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RESULTS OF A PROGRAM TO MEASURE

?THE TRAJECTORY OF WATER AT A DEPTH

(OF 100M SOUTH OF PUNTA TUNA, PUERTO RICO

?DECEMBER 1980

by

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CENTER FOR ENERGY AND ENVIRONMENT RESEARCH,

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RESULTS OF A PROGRAM TO MEASURE THE TRAJECTORY OF WATER

AT A DEPTH OF 100M SOUTH OF PUNTA TUNA, PUERTO RICO

by

GARY C, GOLDMAN

for

Center for Energy and Environment Research

University of Puerto Rico

College Station

Mayaguez. Puerto Rico 00708

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EXECUTIVE STATEMENT

As Puerto Rico is considered among the prime world

locations for a land-connected, Ocean Thermal Energy

Conversion(OTEC) electrical generating power plant, the

U.S. Department of Energy is looking at the oceanographic

conditions around the island. The main emphasis is being

directed toward Punta Tuna, on the southeast coast of

the main island.

?This document is in response to a project designed to secure oceanic water trajectory data from the Punta

?Tuna area in answer to where potentially mixed warm and

cold water effluent may go after leaving a full-scale

orc plant. ?The project provides for:

?The design and construction of deep-sea current

followers, or drogué

at 100 meters depth in the caribb

?A series of cruises, during a one year period,

to the Punta Tuna area in order to release and follow

the drogue!

?The analysis and interpretation of the results

of these water following cruises.

Recommendations for future studies of the Puerto

Rico OTEC oceanographic water current program,

?The final drogue design was a compromise between eas:

of field operation, sensitivity to the 100 meter depth,

and cost. ?The design is composed of a surface floatation

menber, with radar reflector, radio beacon, light beacon,

and flag, and a large two dimensional underwater panel,

unfurling similiar to a windowshade, and located at a

depth of 100 meters,

During the contract period, a total of eight cruises

were made to the Punta Tuna area to deploy and follow

these drogues:

to be sensitive to water motion

sat

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9 November 1979

28 January to 1 February 1980

18 to 22 February 1980

24 to 25 March 1980

7 to 11 May 1980

10 to 12 June 1980

24 to 27 June 1980

16 to 23 July 1980

?The cruise procedure was virtually the same for all but the first cruise. One or more drogues were deployed from a permanently moored vessel (conducting OTEC biofouling and corrosion studies) about 4 km southeast of Punta Tuna, Puerto Rico, over 1150 meters of water. The movement of the rogues was followed, relative to the moored vessel, as a function of time,from the radar aboard the vessel. at the conclusion of the cruises, the drogues were recovered using a second vessel. the first cruise differed from this procedure in that the moored vessel w:

as yet, and the tracking vessel was always changing location.

A total of 422 hours, spread over 24 days, were devoted to collecting usable trajectory data. During that ?time 13 drogues were launched, and the positions were ?observed on these drogues on the average, every 2 hours.

In 60% of the cruises, the 100 meter deep water

was moving clearly southwest, at least some of the time.

During 30 t of the cruises, the 100 meter deep water wi

moving northeast, at least some of the time. There was

Little long-term motion that was not along either of these

two directions. the water actually moved westerly

(225-314 deg-7) about 60% of the time, and easterly

(045-134 deg-7) about 15% of the time. ?The directionality

of the 100 meter deep water correlated poorly with the

surface water direction, the wind direction, and atmospheric

pressure changes.

not on location

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?There were two cruises during which the 100 meter deep water may have come into contact with the large island slope leading up to the shallow, south-central reef area, less than 10 km west from the drogue deploy area. However, at no time during the program was any 100 meter deep water seen to move directly northward from the drop-off site toward the active reef structure, just offshore from Punta Tuna. The water did occaisionally move northward, but only after moving eastward, past the eastern edge of the island.

Inertial motion was clearly evident at 100 meters, a: was an occaisional tidal cycle. Neither of these seriously altered any prevailing flow direction. ?There wa! apparent seasonality to the 100 meter deep water flow in this area.

Although during individual time intervals the 100 meter deep water was seen to move at up to 60 cm/sec, the cruise averages ranged from 5-23 cm/sec. The overall program average speed was 13 cm/sec, based on 192 observations. Ninty percent of the time the speed was less than 24 cm/sec.

Included in the recommendations, along with the suggestions for more long-term oceanic programs to help define any cyclic behavior, and integration between plant designers, flow modelers, and field-data collector: is the strong urging to develop usable predictive correlates to help anticipate changes in effluent flow patterns

during actual plant operations.

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tions for their help and support to create, develop, and

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De. Peter Duncan, of the University of California's Lawrence Berkeley Laboratory, was most helpful with frequent @iscussions and advice during the field and analysis phases of the study. Dr. Lloyd Lewis of the U. S. Department of Energy was instrumental during the conception and implementa tion phase of the progran.

A very special acknowledgement and thanks goes to Mr. Thomas Sadler of the OTEC Division of UPR/CEER. He gave in exhaustable help, time, effort, care, ané concern during the design, construction, and field phases of the study. Tom was truly the backbone of the program.

Finally, I want to thank the Puerto Rico Electrical Power Authority (PREPA) for their farsightedness and support as they originally integrated this study with their own oTEc activities so as to encourage us to gather an environmental understanding of the area in anticipation of an operational

orec plant in the future.

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?The purpose of this study was to improve the predicta: bility of the fate of potential effluent from an Ocean Thermal Energy Conversion (OTEC) plant, if it were situated in the deep, nearshore waters, southeast of Punta Tuna, Puerto Rico. An OTEC plant converts the thernal energy difference between the warm tropical surface water and the cold deep water into mechanical then kinetic energy, and finally into either electrical energy, or some energy-intensive by-product (Cohen, 1978). To orient the reader, this energy conversion | process is accomplished by using a large, but simple heat exchanger system. ?The system first cools and liguifies a working fluid (such as ammonia or Freon), then heats and vaporizes the fluid. ?The cooling is accomplished by pumping large amounts of water (about 1600 m/sec for a 400 MWe plant) up from a depth as great as 1000 meters, where it may have a tenperature of about 5°c. ?The heating of the working fluid is accomplished by passing surface water (a flow rate nearly equal to that of the deep water) past the working fluid's heat exchange area.

The surface water temperature could range from 25°C to 29°C.

?The sea water never comes into actual contact with the working fluid, but is drawn into the large heat exchanger areas where it is separated fron the working fluid by durable, high con- ductivity metal housings. The cooled working fluid moves from the condenser as a liquid, past a turbine (conversion from

thermal to mechanical/kinetic energy) into a vaporizor where

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it Se heated to the gaseous state and is drawn back into the condenser area again. The turbine is the mechanism that could turn the kinetic energy of the moving fluid into either electrical energy or perform work directly.

As this process proceeds, the warmed, or cooled (gina * Toriginar + 20°) water is then discarded back into the sea as effluent. The water may be either returned separatedly as slightly warned cold water and slightly cooled warm water, or the two effluents may be combined and returned into the sea as a mid~ temperature mixture, containing about equal anounts of the deep and surface water. This mixture would be released toward some mid-depth, depending on its final temperature and salinity (density) and mixed ratio.

There are numerous benefits and potential environmental hazarde with this OTEC type of energy conversion. Some of the benefits include: no air pollution, not dangerous to large population centers, theoretically limitless renewable energy source, uses the earth's tropical oceans as its natural solar collector, can be either near land for direct connection into a local power grid or offshore as in the case of an energy-intensive material production. Some potential hazards that may accompany such an OTEC plant are: working fluid (ammonia) leakage, oceanic navigation and security problems, biocide land heavy metal contamination through the effluent, ocean thermal changes, destruction of surface and/or deep water organisms, and upwelling of deep ocean water with considerable

nutrients.

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Tt is this last potential hazard that produced the con-cern that ultimately generated this study. If the effluent

of the plant contains a ratio of about equal quantities of deep and surface water, the new mixture will have a high nutrient level, compared to the usual normal tropical euphotic layers.

The deep ocean waters contain 10-100 times the available dis solved phosphates, nitrates, and silicates (that may be used for primary production) compared to the tropical surface waters. These tropical surface waters are usually nutrient-Limited as far as primary productivity is concerned, with the normal phytoplankton standing crop being much below that of nutrient-rich oceanic areas. The addition of large quantities of artificially upwelled nutrients, and subsequently possible increases in the phytoplankton population could cause considerable changes in the normal ecosystem by altering the standing crop of grazers and preditors, and by changing the turbidity of the water, reducing light penetration to the deeper organisms. Furthermore, this aforementioned mixed effluent would be cooler than the normal tropical euphotic waters {although possessing the sane density), causing additional stress on any affected organisms.

Tt is not within the realm of this study to evaluate or enumerate the ecological possibilities that might occur. Rather, the purpose of the study was to make some assumptions about the physical characteristics of a potential mixed effluent from a hypothetical oTEc plant that would be located

about 4 km southeast of Punta Tuna, Puerto Rico, situated in

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1150 meters of water, After considering the local parameters, it was concluded that the mixed effluent might be located about 100 meters deep. The scope of this report is to dis~ cuss the results of the current measurenents to determine the trajectory of this 100 meter deep water after it leaves the hypothetical OTEC site. As this site is quite near shore, and south and east of a rich, living coral reef complex, the moverent of this quantity of cooled, nutrient-rich water is of @eep concern to those who must decide upon the geographical

placement of such a plant.

1.1 BACKGROUND OF AREA

The following sections will help to describe an under-

stand the state of knowledge of the area southeast of Puerto

Rico and the potential OTEC site which encompasses the geo

graphical area covered during this study.

1.1.1 GEOGRAPHY OF AREA

?The Commonwealth of Puerto Rico consists of the main island (called Puerto Rico) and several smaller islands. These are all a part of the Antilles Chain of islands, which extend

from Venezuela to Florida (see Figure 1). The Antilles Chain

serves as the practical boundary between the Atlantic Ocean

to the north, and the Caribbean Sea, tothe south. Puerto

Rico is situated near the center of the Chain, considering

both geographical location and relative size. As its location

of 18° N, Latitude and 65° w. Longitude, Puerto Rico is con-

sidered subtropical, and is affected by the east-to-west trade

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wind belt. The rainfall is relatively light from early winter

to late spring, and much heavier during the rest of the year.

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

The surface waters surrounding the island could be typified as having biseasonal characteristics also. During the summer/fall season, the surface waters are usually warmer, with lower salinities. In the winter/spring season, the op-posite is usually the case. If there is any seasonality to the subsurface waters, it has not been reported as yet.

From a geological standpoint, Puerto Rico, Hispanola, and the Virgin Islands, are emergent points of a rock mass which forms the Eastern Greater Antilles Ridge. This riage rises more than 5 km above the floor of the Caribbean Sea to the south, and 8 km above the bottom of the Puerto Rico Trench to the north. ?The ridge branches to the east, forming the Anegada and Virgin Islands Troughs. The deep Windward Passage to the west, between Hispanola and Cuba, forms the western edge of the ridge. The Mona Passage lies between Puerto Rico and Hispanola, and is about 100 km wide. This passage has a naximun depth of less than 600 meters, with mich of the area less than 100 meters deep. Another shelf, the Virgin Island Shelf, extends 150 km east of Puerto Rigo, with all depths

of this second shelf less than 50 meters.

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North of Puerto Rico, the Greater Antilles Ridge is separated from the Atlantic Ocean Basin by the Puerto Rico ?trench, the deepest area in the Atlantic Ocean, The trench runs east-west, and is about 150 km north of Puerto Rico.

South of Puerto Rico lies the Venezuela Basin, the middle deep basin in the Caribbean. However, between Puerto Rico and this basin of about 4000 meters depth, lies the Muertos Trough, or the Dominican Trench. The trench also runs east-west, and exceeds 5000 meters depth in some areas. ?This trench is less than 100 km from Puerto Rico.

on a smaller scale, the bathymetry of the area south of Puerto Rico can be seen in Figure 2. There is a 15 km wide shallow shelf south of the central part of the island. where this shelf meets the steep drop-off, so typical in these waters, lies a healthy, living reef, running most of the distance fron

?the east coast, along the south coast to the Mona P age. In

the area near Punta Tuna (at the southeastern "corner" of the island), the reef is about 1/2 km from shore, and in places rises to the surface. This reef and its associated shallow water organisms form the island's shallow water/deep water boundary along virtually the entire south coast. The drop-off Line actually turns southward about 30-40 km west of Punta Tuna, leaving the shoreline to follow the edge of the wide shelf.

A group of shoals (one of which is the Grappler Bank) Lies about 20 km south of Punta Tuna. Between this shoaling area and the reef is a rugged, 45° downward slope to about

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2000 meters depth, and then a very flat plain, The plain connects to the Anegada Passage to the northeast and stops in a "box canyon" to the west, with a rise up to about 1500 meters

depth.

1.1.2 WATER MASSES

?The water masses in the Caribbean have been discussed by many authors (Wust, 1964; Parr, 1936 and 1937; Atwood et al., 1976; Craig et al., 1978; Lee et al., 1978; Hernandez Avila et al., 1979; Goldman et al., 1979), but for completeness, ?they shall be mentioned again as the source, depth location, movement, and characteristics of these water masses are important to the understanding of the results describes in this report.

