maximum. Such variation is as large as that observed in the mean depth of the thermocline, seasonally. Superimposed on the M period internal waves are smaller waves of amplitude less than 5 m and a period of 0.6 CPH (Figure 14). At the start of the second 8-day serial occupation of the Benchmark station, on July 11, 1981, a current meter deployment was initiated from a ship anchored at this station. The current meters were deployed at 20 m from July 11, 1981 until November 17, 1981 and at 200 m from July 29, 1981 until November 17, 1981.

November 1981. Both meters were equipped to measure temperature as well as current speed and direction. The data tapes have all been visually examined by Fornshell and appear to contain a good record over the 131 days of the current meter deployment. The format of the data record is an analog chart of speed, direction, and temperature. These must be read manually in order to generate a digital data format which can be fed into a computer for automatic data processing.

The current meter data for the month of October have been reduced to geophysical numbers and Fourier analyzed by Jorge Capella. These data show a mean current of 4.98 cm/sec at 24.7. The mean speed is 14.79 cm/sec. The Fourier analysis showed that the variability was fairly evenly distributed with no more than 78% of the variability being accounted for by any time period between 14 days and twenty minutes.

This work is a part of the Marine Ecology Division's OTEC/OHER research and part of a Master's Thesis by Jorge Capella.

Test

SUMMARY

The reported research program in the Marine Ecology Division of CEER represents the first attempt to study the physical process of the northeastern Caribbean Sea on a space scale smaller than 100 km or time scale shorter than a long term, several years mean. The database for our 50 x 130 km survey area contains more station data than does Wust's (1964) Atlas. It contains the first measurement of the influence of internal waves on dynamic heights in the Caribbean. The current measurements are of fundamental value for their length and because they represent an unusual opportunity to look at currents in close proximity to the amphidromic point of the eastern Caribbean Sea.

The hydrographic and bathythermographic data analyses have yielded the following major findings:

1. The flow pattern most often observed is westward flow. Mesoscale eddies appear to be common features in this. The hydrography of

These mesoscale eddies indicate an origin as vortices shed by islands in the windward chain. There is a pronounced seasonality in the dynamic height field which is confined to the upper 500 m. Internal waves are a significant source of temporal variability in our survey area.

6. The largest internal waves are internal tides.

7. The internal waves may account for as much as 75% of the temporal variability in the dynamic heights.

These results have implications for the possible operation of an OTEC power plant in this area. First, our results show that there is a year-round 20°C+ thermal gradient between the surface and 1000 m at Punta Tuna. At times it is near 25°C. The ambient flow pattern is characterized by a mean flow towards the west at about 0.1 knots. Superimposed on this is a mesoscale turbulence composed of meanders and eddies. These appear at this time to be von Karman vortex-like eddies being generated by the Virgin Islands to the east of our survey area. Against the background of such turbulence, the effects of an OTEC plant on the mean flow will be undetectable.

The completion of this work will be documented in a series of scientific papers which will be submitted for publication to refereed journals. A partial list of the work underway at this time, with targeted journals and authors, is given below:

1. Sound velocity properties in the northeastern Caribbean Sea. Submitted to J. Phys. Oceanography, Dec. 6, 1982 - J.A. Fornshell.

2. Internal waves of M2 and M4 period at Punta Tuna, Puerto Rico. J. Geophysical Research.

3. Temporal variability in the water masses south of Puerto Rico. J. Physical Oceanography. J.A. Fornshell and J. Capella, P. Yoshioka.

4. The occurrence of a bi-seasonality in the potential energy anomaly and geostrophic energy anomaly. J. Physical Oceanography. J.A. Fornshell and J. Capella.

5. Seamount circulation dynamics. M.S. Thesis in Marine Sciences Department and probably a major journal article. J. Capella.

6.

"Dissolved Oxygen Distribution in the Northeastern Caribbean Sea" by J. Capella. Journal yet to be selected.

"Tidal Currents at Punta Tuna," J. Physical Oceanography by J. A. Fornshell.

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