?The upper water mass is called the Tropical Surface water (TSW) (see Figure 3). The origin of this water is under the Equatorial Atmospheric Trough (low), which is a tropical rain belt located to the northeast of Brazil in the Atlantic Ocean.

?The TSW is influenced both by heavy precipitation in that. area

and by the massive runoff from the Amazon and Orinoco Rivers.

?This water mass is ériven by wind and coriolis into the

eastern Caribbean Sea through passages in the Lesser Antilles

island chain. As the water. mass continues to move under the

wind stress of the predominant easterly winds, the water is

moved northwest toward the Yucatan. By the time it reaches

Puerto Rico, the temperature and salinity of this upper water

mass has been further affected by the general and local cli-

mate of the area through which it has passed. Additional

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SURFACE TROPICAL SURFACE WATER (TSW)

80-100 » ??_?______ S=(33-36 ppt) T=(25-29° ¢)

SUBTROPICAL UNDERWATER (SUH)

S=(36,8-37,2 ppt) T=(20-24° C)

200 «»

TRANSITION ZONE (1Z)

S=(35-36.8 ppt) T=(7-20° C)

ANTARCTIC INTERMEDIATE WATER

(aw

$=(34,8 per) (6-79 0

TRANSITION ZONE

S=(34,8-35 ppt) T=(5-6° C)

VENEZUELA BOTTOM WATER (VBW)

S=(35.0 ppt) T=(4-5° ¢)

Figure 3, Caribbean Sea water column structure south of

Puerto Rico

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precipitation and runoff (although slight), evaporation from

wind and insulation could further influence both the tempera~

ture and salinity. In the TS the salinity generally ranges

?from 33-36 ppt, and the temperature generally ranges from 25°C to 29°C. This water mass appears to be wedge-shaped, attain~ ing its maximum depth along the northern Caribbean, due to ?the geostrophic subsidence as the water moves westward. The local depth of the water mass may be influenced by atmospheric pressure as well. Normally, atmospheric pressure changes lit~ tle in this area, with a change of 3-6 mm of mercury within a month being considered large. However, as a tropical pressure trough moves through the Caribbean, the pressure is severely reduced, causing the water level to be raised, pushing the upper water mass to the side, and upwelling the cooler, more saline water mass below. This upwelling would occur during a hurricane and, to a lesser degree, during a tropical wave or a tropical storm, The effect on an operating OTEC power plant could be at least to severely reduce the plant's already low operating efficiency, in the case that the plant had not al- ready been shut down.

?The water mass directly beneath the TSW is called the Subtropical Underwater (SUW). This lower water mass (Figure 3) originates directly beneath the Bermuda atmospheric high Pressure zone. The Bermuda High is the atmospheric downwelling component of the Hadley cell which gives rise to the Equatorial Atmospheric Trough, which in turn is related to the origin of

?the TSW discussed above. The air under the Bermda High is an

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generally warm and ary. Due to the lower relative humidity, evaporation is great and the salinity is increased. This water mass contains the most saline water in all the Caribbean.

?The SUW descends to form the upper portion of the thermocline in the Caribbean. The salinity within the SUW does not vary much (36.8737.2 ppt) because the water rarely comes into con-tact with any diluting agent. During conditions of low atmospheric pressure, this water is drawn upward, as evidenced by the high salinity seen at or near the surface during these occasions.

?The temperature range within the SUW is 20°C to 24°c. Due to thermal conduction, the temperature does not remain as invariant as does the salinity. The density difference between the TSW and the SUW is usually about two sigma-t units, which 4s large enough that the two remain distinct water masses.

?The SUW moves southward from the higher latitudes near Bermuda and enters the Caribbean through passages along both the north and east under the faster moving, more turbulent TSW. From these passages, the water moves generally southward or westward, or both, to spread throughout the entire Caribbean beneath the TSW. Near Puerto Rico, the water enters the Carib~ bean southward through the Anegada (east of P.R.) and the Nona (west of P.R.) Passages. The core of this water mass general- ly lies at about 125-150m in the Caribbean near Puerto Rico.

Below the SUW lies a Transition Zone (Figure 3) of in- distinct characteristics. The Transition zone contains the

lower portion of the thermocline, and extends into the cold

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water sphere. This transition water is a mixture of North

Atlantic Central Water and diffused and diluted Mediterranean

Water. The salinity ranges from about 36.8 ppt, from the water mass above it, down to about 35 ppt. The temperature range is from 20°c to 70c, This Transition zone extends from a depth of about 200 m down to about 600 m, Just below this zone

Lies the oxygen minimum, which many people define as the boundary of the cold water zone inthe oceans. This transition water enters the Caribbean from the north and from the east, and probably moves southward and westward.

?The Antarctic Intermediate Water (AIW) is found just below (600 m- 800 m) the Transition Zone. This water is formed in an area where precipitation far exceeds evaporation.
?The AIW 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 Anedaga Passage, and the Windward Passage, between Cuba and Hispanola. These latter deep sills may also form a path of departure from the Caribbean for the AIW that has entered through the Lesser Antillian Passages. This water mass spreads to cover much of the Carib-bean Basin, The movement of the AIW near Puerto Rico could be either south and west (having entered either through the Lesser Antilles or the Anegada Passage) or even north and east (departing through the Anegada or Windward Passages). As the water has moved northward through the Atlantic, it has been in contact with higher salinity water, therefore, the

salinity of the AIW as it passes Puerto Rico is no longer the

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Séppt of its origin, but rather about 34,8-34,9 ppt. The tempera~

ture is 6° to 7°.

A second Transition Zone can be found from 800 neters down to 1000 meters depth. ?This thin zone is the transition between the AIW and the North Atlantic Deep Water (NADH).

From about 1000 meters depth down to the bottom of the Caribbean Basin the water has most of the characteristics of the NADW. ?This water mass is formed in the high northern latitudes, and while descending both in depth and latitude, it entrains some of the Mediterranean water, thereby increasing its salinity, density, and depth even more. The water enters into the Caribbean only through the deep sills of the Windward and Anegada Passages. The water moves mainly westward from the Windward Passage, but south and west from the Anegada Passage

80 as to fill all the deep basins in the Caribbean. This water is characterized by 4-5°C temperatures and a salinity of 35ppt. After this water mass has moved into the Caribbean, it is virtually trapped, with only a small passage out through the Yucatan Strait. The water remaining in the Basin is slightly different in silicate content from its origin, the NADW, found outside the Caribbean Basin. For this reason, some people choose to call this deep, cold water mass the Venezuela Bottom Water (VBH). In some areas of the Caribbean

Basin, the NADC (or VBW) is over 3000 meters thick.

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1.2.3 TIDAL acriviry

The dominant tidal action along the northeast coast of

Puerto Rico is caused by the amphidronic system that has its node in the North Atlantic. This system produces a semi-Giurnal tide, and is easily seen at San Juan, where reliable height predictions are available (U.S. D.0.C., 1979). The same activity also continues don the east coast of the island. The tidal motion along the south coast of the island, however, is a manifestation of the system with its amphidronic point in the north-central caribbean, just south of Puerto Rico. This second system produces a diurnal oscillation along the south coast, with a week semi-diurnal component (liernandez Avila et al., 1979). The waters at Punta Tuna may be affected by either, or both of these systems, as both the west coast and the south coast activities could produce a visible in~

fluence on the waters at our study ar

Evidence of a tidal presence in the area has been clearly seen in the works of Lee et al. (1978), where sharp current reversals were seen off St. Croix, V.I., during a spring tidal period, and vertical fluctions of temperature, salinity,

etc., were also seen on a diurnal and semi-diurnal basis. The best available evidence indicates that an ebbing tide at Punta

?Tuna produces an easterly current.

1.2. WATER CURRENTS

Although very few water current measurements have been

made in the Caribbean, the general circulation has been

described by wust (1963), Worthington (1971), Gordon (1967),

as

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Sturges (1965), and Perloth (1971), among others. Sunmaries of their discussions and the results of the few measurements in the area will be discussed in this report for completeness.

?The Caribbean (surface) Current is a warm, westward flow which is formed from the junction of the North Equatorial cur- rent and the Giuana Current. Most of the water for the Carib- bean Current enters the Caribbean Sea through the straits of the Lesser Antilles. As the water passes across the Caribbean, the main flow crosses the Jamaican Ridge, southwest of Jamaica, moves west through the Cayman Basin, and into the Gulf of Mexico by passing through the Yucatan Strait. From this point it becomes part of the Florida current (Burns and Car, 1975).

?The Caribbean Current does display some seasonality with speeds reaching a maxinum at the surface in the summer and a minimum in the fall.

1.2.1 WATER CURRENTS - HISTORICAL

Very few water current measurenents have been made near Puerto Rico. Surface drifters were used by Duncan et al. (1977), Metcalf et al. (1977), Metealf and staleup (1974), and Bane (2965). Current meters both moored and over-the-side, vere used by Burns and Car (1975), Lee et al. (1978), Goldman et al. (1979), Oser and Freeman (1969), and Ostericher (1967).

In virtually all the surface drifter studies mentioned above, the drifters moved westerly. There have been variations, such as northwest or southwest, but always westerly. The

surface waters of the Mona Passage, for ?example, oscillate at

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more than 50 cm/sec north and south with the tidal flow. But this simply gives a north or south component to the strongly predominantly westerly drift.

In the results reported by Burns and Car (1975), three arrays of current meters were moored near Puerto Rico;

Array #11, Array #14, and Array #14A,

Array #11 was set in 1975 meters of water at 17°50.9'

N. Latitude, 65°47.6' W. Longitude, which is about 18 km south-southeast of Punta Tuna. This array had reported results from only the 220 meter depth meter. About 75% of the directional observations with this meter showed the water moving between southwest-to-northwest. The speeds ranged from 5-35 cm/sec, with the average speed about 16 cm/sec. This water would be located near the top of the Transition zone, beneath the sow.

Array #14 was set in 1915 meters of water at 17°52.9' N, 65°54.6" W, or 12 km south of Punta Tuna. Although there were five reported depths for this array (100m, 105m, 610m, 1905m, and 1910m), the results of the upper two shall be combined for this discussion, as will the lower two, The water at 100 meters depth moved westerly 60% of the time. virtually all the speed observations were less than 20 cm/sec, with an average of 5 cm/sec. These meters were usually in the SOW. The water at 810 meters depth (the lowest portion of the AIW) moved toward the west about two-thirds of the time, and the speed observations were all less than 15 cm/sec, with the average

value being 4 cm/sec. The bottom water, at 1900 meters depth

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(vw) moved primarily northeast or west. The speed averaged |
less than 1 cm/sec.

?The third array, #14A, was moored in 1430 meters of water at 17958.4' N, 65°37.8' W, or 27 km east of Punta Tuna. There were four depths reported for this array; 240m, 605m, 1335m, and 1420m, The 240 meter deep water (probably just be~ neath the SUW) moved westerly virtually all the time, having an average speed of 8 cm/sec. ?The water at 605 meters (upper portion of the AIW), was seen to move primarily northeast_

to-northwest at an average of 5 cm/sec. ?The deeper water (vBi) moved either northeast-to-east or southwest-to-northwest at even slower speeds.

Oser and Freeman (1969) report the installation of two deep-water current meter arrays in the area during December 1968. The arrays were located between the island of Vieques and Punta Tuna, and were in 100 m and 1500 m of water, re~ spectively. The generalized reported results of these arrays are that the upper waters (about 300 meters depth) showed up to 25 cm/sec at maximum speed, and was moving primarily wester- ly. One meter at 600 meters depth showed a maximum speed of about 50 cm/sec, with a primary direction indicated as north~ east. The 1000 meter deep water showed itself to be moving northwest and east, and had a maximum speed of 15 cn/sec.

Ostericher (1967) also reports both current meter and @rogue measurements that were made just south of Punta Tuna in 1967. The current meter results are not given in the

report, by the drogue data indicate a westerly or southwesterly

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drift in the surface waters during the six hours of observa~

tion.

Lee et al. (1978) reported over-the-side current meter results from a moored vessel over about 3600 meters of water, while located 15 km north of St. Croix, V.I., at about 17°52" N, 64°41' W. The water motion was measured during the sunmer of 1977 at 10 meters depth at least daily (when possible), and frequently bihourly. These results indicate a strong easterly drift for about 2 weeks, then about 2 weeks to the west. After that time, for one week, a strong diurnal east-west reversal was seen, corresponding to a spring tidal period. After this period, for about one month, the currents were variable in direction, with some tidal influence visible. Another

easterly drift occurred after about 1) weeks. This second easterly flow lasted 3-4 days, then degenerated again.

?Typical speeds of 25-50 cm/sec were seen throughout the measurement period. Also, during this measurement period,

a single current profile was taken in September, 1979. During the profile, the TWS was moving southeast, the SUW moved north-west, and all the rest of the water column, down to 800 meters, moved westerly. The water in the Transition Zone between the

AIW and the VBW ws

moving northwest. ?The speeds generally

decreased from about 20 cm/sec near the surface to 10 cm/sec

at 1000 meters depth.

Goldman et al. (1979) reported the results of over-the-

side current meter profiles and one current meter array. The

profile results were taken bimonthly from August 1978 until

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June 1979 at 17057.6' N, 65°51.9'' W (4 km southeast of Punta

Tuna) while moored at an OTEC DOE/UPR mooring site for bio-

fouling ana corrosion studies over 1150 meters of water. The

profiles were measured four times in one day during each of the

six cruises. The upper water (25m-S0m-~TSW) was seen to move

usually toward the west or the east. The average speed was

10 cm/sec. ?The SUW (100m-150m) usually moved westerly, with

some easterly motion. The average speed at this depth was

8 cm/sec. The Transition Zone (250m-500m) moved almost ex~ clusively westerly, with an average speed of 7 cm/sec. The AIW (650m-750m) moved in either northwest or northeast direction at 5 cm/sec.

?The current meter array reported by Goldman et al. (1979) was moored at 18002.2'N, 65°39.7'W, or 15 km east of Punta Tuna, ?The two reported depths were 215m and 332m, with a total water depth beneath the array of 1216 meters. The 215 meter deep water moved in all directions, with a very slight preference toward the east and the west. The average speed was 7 cm/sec. The deeper water (332 m) had the same general direc-

tional motion, with an average speed of 5 cm/sec. These meters

were probably measuring the upper water in the Transition zone

between the SUW and the AIW.

1.2.2 WATER CURRENTS ~ SUMMARY

In summary, the following are the directional flows seen in the historical records for the components of the water column in the Caribbean Sea, southeast of Puerto Rico.

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?Phe Tropical Surface Water (TSW) has almost always been seen to move westerly or easterly, with very little north or, south component.

?he Subtropical Underwater (SUM) has been seen to move basically westerly, and occasionally easterly.

?The Transition Zone between the SUN and the Antarctic Intermediate Water (AI) has been seen to move almost always westerly.

The AIW has been observed to move past the area toward virtually all directions of the compass.

?The Transition Zone between the AIW and the Venezuelan Botton Water (VBW) is documented as always moving westerly.

?The VBW has been seen to move past southeastern Puerto

Rico toward either the northwest or the northeast, with sone

easterly observations.

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2.0 EQUIPMENT AND PROCEDURES

?Phe following sections contain the progrannatic and hard-

ware design criteria as well as the actual description of the

final hardware and the experinental techniques used during

this program.

2.1 LAGRANGIAN VERSUS EULERIAN

?The U.S. Department of Energy, as one of its near-term
goals for the OTEC program, has to define the extent of an en~
vironmental insult that might occur as a result of the emplace
nent of a full-size (100+ ?) OTEC power plant at any of the
more suitable sites. One aspect of this investigation is to
look at the effects of the effluent from the plant if the two
intake systems were mixed together prior to their being ex-
pelled from the plant.

?There are a variety of methods that could be used to study the fate of such an effluent. However, some assumptions must te made before any particular experimental technique is @ecided upon. ?The effluent shall be assumed to be departing from the plant so that it will settle at the 100 meter depth. ?This means that the density of the water, that combination of temperature and salinity, will be be such that it will be equal to the normal 100 meter depth density, although the temperature ané/or salinity of the effluent will most probably be cén~ siderable different from that at 100 meters depth. This 100 meter depth condition will probably be true some time, with both shallower and deeper conditions also possible. It is

also assumed that the effluent shall be originating at or near

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the ?OTEC area* to the southeast of Punta Tuna, Puerto Rico.

?The currents in the area are poorly known from an en~ vironmental impact point of view, and the circulation is even more poorly known. It was felt that, while current meter ar~ rays were already being placed inthe area to determine flow characteristics throughout the entire water column for a variety of uses, the particular type of neasurement needed for this program was a lagrangian measurement that actually followed a typical water parcel that left the OEC site at the 100 meter depth.

An eulerian (point-type) measurement, such as a current meter, is not as meaningful in this case. The speed, direction, and trajectory of the effluent was considered to be so poorly

understood, that very little could be predicted of the circul:

tion of this 100 meter deep water after it left the site. various types of Lagrangian measurements were considered, such as dye, Swallow floats, bic/chemical tracers, radio-active tracers, and deep-sea drogues. The dye technique, as were the bio/chemical and radio-active tracing, vas eliminated due to cost, ship time, and the potentially low dilution rates. Swallow floats had to be discarded at this tine due to their high cost, although they are probably the most useful compro~

nise for vater-parcel tracking. The deep-sea arogue concept was adopted, as it could be easily combined with other local operations, thus minimizing cost while maximizing the scientific returns and not sacrificing many of the useful characteristics

of the other techniques.

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2.2 DROGUE DESIGN CRITERIA

After the decision was made to use a Lagrangian-type of measurement in the form of deep-sea drogues, the following design criteria were accepted to determine the design of the hardware, the materials, and the experimental procedures.

1. The design of the hardware for the érogue and its

basic components were to have already been proven as functional, reliable, and suitable for this program's needs. There was no allocation in the program for even a modest experimental or developmental phase. A literature survey was made, however, to help evaluate the variety of potential design concepts.

2. ALL hardware used for the construction of the érogue and any ancilliary equipment must have already been proven to be materials that were suitable for thelr proposed use. Again, no material testing program was anticipated, due to the time and resource Limitations. Therefore materials, their capa-bilities, assembly, and use, must be known before they were incorporated into the drogue design.

3. Al hardware to be used at sea must be deployable an@ recoverable fron the available 13 meter long ship-to-shore vessel under reasonable sea conditions. As a droge tracking operation is time-intensive, the availability of a large, chartered vessel to be on-call during the entire cruise operation was prohibitive. ?Therefore, by compromise with the DOE/OTEC Biofouling Group and the UPR/CEER OTEC Division, all field operations that were to be accomplished by this trajectory

Program would be in concert with the already operating Biofouling

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and Corrosion study at the Punta Tuna site, The Biofouling and Corrosion study had, as part of its daily operation, the use of the 13 meter ship-to-shore vessel, along with the moored mother ship. The use of these two vessels would minimize cost and simplify operations for the drogue tracking study.

4. The Grogues were required to be sensitive to the water motion at 100 meters depth (or any other subsequently chosen reasonable depth). In satisfying this criterium, the assembly was to have little air or wind/water-surface drag, compared to the drag at the 100 meter depth. ?This requirenent would apply to any lagrangian measurement (or virtually any type of measurement, as high signal-to-noise ratio). ?The wind at Punta Tuna averages about 5-10 m/sec, with frequent higher gusts, and as the wind may be moving in a direction different from that of the 100 meter deep water, this "sail effect" mst

be minimized. Furthermore, the water current at the surface frequently moves at high speeds, and in different directions from that at 100 meters. Therefore, any error due to this velocity shear mist also be minimized.

5. The field equipment is subject to the usual location/ positioning and cost constraints of a modest program, such as this. Therefore, sophisticated techniques were not anticipated, if not already available in-house. Conventional techniques and equipment were acceptable, if they were already part of the available capabilities.

6. The equipment and procedures were to be useable

for a period of about one year, the length of the program, The

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program length and resource constraints limited the Life-
expectancy of the equipment to this period. A further

extension of any equipment capabilities could result in a Severe rise in cost and design time, neither of which wae

necessary to accomplish the programmatic goals.

2.3. HARDWARE DESIGN

In an attempt to satisfy the above criteria for the deep-sea drogues, the final design is but a minor modification of the basic design of Terhune (1965) or Monahan (1975).

?This design, as seen in Figure 4, consists of three of the usual drogue components: a surface buoyancy/locating menber, a deep-sea motion-sensitive surface, and a connecting line between the two. |

?The subsurface, jnotion-sensitive surface is a large, flat sheet or window-shade shaped panel. The panel is made of 0.15 mm (§ mil) thick plastic sheeting, about 6 meters wide by 15 meters deep. The panel is weighted by a heavy pipe at the bottom to keep it firmly extended downward. The top is supported in the open position by a lighter pipe. To pre~

vent excessive vertical stress on the plastic, vertical lines

are tied top-to-bottom from the ends of both pipes. The lines

are cut to be slightly shorter than the panel, so the lines,

not the plastic, will hold the weight of the bottom pipe.

The panel is then kept open to its full area but feels very

Little of the weight of the heavy bottom pipe.

?The panel assembly is attached through a multi-connection

yoke to the 6.44 mm (1/4 inch) diameter nylon connecting line

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DROGUE PANEL

Figure 4, Final drogue design

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that extends up to the surface member.

The flotation component of the surface assembly con-

sists of a 1.2m by 1.2m by 0.15m (4 t by 4 fe by 1/2 £e)

Piece of molded styrofoam, originally designed as insulation

for walk-in refrigerators and freezers. The styrofoam is sandwiched between pieces of plywood. Resin and epoxy cover ?the entire flotation assembly to minimize abrasion, breakage, ?and water contact. This assembly 1s designed to float about mid-way out of the water, with the large cross-section facing up and down, presenting the minimum drag surface to the air/ water interface. A six meter long mast is connected vertically ?through the float at about the mid-point of both the float and the mast. ?The subsurface portion of the mast is weighted near its bottom to maintain good vertical stability, even with ?the connecting Line and subsurface panel, and its associated ?rag (and downwara force) not present. The uppermost portion of the connecting Line from the panel is attached to the mast immediately below the weights. The upper portion of the mast contains a 1 meter by 1 meter brightly colored flag, two radar flectors, a continuously flashing beacon light, and a continuously transmitting radio beacon. All these devices on the mast are used to help locate the float and drogue beneath ate ?

In order to evaluate the relative success of this design with regard to the design criteria, the following comparison is made: .

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1. Proven design: The pattern and tests for this

?window shade" design were reported as early as 1965 (Terhune, 1965), with actual use of such a pattern extending back as much as 400 years (Monahan and Monahan, 1973).

2. Proven hardware: This design uses no material or component that has not previously Been used for either our in tended use directly, or one similar.

3. Operation from a 13m vessel: This particular over-all design was chosen because the panel can be easily renoved from the free-floating surface assembly, then can be rolled up on either of the to supporting pipes, much as a window shade rolls onto its roller. Also, using this technique, the entire drogue can be conveniently deployed from the small vessel by placing the surface member into the water, then, after connecting the line between the float's mast and panel,

simply unroll the panel into the water. Recovery is accom-

plished by simply reversing the procedur

4. Sensitivity to 100m depth: Briefly, the area of the panel is about 100 times as great as the conbined cross~ sectional areas of all the other elements of the drogue. Under the most severe conditions, this will easily satisfy the re~ quirement that the trajectory of the entire assembly will, in fact, move with the water parcel at a depth of 100 meters.

5. Positioning/locating techniques: The use of a radar system, complimented by both hand-bearing compass and/or

horizontal

xtant readings, maximized the available in-house

capabilities.

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6. One year life: Although the equipment is not neces~ sarily heavy duty, care was taken in chosing the component materials t6 insure a reasonable and rugged life. The projected weak Links in the equipment durability were the mast flexi- bility, the upper panel supporting pipe, and the panel, itself. Experience proved us correct, and the appropriate steps were taken during the program to correct any weaknesses as they appeared. The radar gave us problems, but these appear to be due to the particular instrument, rather than the model or

design.

2.4 EXPERIMENTAL PROCEDURES

With few exceptions, the following procedures were used @uring the field and data processing aspects of this program.

?The field operations revolved aroudn the mother ship, the LcU-1470, This vessel is under contract to the UPR/CEER by the U.S. DOE to perform Biofouling and Corrosion studies while moored in deep, nearshore water off Punta Tuna. The taut-Line mooring in 1150 meters of water gives the mooring buoy a possible 0.5 km radius excursion-circle at the surface. ?The mooring is located at 1757.6" N, 65°51.9' W, about 4 km southeast of Punta Tuna. Because the vessel did not appear on station until mid-January 1980, the first cruise of this Program was conducted from aboard the R/V SULTANA during the course of its CEER-Punta Tuna operations in November 1979. Subsequently, all drogue operations used the LCU and its as~ sociated ship-to-shore vessel.

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The LCU-1470 (Landing Craft Utility) is 35 meters long, 10 meters wide. ?The ship-to-shore vessel is 13 meters long, and made at least one daily round-trip excursion between land to the LcU, when possible. During our round-the-clock opera~ tions, the ship-to-shore vessel was used primarily for drogue recovery (during the daylight hours) or for sextant or hand-bearing compass positioning, if the drogue had travelled beyond the range of the radar aboard the LcU.

Prior to deployment from the LCU, all the érogue compo- nents and auxiliary equipment were checked for good repair and proper operation. The connecting line (running from beneath the mast to the panel) was premeasured to insure that

the mid~

jepth of the panel was set at 100 meters, a depth not varied purposefully throughout the program. All components of the drogue were then collected on the deck of the LcU.

The mast was placed into the water first. However, before its launching, all flags, radar reflectors, radio bea cons, lights, and lines were suitably attached and made operational.

The next step was the unrolling of the drogue panel, a three-man operation. with the panel fully unrolled and connected to the mast via the connecting line, the panel was released to descend to its present depth. At this point, care was taken to try to prevent entanglement between the con necting line and panel, and any sub-surface lines or equipment near the LCU. Occasionally this entanglement did occur, and

the necessary corrections were made, if the fouling was noticed.

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From this temporal point in the procedure, all tines were recorded, such as deployment, position fixing, and re~ covery. All times were noted as local time (Atlantic Standara Time - A.S.7.).

?To obtain the location of the drifting drogue (position fixing), the radar aboard the LCU was employed, when possible. ?This radar is a Raytheon, Model 3100-MKII, with distance (range) scales of 0.5, 1.5, 3, 6, 12, and 32 nautical miles and a probable error on each range of 40.05 km, +0.25 km,

40-6 km, #1.1 km, and +3 km, respectively. The range data from the radar was observed and recorded in nautical miles, then converted to kilometers during the data analysis. the direc tion from the axis of the ship to the arogue (bearing) was determined from the radar, and was readable to +1 degree, with an overall probable error of +5 degrees. ?The viewing screen of the radar was 17.5 cm in diameter. To accurately locate a remote object, the radar was first used to observe two known terrestrial locations? so as to fix both the location of the Lc and its orientation with respect to true north (deg). The radar was then used to make a range and bearing measurement to the drogue. These two sets of measurenents, the fixed loca~ tions and the drogue, had to be made within only a few seconds to insure the sane relative orientation of the LCU to the land points and the drogue, as the vessel was always swinging from its mooring line. This procedure was repeated from the time

of deployment until recovery at intervals of .5-2 hours, or
longer, depending on the conditions of the radar and the
availability of personnel.

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On the few occasions where the drogue was beyond the 10 km range of the radar (the range is forshortened because of the low height of the drogue mast), the radar was out of order, and the ship-to-shore vessel was available, this small vessel was used to determine the location of the drogue. The vessel was brought to a position near the float/mast assembly of the drogue. From the deck of the ship-to-shore vessel, prominent land features were chosen that were both easily identifiable and locatable on both the charts and by either a hand-bearing compass or a horizontal sextant. In the case of the hand-bearing compass, the bearing (relatable to magnetic north) was determined to as many of the landmarks as possible. Using the horizontal sextant, the directional distance, in absolute degrees, was measured between at least three different landmarks. As this procedure from aboard the ship-to~shore vessel involved more in-the-fiela errors, the technique was reserved only to extreme cases.

A typical radar data sheet is shown in Figure 5. The data sheet shows the radar range and bearing values to known land locations (i.e., Punta Tuna, Punta Yeguas, Punta Toro), the range and bearing to the drogue, time, date, wind speed and direction, and surface current direction.

?The actual location plotting is done on a chart, #25659- Punta Maunabo (W.0.S., 1975), with a scale of 1:20,000, or lem = 0.2km, A three-arm protractor has its two movable arms set to the bearings toward the fixed land points. after these

arms are set on the chart range to both locations, the origin

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of the protractor then locates the ICU, and the non-movable arm of the protractor faces the direction of the radar "zero" bearing. The angular scale of the protractor is now showing the bearing to the drogue, and the range is measured from

the origin, using the proper scale. The distance to each successive point and from Punta Tuna?are taken from this chart,

and all the distance and direction information is caléulated and thon transferred to a chart with a scale of 1:100,000 for ease of display. In a few cases, either the subsequent transfer had to be further reduced, or the trajectory was so short as

to eliminate any need for changing the scale from that of the

original chart.

2.5. ERROR ANALYSIS

?There are a variety of errors that are encountered during this type of measurement and analysis program. As with all measurements, an attempt is made to minimize those errors over which there is some control, understand and acknowledge the systemic errors and, finally, chose the measurement procedure, equipment, and analysis method to optimize the compromise between accuracy, efficiency, cost and time. ?The procedure, described previously, is such a compromise. The final results of this program can then be evaluated after taking into consideration, that these results may include a combination of various errors, The major errors will now be enumerated and Aiscussed, with quantitization indicated, where possible.

The final product of this program-is to produce knowledge

regarding the trajectory of the water moving past Punta Tuna

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at 100 meters depth. Therefore, the results shall be a drawn trajectory that 48 made up of a series of connected vectors. Bach vector shall deseribe the speed and the direction of the water during @ specific time interval, These results are created fron a series of basic measurenents, Calculations are then performed, and the values aré plotted onto a chart. to describe the motion. However, the actual speed and direction are not the prinary product of this method, they are a final Product and, therefore, are based upon all the previous results (and the associated errors) leading up to the mathenatical determination of the speed and the direction. A nore accurate description of the data analysis is seen in Figure 6. ?The basic measurenents are "DISTANCE" and "DIRECTION" to the various points (landmarks and the drogue) from the vessel that is secured to the buoy. The buoy is moving relative to the un= known, also. Tt 9 acted upon by various forces, both at the water surface and along its anchoring line. the vessel. (the 120) 4s also moving relative to the bioy, twisting, swaying,

and swinging on its mooring line. All these various factors must be taken into account to determine both the desired results

of this study, and a true estimate of the accuracy of those

results.

The major mileposts along the measurement and analysis

path (assuming the typical experimental procedure) are

1. Time Measurenent

2. Range Measurement

3, Bearing Measurement

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4, Position Determination of the LCU

5. Position Determination of the Drogue ~ the Trajectory

6. Determination of the Elapsed Direction

7. Determination of the Elapsed Time

8. Determination of the Elapsed Drogue Travel

9. Determination of the Drogue Speed

?Time Measurements - This is a primary measurement, usually

read from a single, hand-held clock or watch during the course of the cruise. As the reading of range and bearing to the ?two landmarks and to the drogue may take about one minute (60 sec), and the watch is readable to +1 sec, the estimated error shall be indicated as 430 sec. The relative percentage of this error will change, depending on the elapsed tine between readings. During this error discussion, a time interval of fone hour (3600 sec) shall be assumed for the calculations, yielding a possible error of +18.

Range Measurements - This is a secondary measurement. ?The radout is through the eye of an observer and is interpreted off an electronically produced image on the radar screen. ?The radar manufacturer states that the error could be as high as #28 of the reading. However, this estimated does not take into account the rolling and moving of the ship, and the rush to complete the measurement before the LCU swings on the mooring line. A better estimate of the true error of this measure~ ment is 478. For this discussion, a typical distance measure- ment will be taken to be 4 km (2 nautical miles) from the ship, yielding a probable error of +0.25 kn.

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Bearing Measurements - This 1s also a secondary neasure~ ment that is read from the radar screen, as is the range measurement, ?The manufacturer's specificatins indicate only that the bearing measurenent is readable to +1 degree of bearing. However, considering the motion of the vessel and the parallax involved in reading from the screen, a 42.5 degree error is more realistic.

Position Determination of the LCU - This measurenent is 4 complex series of steps using the previous range and bearing values toward at least two separate, but known landmarks, then transferring these values to a chart by using a three-arm protractor and a chart scale of 1 cm = 0.2 km. ?The resultant procedure yeilds an error of up to +0.15 degrees of latitude or 40.28 km, and 40.28 degrees or 40.49 km of longitude. This is the maximum error, with the probable error (typically a cir- cle of confusion) being less than half that value.

Position Determination of the Drogue ~ the Trajectory -
This is also a combination of measurements, one of which is the Position Determination of the LCU. As a result, the maximum

error for this measurement, using the assumed 4 km distance from the LCU as a working distance, could be as high as 40.25 degrees of 40.46 km of latitude, and 40.45 degrees or 40.79 km of longitude. However, again, these values may be reduced realistically to £0.18 degrees of +0.33 km of latitude, and 40.25 degrees or +0.46 km of longitude. The average probable error for the 4 km distance is then +

4 km, or +108.

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Determination of the Elapsed Direction ~ This measurement is determined from the results of two successive Position

Determinations of the Drogue, and has a probable error of #15 degrees~True (relative to North being 000 deg-n).

Determination of the Elapsed Tine - This is simply the subtraction of two consecutive Time Measurements, with a re~ sultant probable error of +45 sec, and a maximum (but un-realistic) error of up to #60 sec.

Determination of the Elapsed Drogue Travel - This determi-nation is the charg distance between two successive Position Determinations of the Drogue. A realistic estimate of the probable error in this measurement is based on the probable errors between the two successive events, or +0.56 km, based on our previous assumptions.

Determination of the Drogue Speed - This calculation is based on the results of both the Determination of the Elapsed Droque Travel and the Determination of the Elapsed Time. The most probable error for this calculation is +108, with the maxi-mun possible erros being up to +208, using the maximum possible

errors for each of the constituent parts.

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3.0 RESULTS

During the course of this program, extending from Sep-tember 1979 until October 1980, eight cruises were conducted in the waters near Punta Tuna. The purpose of each of the cruises was to follow the trajectory of water parcels leaving the

possible OTEC site. The method, in all c was to determine

the trajectory starting from the site at 17°56.9' N, 66°51.9'W, by using deep-sea drogues set to be sensitive to the 100 meter depth. This depth was decided upon after consultation with OTEC designers, environmental measurement experts, and environmental impact modelers.

?The cruises occurred in virtually all seasons of the year, beginning with the autumn of 1979 and extending through to the summer of 1980. The actual dates of the cruises were:

9 November 1979

26 January to 1 February 1980

18 to 22 February 1980

24 to 25 March 1980

7 to 11 May 1980

10 to 12 June 1980

24 to 27 June 1980

16 to 23 July 19

In the following sections, each cruise will be described,

with its results discussed.

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3.1 CRUISE OF 9 NOVEMBER 1979

On 9 November 1980 a cruise was conducted to Punta Tuna.

?The following sections describe that cruise, as it pertains to

this ?purpose.

3.2.1 NARRATIVE

?The drogue operation described herein was performed by members of the Marine Ecology Division of UPR/CEER during the course of their operations in the vicinity of Punta Tuna, P.R.

?The drogue, without its radar reflectors, radio beacon, or flashing light, was launched at 0800 A.S.T. on 9 November 1979. ?The location of the deployment was 0.4 km at a bearing of 241 deg-T from the mooring buoy. Unfortunately, during this entire cruise all ranges and bearings were taken relative to the mooring buoy, rather than fixed landmarks. The buoy may have moved through a circle of radius of at least 0.5 km during the time of the cruise.

?The vessel used for deployment and for all range and bearing measurements was the R/V SULTANA, operated by the UPR/CEER. This vessel is 14 meters long, and is equipped with

an onboard radar whose capability is probably more accurate

than + 0.1 km and + $°, when operated on its most sensitive range by experienced personnel.

During the deployment, the drogue's mast was broken,

ie was repaired while still in the field, with subsequent

structural weakening, The previously described method for de-

ployment was not used.

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The drogue trajectory was followed from 0800 until 1540

that afternoon, a period of almost 8 hours. The drogue was

last seen on the radar at 1630, but not again. At its last

siting, it was about 0.5 km northeast of the deployment position.

?The drogue was never recovered.

3.1.2. RESULTS

The 100 meter deep water was tracked for slightly less

than eight hours (0817-1540 A.S.7., 9 November 1979). During

that time, the trajectory took the path shown in Pigure 7. Al

though the net travel during the total period was to the north-

west, the water moved northeast then westerly, with a gyre developing during hours 2-6 of the observation period.

During the érifting period the wind was generally out of the east at 2-4 n/sec.

?The elapsed tine between drogue sitings ranged from 0.9-1.7 hours, and the distances traveled during the elapsed time ranged from 0.04-0.56 km (not considering any error due to the buoy movement). ?This information and other used to determine the statistical properties of the drogue movenent can be seen in Table 1. The speeds observed during the crvis ranged from 1-10 cm/sec, with an average of 5 cn/sec. As seen in Table 2, the percent of time of the speeds was between 1 and 10 en/sec and is fairly uniform, as are the direction of notion observations.

Figure § shows the predicted directionality for the two tidal systems as well as the observed directionality of the @rogue. The tides do not appear to be influencing the observed @rogue motion.

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Figure 7.

Trajectory for drogue off Punta Tuna, Puerto Rico

begining 0830 on 9 November 1979. (Numbers are

elapsed time in hours; depth is 100 meters)

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TABLE 2

SUMMARY OF DROGUE "A" WATER MOTION MEASUREMENTS:

Cruise of 9 November 1979

SPEED Te DIRECTION TIME,

(cm/sec) ® (Deg-7) io)

- 2 33 345 - 014

5 32. 01s - 044 13

- 38 ° 045 - 074 12

9-1 36 075 ~ 104

wz - 14 ° 10s ~ 134

as - 17 ° 135 - 164 20

18 - 20 ° 16s - 194

aL- 23 ° 19s - 224 a2

24 - 26 ° 225 - 254

27 - 29 ° 255 - 284 22

30-32 ° 205 - 314

33-35 ° 315 - 344 20

Average Speed = 5 cm/sec

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@rogue motion.

?The most important consideration during this brief observational period is the potential error in positioning the rogue due to the unknown location of the mooring buoy, relative to which the drogue was located. The buoy is subject to considerable surface wind and water motion, because of its large cross-sectional area. ?The buoy system also has a large cross~sectional area (about 5-10 times that at the surface) devoted to its 5 cm diameter 1150-meter-long anchor line. These two arag forces combine to produce a variety of directionally additive forces pushing the buoy around. At no time during this © cruise was any attempt made to accurately locate the buoy rela~tive to any landmarks. As the buoy could move anywhere within a circle of radius of 0.5 km, and as the estimated accuracy of the radar is only + 0.1 km, and because of the greatest elapsed distance measured was only 0.56 km, it is quite possible that the error in positioning the drogue and, therefore, the water

parcel is larger than the measured travel distance.

3.1.3 INTERPRETATION

Due to the large uncertainty of the buoy location, and the normal errors in locating the drogue relative to the buoy, it is unlikely that any validity can be related to the water trajectory movenent during this cruise.

The time periods, both inter-siting and total for the rogue following, are short enough to leave considerable doubt as to the causes of the water motion, aswell as the reliability

of the description of the motion.

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3.2 CRUISE OF 28 JANUARY - 1 FEBRUARY 1980

The following sections describe the activities and re-

sults of the cruise of 28 January - 1 February 1980.

3.2.1 NARRATIVE

Drogue "A" was deployed from the LCU~1470 at the mooring, as per the usual deployment procedure. The deployment was ac~ complished at 0830 A.S.T. on 26 January 1980. The drogue was tracked using the radar aboard the LCU for about 48 hours. Hiow- ever, the last eight hours of this period yielded unreliable results due to a combination of radar electronic problems and the inability of the radar to uniquely detect the above water section of the drogue at distances greater than 10 km. The next half-day of tracking involved using both the horizontal sextant sitings from the ship-to-shore vessel (maneuvered near the @rogue) and using the LCU's radar to determine the position of the small vessel, rather than try to identify the arogue on the radar. The sextant readings later proved unreliable. The @rogue again became clearly visible on the radar at 1700 on 31 January. ?The radar tracking was continued until 1400 on 1 February, for a total drift of 101 hours. The recovery using the ship-to-shore vessel was accomplished at a distance of only 3 km southwest of the LCU. rogue "Cc" was deployed at 1100 on 30 January and was seen to drift until 1100 on 1 February, a period of 48 hours. However, due to a variety of reasons, no

reliable trajectory data resulted for this second drogue.

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3.2.2 RESULTS

Aside from the occasional losses of data for drogue "A",

about 30%, and the loss of the entire trajectory of drogue "c",

the cruise was moderately suc!

ful. The 101.5 hours of

rifting for drogue "A" produced sufficient time to identify a

variety of phenomena, as well as log the longest deep rogue tracking in this part of the Caribbean sea. (This duration on a single drogue was not to be duplicated during any other tracking period throughout this program.)

As seen in Figure 9, the trajectory of arogue "A" moved in a generally easterly direction (both northeast and southeast) for about 40+ hours. After that time,'the path was almost due west. Furthermore, at about hours 8, 40, and 85, a clockwise gyre was seen (hour 85 actually had insufficient data to identify any more than a short @irectional change). The average elapsed time between these gyres is 38+ hours. The inertial period for the latitude of the drogue is 39 hours.

Although the direction of the surface current was noted only during the first day of the observation period, that observation is significant, as the surface water moved westward while the 100 meter deep water was being observed to be moving astward. This points out the different forces and reactions to these forces by the upper water mass (Tropical Surface Water), and the water mass of our concern, the Subtropical Underwater.

?The wind was seen to be out of the easterly quadrant throughout the majority of the drifting period:

Furthermore,

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the atmospheric pressure was moderate during the first half of

the period, then dropped to the lowest in two months during the

last two days of the period. Table 3 shows the data from which

the statistics for the speed and direction were calculated for

this cruise. ?The average time involved between sitings was thre

hours, with the actual time intervals ranging from 0.8-29 hours.

?The distance traveled between sitings ranged from 0.09 - 5.96 km.

?The actual statistics for the speed and direction are

shown in Table 4. The speeds rangea from 2-24 cm/sec, with the

speed range of 6-8 cm/sec seen most of the time, and: the average speed was 11 cm/sec. The distribution of observed directions of travel show the east-west bimodality of the trajectory. Forty-nine percent of the time the water moved toward between 045-164 deg-T and 46% between 255-284 deg-T.

Figure 10 shows the relationship between the two tidal systems and the drogue directions over the same time period. Of the 4 strong diurnal periods corresponding to an ebbing flow for the "Galveston" system, three correspond to a relative easterly change in motion for the drogue. However, due to the extended time involved in an inertial wave, these same three cases may also match the inertial motion, considering possible time errors. Conversely, two of the four westerly tidal drifts correspond to similar relative westward motion of the drogue.

With regard to the more pronounced semidiurnal oscilla~ tion of the "San Juan" system, only those activities that also coincided with the "Galveston" diurnal component matched

any relatable east-west motion of the drogue.

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TABLE 4

3 SUMMARY OF DROGUE WATER MOTION MEASUREMENTS

Cruise of 28 January ~ 1 February 1980

SPEED TIME DIRECTION ?TIME

° (cm/sec) (a) (Deg-7) i)

- 2 1 345 - O14 6

3-5 2 015 - 044

° 6-8 52 045 - 074 9

9 -aL 4 075 ~ 104 9

a2 - 14 10 105 ~ 134 9

° us -17 4 135 ~ 164 1a

18 - 20 10 165 - 194° 1

2. - 23 6 195 ~ 224

o 24 - 26 L 225 - 254 2

27 - 29 ° 255 ~ 284 46

30 - 32 o 285 - 314

Qo 33-35 ° 315 - 344

Average Speed = 11 cm/sec

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3.2.3 INTERPRETATION

During this period, the tracked water parcel that contained drogue "A" appeared to be influenced by at least three separate forces. There was some tidal relationship, there was an identifiable inertial motion, and, lastly, some longer period energy w

for about half the 100+ hours then reverse during the latter half,

?The cause of this last reversal may be very difficult to identify, as we were apparently only observing a sma-1 portion of the period, if any periodicity exists at all.

There is strong evidence that the lower, Subtropical Underwater, is moving independent of the Tropical surface Water, which was moving westerly, with the wind, throughout the cruise.

causing the entire water parcel to move eastward

3.3 CRUISE OF 18 ~ 22 FEBRUARY 1980

?The following sections describe the activities and results of the cruise of 18-22 February 1980.

3.3.1 NARRATIVE

Drogue "A" was deployed from the moored ICU at 1430 A.S.T. on 18 February 1980, The depth sensitivity (panel depth) was set at 100 meters. The drogue was tracked using the radar aboard the LCU from the time of deployment until about 0400 hours on 19 February. ?The position fixing was accomplished either hourly or bihourly whenever possible. After 0400 on 19 February the drogue was no longer discernable on the radar, nor was it heard transmitting on its radio frequency, nor was its beacon Light visible, At 0830 on 20 February a search was conducted using the ship-to-shore vessel, but no trace of the drogue "A" was found on that day. (Note-on 26 March 1980 drogue

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located in a storehouse of a fisherman who claims to have ?re~ covered it for us" in the early morning of 19 February.) The total time for reliable data for this drogue was 13.5 hours.

Drogue "C" was deployed at 0930 on 21 February 1980. Again, the deployment was carried out from the LCU, and the

rogue was set for 100 meters. This drogue was tracked success

fully using the LcU's radar for just over 24 hours, whereupon it was recovered using the ship-to-shore vessel. The recovery took place at 0945 on 22 February, at a distance of 7 km south~ west of the LCU. ?The recovery was accomplished at this tine

ue to weakness of signal on the radar and confusion as to the

fate of drogue "A"

3.3.2. RESULTS

Although one @rogue was lost, and its respective tracking time forshortened, some data were collected during this cruise which both answer some questions, and ask others.

Figure 11 shows the plotted trajectory of drogue "A" from

the time of its deployment at 1430 A.8.T. on 18 February 1980

until its last known location at 0400 on 19 February. The drogue

trajectory is almost true west-southwest, with few minor devia~

tions.

During the 13.5 hour tracking periud of this drogue, the

wind was 2-7 m/sec from the

tern quadrant. No surface cur-

rents were indicated by the observers during this period. the

atmospheric pressure was medium-to~high both during this cruise

and for more than a week after its completion.

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Table 5 displays the data on which the speed and direc-

tion calculations and statistics are based from arogue

?The total period for the drogue tracking was 13.5 hours,

with an elapsed time between sitings of 0.5-2.3 hours. The range of distances traveled between the sitings was 0.4 - 1.9 km. the

ranges of speed seen (Table 6) for the drogue were 10-26 cm/sec, and the most often seen speeds were 12-14, 15-17, and 24-26 en/sec. ?The average speed was 18 cm/sec. The singularity of Airection at the 100 meter depth during this period is seen in that 1008 of the time the direction was in the range of 195-315 deg-7, with observations between 225-284 deg-7 for 85% of the time.

Figure 12 shows the plotted trajectory of rogue "c" from the time of its deployment at 0930 on 21 February 1980 until its recovery at 0945 on 22 February, a period of slightly more than 24 hours. During this time the wind speeds ranged from 0-5 m/sec, and were from the east-southeast or east. No surface currents were monitored during this period. The trajectory was basically southwest, similar to drogue ?A*, but there were a few significant deviations to the east.

Drogue ?c* was under observation for 24.2 hours from the time of deployment to recovery, with the elapsed time between observations ranging from 0,8 hours - 4 hour:

and most of the

time intervals being about 1-2 hours. the @istances traveled

between sitings ranged from 0.2 - 2.3 km.

Table 7 displays the data on which the speed and direc

tion calculations and statistics for drogue "Cc" are based. ?The

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?TABLE 6

SUMMARY OF DROGUE "A" WATER MOTION MEASUREMENTS:

cruise of 18-19 February 1980

SPEED TIME DIRECTION TIME

(cn sec} 3) Deg.-T) ty

- 2 ° 345 - 014 °

3-5 ° 01s ~ 044

- 8 ° 045 - 074 °

9 =u 10 075 = 104 °

12-14 as 105 - 134

as - 17 22 135 - 164 0

18 - 20 12 165 - 194

21-23 7 195 ~ 224

24 - 26 24 225 - 254 6.

27 = 29 ° 255 - 284 24

30 = 32 ° 285 - 314

33-35 ° 31s - 344 °

Average Speed = 18 cm/sec

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?TABLE 7

DATA AND CALCULATIONS FOR DROGUE "Cc":

February 1980

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results of these calculations are also shown in Table 8.

Drogue "Cc" speeds ranged from 2-24 cm/sec, with 15-17 cm/sec being the most often seen. The overall average was 11 cm/sec. The distribution of the speed observations are more uniforn ?than those of drogue "A". ?The directional data does show the bimodality of both easterly and westerly motion, but more than

half of the time the drogue moved toward 195-254 deg-T, and between 195-314 deg~? for 968 of the time.

Figure 13 shows the temporal and directional relation
ship of the predicted tidal currents and the movement of the
@rogue. If there is any tidal influence during this 5-day
period, it remains undetected.

Overall, both arogues appeared to run somewhat parallel
to the 1000 meter depth contour, which runs southwest and paral-
Jel to the coast for this part of the island. This contour
turns sharply southward further west from where the drogue
tracking terminated. ?There are insufficient data to determine
if the drogues would have continued to follow the 1000 meter
contour or moved onto the continental rise off the coast, south
of Jobos, thus rnning aground.

Another important factor to consider is which water mass
was actually being followed by the 100 meter deep arogues. No
hydrographic data were taken during this cruise, however,
historical data indicate that the ?most probable" depth of the
upper mixed layer (core of the upper, Tropical Surface Water)
Lies at about 100m during February and March. This TSW usually
influenced by the wingeven at its deeper portions. However,

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SUMMARY OF DROGUE "C" WATER MOTION MEASUREMENT!

SPEED

(cm/sec:

- 2

- 5

- 8

9-1

a2 - 14

as = 17

1s = 20

21-23

24 = 26

27 = 29

30 = 32

33-35

Average Speed = 11 cm/sec

TABLE

cruise of 21-22 February 1980

TIME

cme

as

24

20

34

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DIRECTION

Deg")

345 - 014

015 ~ 044

045 ~ 074

075 ~ 104

105 ~ 134

135 - 164

165 - 194

195 ~ 224

225 ~ 254

255 - 284

285 - 314

315 - 344

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the water mass directly beneath the TSW, the Subtropical Under~

water, is different in both density and water characteristics,

seldom mixes with the TSW, and is driven by forces other than the local wind conditions.

3.3.3 INTERPRETATION

Although there are a few deviations from the southwest course, both drogues followed this path quite closely. There is sufficient circumstantial evidence to indicate that the 100 meter deep water was moving with the surface water mass (TSW) under the influence of the wind. At this time of the year, the lower SUW may well have been out of reach of our 100m deep rogues. If this were the case, there is a strong Probability that the path followed by the drogues would have taken them up over the shallow areas to which they appeared to be headed. Finally, no clear periodic influence could be

seen during this observation period.

3.4 CRUISE OF 24 - 25 MARCH 1980

?The following sections describe the activities and re~

sults of the cruise of 24-25 March 1980.

3.4.1 NARRATIVE

Drogue "C" was deployed from the moored LCU at 1500 A.S.7. on 24 March 1980, The depth sensitivity (panel depth) was to have been set at 100m, The drogue was tracked approximately hourly using the LCU's onboard radar. Tracking continued until about 1200 on 25 March, however, data are available only until

1900 on 24 March. This track covers a period of only 4 hours.

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Upon recovery with the ship-to-shore vessel at 1230 on 25

March, it was leanred that the panel had become entangled in

the connecting line between the mast and the panel. This en-

tanglenent has probably occurred during deployment. The panel was only slightly below the 3 meter depth of the mast, and Probably not fully open either. The panel was also danaged, either upon deployment or upon recovery. The drogue was 5 km southwest of the LCU upon recovery.

Drogue "E" was deployed from the LCU at 1800 on 25 March. ?This drogue was also set at 100 meters depth. The tracking took place hourly until 0330 on 26 March, at which time it was last seen on the radar. The last useable radar value, however, was at 2200 on 25 March, resulting in a tracking period of only 4 hours, again. At 0830 on 26 March the Radio Direction Pinder indicated that the drogue, although not observable on the radar, was moving swiftly shoreward. An inmediate inspection of this abnormal activity provided the recovery of the arogue from a fisherman who had "recovered it for you." He had the entire system carefully taken apart and set into his small open fish ing boat (thusly verifying our concept of recovable in a small boat without damage). He also indicated that he had our drogue "a" stored on his property onshore, and we recovered that mis~

sing unit, as well.

3.4.2. RESULTS

Only eight hours of tracking were salvaged from this cruise, although considerably more time was spent collecting

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data. Also, the panel for drogue "Cc" was tangled from the outset, resulting in the tracking of a much shallower water than desired.

Figure 14 shows the plotted trajectory of drogue "c? from the time of its deployment at 1500 A.S.1. on 24 March 1980 until 1900 on 24 March, ?The Grogue depth was inadvertently set to be only 10-20 meters deep, and the panel was probably not fully open either. During this tracking period the wind was 10-13 m/sec from the east, and no surface currents were monitored during this cruise. The drogue moved generally southwest, with a sharp southward turn at the end. Table 9 @isplays the data on which the speed and direction calcula~ tions and statistics are based for this drogue. The results of these speed and direction calculations are shown in Table 10 for Grogue "Cc". The speeds ranged from 34-86 cm/sec, with the speed being 30-49 cm/sec almost 908 of the tine. The average speed for this drogue was 46 cm/sec. The direc tions are shown to be mainly westerly, with the flow being between 225-264 deg-T 1007 of the tine. Again it must be mentioned that due to both the forshortening of the depth line and the tangling of the panel, it is not clear if the drogue was following the shallow water or if the surface float was pulling the entangled panel as the float being pushed by the brisk wind. In either case the drogue was not sensitive to the desired 100 meter deep water. .

Figure 15 shows the plotted trajectory of drogue "E" from the time of its deployment at 1800 on 25 March 1980 unti1 2200

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TABLE 10

SUMMARY OF DROGUE "C" WATER MOTION MEASUREMENTS:

° cruise of 24 March 1980

SPEED TIME DIRECTION

on see) 3 Deg=T)

5

o- 9 ° 345 - 014

lo - 0 ° 01s - 044

20 - 29 ° 045 - 074

°

30 - 39 38 075 ~ 104

40-49 50 105 - 134

50 - 59 ° 135 - 164

°

60 - 69 ° 165 - 194

70 - 79 ° 195 - 224

80 - 89 a2 225 ~ 254

°

Average Speed = 46 cn/sec 255 - 284

265 - 314

315 - 344

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on 25 March, only four hours later. This drogue remained at 100 meters depth. The wind was only 1-3 m/sec from the south-east during this time period. The trajectory shows a basically westerly movement, with a deviation somewhat norther-ly then back again to the west, Table 11 displays the data on which the speed and direction were calculated for drogue ?E". The results of these calculations are also shown in Table 12.

Drogue "E" speeds ranged from near zero to 16 cm/sec, with the speed ?between 12-17 cm/sec 76% of the time. The average speed was about 11 cm/sec. This drogue also moved westerly such that 878 of the time the water moved between 225-284 deg-T.

No tidal comparisons were made with the data collected from this cruise, due to the short time spans (4 hours each) involved.

Also, as no hydrographic data were taken during this cruise, it is difficult to determine directly if the two @rogues were in the same water mass. Historically, the TSW

frequently does extend to 100m depth in March.

3.4.2. INTERPRETATION

Both drogues moved westerly, indicating the water from the surface to 100m was moving in that direction. However, if both drogues were fully sensitive to the surrounding water (fully open panels) this short test indicates a considerably

faster moving near-surface water (also subjected to a 13 m/sec

wind) than the 100m deep water. ?The speed ratio was 4:1. the

upper drogue ("Cc") was definitely in the TSW, but may have

been pushed along primarily by the wind acting directly to

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?TABLE 12

° SUMMARY OF DROGUE "E" WATER MOTION MEASUREMENTS:

Cruise of 25 March 1980

SPEED TIME DIRECTION TIME

° (ony sec) 4) Deg-7) 3

o- 2 25 345 - 014 °

3-5 ° 01s - 044 °

6-8 ° 045 - 074 °

°

g-n ° 075 - 104 °

a2 -14 38 105 - 134 °

as -17 38 135 - 164 °

o

1s - 20 ° 165 - 194 °

21 - 23 ° 195 = 224

24 = ° 225 ~ 254 62

°

Average speed = 11 cm/sec 255 - 284 25

285 - 314 °

315 - 344 12

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push the surface float and mast.. The deeper drogue, "EB", at

100m, may have been near the bottom of the TSW, but more

probably was in the SUW, whose movement could be quite dif-

ferently regulated from that of the TSW above.

3.5 CRUISE OF 7 - 11 MAY 1980

The following sections describe the activities and results

of the cruise of 7-11 may 1980.

3.5.1 NARRATIVE

On 7 May at 0800 A.S.7., arogue "E-1" was deployed from the moored 1cU. Tracking vas accomplished primarily using the radar aboard the LCU. ?The drogue's sensitive depth (panel depth) was set at 100 meters, as it was throughout this cruise for all the drogues. This arogue drifted southwest for about 30 hours (until 1430 on May 8), at which tine it was recovered about 7 kn southwest from the LCU using the ship-to-shore vessel. There were no obvious difficulties encountered during this drogue's tracking period.

Drogue "E-1" was then returned to the LCU and deployea again at 1600 on 8 May as "E-2", ?This tine the drogue drifted west-southwest (with more short north, south, and east excursions), and was tracked for about 34 hours, until it was lost on the radar screen. The drogue was recovered successfully using the ship-to-shore vessel at 1100 on 10 May, more than 9 km from the LcU.

Drogue "B-2" was returned to the LCU, from where it was deployed as "E-3" on 10 May at 1200. Under slightly more brisk

---Page Break---

wind, it moved less distance, and more circularly, frequently moving upwind. The radar aboard the LCU again began to mal~ function, and tracking was terminated after only 26 hours, at about 1600 on 11 May. ?The drogue was recovered about 1 km north of the Lev.

At noon on 9 May, a second drogue unit, "Vv", was deployed

from the LCU. Drogue "Vv" drifted virtually parallel to "E-2", its contemporary, moving west-southwest, with numerous short excursions fron this direction. This drogue was tracked for about 49 hours but, upon analysis, it was learned that the panel had apparently becone entangled with either the ocean bottom or a fisherman's apparatus, and the drogue did not appear to move after the 39th elapsed hour. This drogue was also recovered in the late afternoon of 11 May, using the

ship-to-shore vessel.

3.5.2 RESULTS

Throughout this cruise, which lasted from 7-11 May 1980, all the drogues were set to be sensitive to 100m depth (pane? depth). Also, all position tracking of the drogues was accomplished using the radar onboard the LCU. All drogues were deployed fromthe LcU and all were recovered using the 13 meter ship-to-shore vessel, after a total of 130 hours of drogue tracking.

During the cruise, the atmospheric pressure remained at about the monthly average, or even slightly higher. After the cruise, a significant pressure decrease. did not occur for at

least two weeks; however, the pressure was relatively low

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3-4 days before the drogues were deployed.

Figure 16 shows the plotted trajectory of drogue "E-1" from the time of its deployment at 0800 A.S.T. on 7 May 1980, until just before its recovery at 1430 on 8 May, an elapsed tracking time of about 30 hours. During that time, the wind went from moderate (4 m/sec) out of the south to very low (0-2 m/sec) with variable direction. Also, throughout this time, the surface water was moving to the east past the LcU. The 100 meter deep water, as typified by the drogue trajectory, moved in a generally southwesterly direction with Little directional deviation, Table 13 shows the data on which the speed and direction calculations were based for "E-1". Table 14 shows the overall speed and direction results for this arogue.

?The elapsed time between sitings for this drogue varied from 0.5~4.0 hours, with most of the values being 2 hours or less, and the total number of observations being 22. The distance the drogue traveled between sitings ranged from 0.04-2.2 km, he average observed speed was 11 cm/sec, and 898 of the time the speed was between 6-17 cm/sec. Two speed maximums were observed, one being 6-8 cm/sec, and the other at 15-17 cm/sec. The direction of motion was between 195-254 deg-? for

more than half the time, and more than 90% of the time the

water direction was between 195-314 deg~T. At one time during

the tracking period, the érogue appeared to be moving shore

ward, toward shallow water, but it reversed direction and

moved offshore again.

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24

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Average Speed = 11 on/sec

SUMMARY OF DROGUE "?E-1" WATER MOTION MEASUREMENTS:

-u

-u4

-u

- 20

- 23

- 26

~ 29

~ 32

- 35

TABLE 14

Cruise of 7-8 May 1980

TIME,

2.

8

5

32

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DIRECTION

Dea-7)

345 - 014

01s - 044

04s - 074

075 - 104

105 ~ 134

135 - 164

16s - 194

195 - 224

225 - 254

255 - 284

285 - 314

ais - 344

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Figure 17 shows the plotted trajectory of arogue "E-2".

?This drogue was deployed at 1600 on 6 May and was tracked for almost 1-1/2 days. Although the recovery was completed at 1100 on 10 May, tracking was terminated at 0200 on the same day, as the Grogue was no longer discernible on the radar screen, and the ship-to-shore vessel was unavailable for either magnetic or sextant sitings until much later in the day. During the 34-hour tracking period the wind went from calm to moderate from the south near the termination. Also during this entire period, the surface water continued to move eastward past the LCU. ?The path of the 100 neter

deep water during this data set was generally to the west-

southwest, with many excursions in other directions. This

@rogue made a more serious excursion toward the shallow water,

and might have gone aground had it continued for a short tine

longer on such a course. Table 15 shows the data on which

the speed and direction calculations are based for this

Grogue, and Table 16 shows the results of the speed and ai-

rection calculations for drogue ?E-2".

The elapsed tine between the 23 observations for this

drogue varied from 1.0-4.0 hours, with most of the values being

fone hour. The distance the drogue traveled between observa

tions ranged from 0.1 ~ 1.2 km. The average speed during

this tracking period was about 12 cm/sec. More than 608 of

the time the speed was between 6-14 cm/sec, with observational

Peaks at 6-8 cm/sec and 12-14 cm/sec. Half of the directional

observations occurred inthe 225-284 deg-T range, but there

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TABLE 16

SUMMARY OF DROGUE "E-2" WATER MOTION MEASUREMENTS:

Cruise of 8-10 May 1980

a

SPEED ?TIME DIRECTION TIME

en/ sec) 2 Deg-T) 8

° o- 2 3 345 - 018

3+ 9 01s - 044 3

6-8 3 045 ~ 074

g-n 6 075 ~ 104

a2 - 4 2 105 - 134

as - 17 4 135 - 164

o 18 - 20 3 ies - 194 6

2l = 23 6 195 ~ 224 13

24 ~ 26 3 225 ~ 254 38

° 27-29 3 255 ~ 284 a2

30 ~ 32 3 285 - 314

33 = 35 ° 315 - 344

° Average Speed = 12 cm/sec

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was much variation. This drogue track varied its speed and direction mich more than did drogue "E-1".

Pigure 18 shows the plotted trajectory of drogue "E~.

This drogue was deployed at 1200 A.S.T. on 10 May; however, the first radar observation was not taken until 1700 of the same day due to a radar malfunction. During the 26 hours of this drogue tracking period, the wind moved from the south and southeast and remained moderate (2-5 m/sec) all the tine. The surface continued to drift eastward. This drogue appeared to move in an erratic fashion, which may be either the true water trajectory or an artifact of the measurement due to continued, but undetected, problems with the radar. The @rogue motion was westerly, then took a clockwise loop and ultimately moved around past west to the northeast. Table 17 shows the data on which the speed and direction calculations and statisc are based, with Table 18 showing the results.

The elapsed time between the 14 observations varied from 1+5 hours, with all but two of these time intervals being 1 or 2 hours. The distance the drogue moved between observations ranged from 0.1-1.4 km. The speeds for this period were much slower, and 925 of the time the speed was less than 9 cm/sec.

?The average speed wi

6 cu/sec. The direction, although highly variable, may possibly be separated into easterly (045-134 deg-t) at 468 and westerly (225-314 deg-T) at 35% of the

time.

Figure 19 shows the plotted trajectory of arogue "v", which was deployed at 1500 A.S.7. on 9 May and tracked until

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?TABLE 18

SUMMARY OF DROGUE "E-3" WATER MOTION MEASUREMENTS:

°

Cruise of 10-11 May 1980

Time DIRECTION rime

* Deg-T) 2

°

19 345 - 014 °

23 015 - 044 8

50 045 - 074 23

°

9-1 ° 075 - 104 15

a2 =a 8 10s ~ 134 a

as - a7 ° 135 - 164 8

°

1s - 20 ° 165 ~ 194

21 ~ 23 ° 195 ~ 224

24 - 26 ° 225 - 254

°

27-29 ° 255 ~ 284 27

30 - 32 ° 285 - 314

33 = 35 ° 31s - 344

°

Average Speed = 6 cm/sec

°

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1630 on 11 May, a total of 39 hours. This drogue was adrift during the tenture of "E-2" and "E-3". ?The wind was moderate during this time, and the surface current was moving eastward.

The trajectory for "Vv" is not unlike that of "E-2", however

"v" made a further shoreward excursion and ultimately appeared to run aground in water that should have been deeper than

the 100 meter depth of the drogue (according to the bathymetric charts of the area). Either an uncharted submarine rise or one of the frequently seen fishermen's "fish pots" nay have stopped the drogue. ?The data on which the speed and direction calcula tions are based are seen in Table 19, and the results are seen in Table 20.

The elapsed time between the 24 observations for this @rogue varied from 0.5-7 hours, with all except two being two hours or less. The distance the drogue moved between the ob- servations ranged from 0.1-1.5 km. As this drogue's tracking period overlapped that of drogues "E-2" and "E~3", it is not surprising to see the speed results for "V" lie between those of the faster "B-2" (12 cm/sec) and the slower "E-3" (6 cm/sec).

?The average speed for "V" was 9 cm/sec, with considerable variation in speed values. More than half the observations were between 3-8 cm/sec. ?The direction of this drogue also varied quite a bit, but 368 of the tine the water moved toward between 225-264 deg-T, with the rest of the values spread ?throughout the compass quite evenly.

Table 21 shows the overall speed and direction results for the 130 hours of drogue tracking during this cruise. the

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TABLE 20

SUMMARY OF DROGUE "V" WATER MOTION MEASUREMENTS:

°

Cruise of 9-11 May 1980

SPEED TIME DIRECTION TIME,

° (cm/sec) @ (Deg~T) @

- 2 8 345 - 014 10

- 5 aL 01s - 044

° 6-8 20 045 - 074

9 -n 2 075 - 104 2

12-14 10 105 - 134

° as -17 a 135 - 164 26

18 - 20 as 165 - 194

21 - 23 5 195 - 224

24 - 26 ° 225 ~ 254 12

27-29 ° 255 - 284 26

30 - 32 ° 285 - 314 5

° 33 - 35 ° 35 - 344

Average Speed = 9 cm/sec

---Page Break---

TABLE 21

SUMMARY OF ALL DROGUE WATER MOTION MEASUREMENTS:

cruise of 8-11 May 1980

SPEED TIME DIRECTION TIME,

(ony sec) ty g-T) *

o- 2 9 345 - 014 4

3-5 a7 01s - 044 2

6-8 34 04s - 074 5

9 -n 4 075 - 104 5

a2 - 14 a2 105 - 134 6

as - a7 12 135 - 164 22

18 - 20 6 165 - 194 4

2. = 23 3 195 ~ 224 na

24 - 26 1 225 ~ 254 20

27 = 29 1 255 - 284 18

30+ 1 285 ~ 314 8

31s - 344 3

Average Speed = 10 cm/sec

100

---Page Break---

average speed of the 100 meter deep water was 10 cm/sec

throughout this time, with the speed being between 6-8 cm/sec

more than 308 of the time, and a total speed range of 2-30 cm/sec. There was a slightly predominant motion towara the southwest, with more than half the observed values between 195-314 deg-?, and the most frequently observed ranged of values being 225-254 deg-T and 255-285 deg~7.

Figure 20 shows the relationship between the predicted ?tidal currents in the area and the observed water direction at 100 meters. Predictions are given for both the Galveston and San Juan "systems", although both appear sinilar for this time period. ?There appears to be no clear tidal relationship

@uring "B-1", however, just before noon on 9 May, both pre~ Aictions tend eastward, as did "E-2". Also, about midnight of 10-11 May, both predictions show an eastward tendency, as aia both "E-3" and ?"v".

Finally, if the two clearly clockwise gyres from drogue "5-2" at elapsed time of 12-18 hours and "E-3" at elapsed tine of 8-18 hours are considered, the elapsed tine between these two circular movements is 43 hours, which corresponds closely

to the 39 hour inertial period.

3.5.3. INTERPRETATION

The 100 meter deep water was moving basically southwest to south-southwest during most of the cruise at a moderate average speed of 10 cn/sec. Tidal and inertial oscillations

appear to be superimposed upon the general southwesterly flow.

Historically, this time of the year has the 100 meter deep

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water lying totally within the Subtropical Underwater. The upper, Tropical Surface Water, moving eastward, was moving into the wind, forming a pair of shear zones: Wind-to surface water (southwest-to-east), and TSW-to-SUM (east-to-west) . Finally, if a 100 meter deep drogue dia actually run aground only 7 km west of the possible OTEC site, a power plant effluent might do likewise, if released in the same location. In the case of flowing water, the effluent would move along the bottom, possibly upwelling until another path of egress in encountered.

3.6 CRUISE OF 10 - 12 JUNE 1980

?The following sections describe the activities and results of the cruise of 10-12 June 1980.

3.6.1 NARRATIVE

On 10 June 1980 at 1200 A.S.7., drogue "A" was deployed from the LCU. Tracking was accomplished primarily by using the radar aboard the LCU. When the rogue was no longer visible on the radar, an attempt was made to use hand-bearing compass readings from the ship-to-shore vessel to fix the position of the drogue, but these values were not sufficiently accurate to be included in this report. The drogue's sensitive depth (panel depth) was set to be at 100 meter:

?The drogue drifted 51 hours, with position fixing during the first 39 hours indicating that the direction was to the northeast. Recovery was done using the ship-to-shore vessel at 1440 on 12 June. The drogue was more than 10 km to the northeast of the LCU upon recovery.

During and before this cruise some minor modifications to both equipment and procedures were made. Compression unions were installed above and below the flotation assembly

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on the mast to strengthen the mast, which was pre-weakened by drilling holes to secure it to the float. A safety line was attached from the top of the mast to the float to prevent total loss of all above-water equipment if a mast separation should occur. And more weight was added to the lower panel supporting pipe to assure its more rapid descent than that of the top pipe and thusly minimize tangling. Finally, a solu-tion was found for the recurring radar image problem. The radar unit can be simply turned "OFF" for a sufficient tine to allow for component cool-down. After this period, the image again will be properly displayed, with the instrument operating

according to the manufacturer's specified accuracy.

3.6.2. RESULTS

?The drogue "A", which was used during this cruise, was set to be sensitive to a depth of 100 meters. ?The successful tracking of the drogue was accomplished using the radar on-board the Leu.

Figure 21 shows the plotted trajectory of the drogue fron the tine of deployment (1200 A.S.T. on 10 June 1980) until its image was lost on the radar, 39 hours later. ?The drogue was

recovered at 1440 on 12 June. During the time of drift, the wind was brisk, coming from the east or southeast at 9-13

m/sec. However, the surface water moved into the wind (east-

ward). The drogue moved in a northeasterly direction with

numerous clockwise loops. ?Throughout the cruise the atmospheric

Pressure was moderate-to-high. However, the two days pre-

ceeding the cruise had relatively low pressure. After the

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cruise, the pressure continued to rise.

Table 22 shows the data from which the speed and direction of the drogue were calculated and Table 23 shows the results of those calculations. The time that elapsed between each of the 31 observations varied fron 0.7-6 hours, with oniy one value greater than 2 hours. The distance traveled by the drogue between observations ranged from 0.04-2.0 km.

?The average speed during the 39 hours of tracking was 14 cm/sec, with a range of 1-56 cm/sec. The speed was between 3-11 cm/sec more than half the time, with 948 of the observa~ tions less than 27 cm/sec. The direction traveled most often was between 015-044 deg-7, with more than 808 of the observa~ tions between 0-180 deg-r.

Figure 22 shows the relationship between the predicted tidal currents in the area and the observed water direction at the 100 meter depth. ?The predictions are given based on both the San Juan and the Galveston tidal systems. Both systems appear similar during this period, however, the San Juan system is more clearly a semi-diurnal cycle, and the Galveston does have a mich smaller semi-diurnal component added to its dominant diurnal period. If any correlation between the tidal currents and the 100 meter deep water movement might be

seen, it could be at about 1400-1800 on 10 June, when the pri dicted tidal current was westerly. There was a strong westerly

turn in the 100 meter deep water, but at elapsed time ?hour 5"

the drogue did take a sharp northeast turn. Also, the drogue

movement at about 2200 hour on 10 June and again at about

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SUMMARY OF DROGUE

SPEED

(cm/sec)

o- 2

3-5

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9 -n

w= 14

as - 17

18 = 20

21-23

24 - 26

27-29

30 32

33-35

36 - 38

39 = 41

42-44

45-47

48 - 50

sl = 53

54 - 56

57 = 59

60 - 62

Average Speed = 10 cm/sec

TIME

ae

1s

25

16

10

" WATER MOTION MEASUREMENTS:

Cruise of 10-12 June 1980

pirecrroN

(deat)

34s - 014

015 - 044

045 - 074

075 ~ 104

105 - 134

135 - 164

165 - 194

195 - 224

225 - 254

255 - 264

285 - 314

31s ~ 344

TIME

a

26

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0900 on 11 June was more easterly than "average", and those

times did correspond to easterly tidal flows. These are weak

comparisons however.

3.6.3 INTERPRETATION

During this erui:

the 100 meter deep water moved north-

east, and along with the eastward surface water, moved into the eye of the brisk, easterly wind. This tine of the year should have found the 100 meter depth fimrly into the lower Subtropical Underwater, with a separate, shallow Tropical Surface Water above it. Whatever is forcing the SUW eastward may, or may not be also moving the TSW in the sane direction.

Any tidal influence is truely weak during this period.

3.7 CRUISE OF 24-27 JUNE 1980

?The following sections describe the activities and results

of the cruise of 24-27 June 1980.

3.7.1 NARRATIVE

Drogue "A" was deployed from the LCU at 0930 A.S.T. on 25 June 1980. The depth sensitivity of the drogue (panel depth)

was set at 100 meters. Throughout the 23 hours of tracking,

the position of the drogue was determined by using the radar aboard the LCU. A current meter had been suspended from the Lcu to a depth of 100 meters also. This meter would enable a check of the general drogue operation.

The lines of the drogue running to the bottom of the

Panel became entangled with the current meter upon deployment.

However, this situation was not promptly diagnosed, and then

a

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@ solution was not affected until 1700 that sane day. After

this time, the drogue drifted freely in a southwesterly direc-

tion for the next 23 hours. It was recovered about 7 km south=

west of the LU at 1600 on 26 June.

?The current meter was ready every 1-2 hours throughout

the cruise.

3.7.2 RESULTS

?Throughout the cruise, lasting from 24-27 June 1980, both

the drogue "A" and the current meter were set so as to be sensi-

tive to the depth of 100 meters. Also, all position tracking

of the drogue was accomplished using the LCU's radar. ?The

@rogue was deployed from the LU and the current meter was suspended from the same vi

el. ?The drogue was recovered using

sel.

?the 13m ship-to-shore v

Figure 23 shows the plotted trajectory of arogue ?A?

from the time of its release from entanglement with the current

meter line (1700 A.S.T. on 25 June 1980) until its recovery

23 hours later at 1600 on 26 June. During that time, and for

@ significant previous period, the wind was moderate to brisk

(5-13 m/sec) out of the southeast to northeast. The atmospheric

Pre

sure remained at least normal or higher both before and

during the cruise.

A noticeable decr

se in pressure did not

Occur until about two weeks after the termination of the cruise.

?The surface current ran toward the west (with the wind) most

Of the time. The water parcel containing the drogue moved

steadily southwesterly with very little deviation. Table 24

contains the data on which the speed and direction calculations

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for drogue "A" are based. Table 25 shows the actual results

of those calculations.

?The elapsed time during the 22 observations varied fron 0.53 hours, with all but two being less than 1.5 hours. ?The Gistance the drogue moved between observations ranged from 0.1 ~ 1.4 km, The average speed was 11 cm/sec, and the water moved in the range of 6-14 cm/sec more than 808 of the time. The range of observed speed values was 3-18 cm/sec, and the nost frequently seen values are 12-14 m/sec, followed closely by 9-11 cm/sec and 6-8 cm/sec. AS verification of the westerli- ness of the drogue's motion, 95% of the time the water moved between 195 - 314 deg-7, and more than half the time the water moved between 195-254 deg-T. The drogue again closely followed the 1000 meter contour toward the southwest.

Figure 24 shows the plotted trajectory of drogue ?A* together with the plotted progressive vector of the current meter results. Although the scale of this figure differs from that of the preceeding figure, the scale is the same for both the drogue and current meter. The elapsed times (in hours) are shown for both instruments, using the drogue disentangle~ ment time (1700 on 25 June) as "0" hours. The separation in the current meter vector resulted from the false values of the instrument that occurred during the entanglement with the @rogue. ?The current meter "trajectory" appeared to follow that of the drogue quite closely; however, the estimated distances are mich greater for the current meter due to its much greater indicated speed. The curtent meter data was

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TABLE 25

. SUMMARY OF DROGUE "A" WATER MOTION MEASUREMENTS:

Cruise of 25-26 June 1980

SPEED THe DIRECTION

(en/ sec}) Deg=)

o- 2 ° 345 - 014

3-5 4 01s = 044

6-8 23 045 - 074

9 -a a 075 ~ 104

12-14 37 105 - 134

as -17 an 135 - 164

1s - 20 4 165 - 194

al = 23 ° 195 ~ 224

24 - 26 ° 225 - 254

Average Speed = 11 cm/sec 255 - 264

2es - 314

31s - 344

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observed over an elapsed time of nore than 50 hours.

Table 26 displays the results of the current meter speed

and direction, The average observed speed for the current

moter was 29 cm/sec, with a range of 10-41 cm/sec. The

most frequently observed valu

were 24-26 cm/sec and 30-32

en/eec. Almost 80% of the observations were greater than

23 om/sec. These values are about triple those of the drogue,

which may be due to the readability of the instrument, calibration, actual differences, or errors due to the swing of

the ICU on its mooring. (On subsequent investigation of

the current meter, it was found to be horizontally mis oriented, and after proper alignnent, the speeds decreased noticeably. The directionality of the current ineter, however, was much nore closely related to that of drogue. The most frequently observed values were between 225-264 deg-T, with only 44 of the observations not between 165-314 deg, compared to 58 for the arogue.

Figure 25 shows the relationship between the predicted tidal currents in the area and those observed water directions seen by either the drogue or the current meter (both at 100 noters depth). The predictions are given for both Galveston and San Juan tidal systems. During this cruise, both of these predictions appear quite similar, although the reduction of the seni-aiurnal component for the Galveston system te evident. There appears to be little correlation between the rogue direction and any tidal influence, when observed alone. However, there seems to be sone tidal affects in the current

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TABLE 26

SUMMARY OF CURRENT METER WATER MOTION MEASUREMENTS:

Cruise of 24-27 June 1980

SPEED TIME DIRECTION

(en/sec} 3 Deg~1)

o- 2 ° 345 - 014

3-5 ° 01s - 044

6-8 o 045 - 074

9-1 4 075 ~ 104

12-14 ° 20s ~ 134

as - 17 4 135 - 164

18 - 20 a2 165 - 194

a - 23 ° 195 - 224

24 = 26 29 225 - 254

27 = 29 ° 255 - 284

30 = 32 29 285 ~ 314

33-35 ° 315 ~ 344

36 = 38 °

39-42 2.

42-44 °

Average Speed = 29 cm/sec

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meter directionality as seen early on 24 June, late 24~early

25 dune, mid 25 June, midnight 26 June, and maybe 1000 on 26 June, ALL these occasions show easterly shifts that correspond to an easterly tidal flow. when these observations are seen next to the drogue results, sone possible influence may be implied in the drogue results as well.

3.7.3. INTERPRETATIONS

?The water at the 100 meter depth is moving parallel and slightly seaward of the 1000 meter contour, This was satis~factorily confirmed by good agreement between the directional results of the drogue and the current meter. This motion appears to be somewhat parallel to the surface water mass,

which may be wind-driven at this time.

3.8 CRUISE OF 16-23 JULY 1980

?The following sections describe the activities and results

of the cruise of 16-23 July 1980.

3.8.1 NARRATIVE

On 15 July 1980 the group left Mayaguez and arrived at the ICU in anticipation of deployment of the drogues the next day. Although the cruise participants were aboard the LCU by the afternoon of 15 July, poor weather, in the form of a tropical wave, prevented the ship-to-shore vessel from leaving

port until 19 July. As the small v

el is considered a

ary back-up for the drogue operation (both during tracking and recovery), the drogue deployment was postponed. The period fron 16 - 18 July was devoted to current meter rebalancing for

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more accurate speed measurements (the meter was originally

balanced so as to be pointing ni

ly vertical, and it also

had tangled its electrical line with the support Line.)

?This work was completed by 16 July. As rough seas remained throughout the cruise, only one drogue was deployed so as to minimize possible losses due to the seas or not being able to affect recovery.

?The actual drogue "A" deployment was accomplished from the deck of the LCU at 0900 A.S.T. on 19 July 1980. The depth sensitivity of the panel was set at 100 meters. However, upon recovery, it was determined that the panel had been severely damaged, leaving only a small portion of the upper Part of the panel intact, and no weight at the bottom. This damage changed the depth sensitivity of the panel considerably. upon deployment, the drogue began to move beneath the LCU, so a small ve:

el was used to tow the drogue assembly about 15 meters northwest of the LCU so as to prevent entanglement with other down-lines. Immediately, a diver was dispatched

to inspect the drogue

sembly for damage, but none was found at that time.

The drogue was tracked for a total of 76 hours. During the first 14 hours, the position of the drogue was determined by the radar aboard the LcU. After that time, the ship-to~ shore vessel visited the drogue, locating it by the RDF beacon. Positioning was accomplished during the last 60 hours of tracking by the use of a hand bearing compass aboard the

ship-to-shore vessel and using known locations on land. Due

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to the rough seas and increasing distance fron the ICU, these trips to the drogue were limited to once daily. ?The érogue was recovered at 1300 on 22 July, after it had been drifting for 76 hours, and was about 60 km southwest of the ICU, near Isla Caja de Muertos. However, sometine during the drift, the Panel was damaged, producing a change in the depth sensitivity, drag, and drift characteristics.

The current meter, untangled, rebalanced, and set back into the water at the 100 meter depth on 16 July, was read bihourly, when possible, until 1300 on 23 July, for a total elapsed time of 164 hours.

on 23 duly, after recovery of the drogue, an XBT trace was obtained with the help of Mr. D. Corales of CEER.

3.8.2 RESULTS

?Throughout the testing period, 16 - 23 July, the comparative current meter was set at 100 meters depth. ?The drogue was originally set to this depth also, lit sometine during the arifting period, the lower half of the panel was torn away, causing the panel to lose its anchoring weight, and more than

half its drag area at 100 meter:

These losses have probably resulted in the panel, rising up into the upper water mass, thereby no longer being valid as a follover of-the 100 meter @eep water. The tine of this separation and change can only be weakly surmised from the data, and shall be discussed later. The position tracking for the first 14 hours of the @rogue's drift was accomplished using the LCU's radar. The Grogue was deployed from this vessel, and the current meter

aa

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was also suspended therefrom. During the remaining drogue @rift (elapsed times of 30 to 76 hours), the positioning

was done with a hand bearing compass from aboard the ship-to shore vessel. This vessel was also used during the recovery

of the drogue.

Figure 26 shows the plotted trajectory of the drogue from the time of its deployment (0900 A.S.T. on 19 July 1980) unté1 its recovery, 76 hours later, at 1300 on 22 July. During that time, the wind was moderate to brisk (7-10 m/sec) from the east-to~southeast. The surface current moved westward through~ out the cruise. During this time the atmospheric pressure was at a relatively low value, compared to the average or preceding couple of weeks. Furthermore, within a week after the start of the drogue drift, the pressure reached the month's lowest value, then quickly recovered.

During the first 14 hours of the drogue track, it moved southwest, with numerous north and south excursions. The average speed during that period was 21 cm/sec, averaging the separate values. The drogue was no longer visible by radar after that time, so the ship-to-shore vessel was sent daily to determine the drogue's position by hand bearing compa:

During

the latter three days, the drift averaged 23 cm/sec. This

lack of definite change in the arift speed appears to make any

guess as to the time/location of the panel tearing almost

impossible. However, other evidence may help. During the

first 14 hours, the average speed, based on the total tine

and total distance covered, is only 17 cm/sec. ?The remaining

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Gaily averages are 22, 23, and 24 n/sec. This may indicate

that the panel tear occurred between elapsed-tine 14 hours

and 30 hours, as the drogue moved into the shallower water.

Also, for the period from hour 30 to hour 40, the drogue was

near the very steep slope of the island shelf. A slight

error in drogue positioning (easily possible using the hand

bearing compass) could place the drogue in le:

than 40

meters of water, as the bottom drops from 30 to 400 meters depth in less than 1 km in this area.

Table 27 contains the data on which the speed and direction calculations for the drogue are based. Table 28 shows the actual results of these calculations.

During the 76 hours of drift, there were a total of 17 observations. The time interval between observations varied from 0.7 hours during the first period (using the radar) to 22 hours (using the ship-to-shore vessel). The distance traveled between observations varied from 0.3 km during the early period to 19 km. Overall, the drogue averaged about 23 cm/sec, with more than 3/4 of the tine the observations were between 15-26 cm/sec. The most frequently observed speed range was between 21-23 cm/sec. All the direction observa~ tions were between 135-314 deg-T, and 938 of the time, the water moved between 225-264 deg-r.

Figure 26 also shows the progressive vector of the current meter results. The scale of both the drogue and the current meter results are the same on the figure. ?The elapsed ?time (in hours) are shown for both devices, using the drogue

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TABLE 28

SUMMARY OF DROGUE "A" WATER MOTION MEASUREMENTS:

2 cruise of 19-22 guly 1980

SPEED TINE DIRECTION TINE

en/sec, % deg *

° 0-2 ° 345 - 014 °

35 ° 01s ~ 044 °

6-8 2 045 ~ 074 °

°

9-1 a 075 ~ 104 °

wm -14 ° 105 - 134 °

as -17 3 135 - 164 2

° 18 - 20 4 165 - 194

2-23 52 195 ~ 224 1

24- 26 31 225 - 254 59

° 27 - 29 a 255 - 284 34

30- 32 1 285 - 314

33 - 35 1 315 - 344

°

36-38 3

39-4

42-44 °

o

Average Speed = 23 cm/sec

9

130

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deployment (0900 on 19 July) as ?0? hour. The ?trajectory? of the current meter, or the progressive vector, is also basically southwesterly, with a short easterly excursion at the beginning (elapsed time -64 to -34 hr), and again at elapsed time 58 to 70 hours, with numerous north and south excursions throughout the period. The tine interval between the two strong easterly excursions was about 125 hours.

Table 29 displays the speed and direction results of the current meter. The average speed was 16 cm/sec, with nore than half the observed values between 15-20 cm/sec. No value vas observed less than 9 cm/sec, and only one value was more than 23 cm/sec (and that was 31 cn/sec.). Eighty percent of the direction observations were between 195 - 314 deg~n, with the range with the highest frequenty of observations being 225 = 254 deg-7. As opposed to the drogue results, several observations were between 315 - 134 deg-T., but these usually occurred either before the drift of the drogue began, or between drogue observations, when only one drogue observation was being taken daily.

Figure 27 shows the relationship between the predicted

tidal currents in the area and those observed directions seen

either by the drogue or by the current meter. The predictions

are given for both Galveston and San Juan systens. During this

cruise, both of the predictions appear similar, although the

semi~diurnal component for the Galveston system is evidently

weak. As the short-term drogue observations (bihourly) lasted

only 14 hours, little correlation is possible with the drogue

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TABLE 29

SUMMARY OF CURRENT METER WATER MOTION MEASUREMENTS:

SPEED

(en/ sec}

-2

- 5

- 8

g-n

a2 -14

as -17

1s - 20

i = 23

24 - 26

27 = 29

30 ~ 32

33-35

Average Speed = 16 cm/sec

cruise of 16-23 July 1980

TIME

aL

4

18

33

133

DIRECTION

?(dea=t)

345 - 014

01s - 044

045 - 074

075 ~ 104

105 ~ 134

135 - 164

165 - 194

195 - 224

225 - 254

255 - 284

285 ~ 314

315 ~ 344

?TIME

12

a

23

a4

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3

g

3

5

a

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movement. However, the current meter observations show frequent eastward excursions that appear to match the tidal oscilla~ tions for the area. These likely correlates are: 1200 on 17 July, 1400 on 18 July, 0300 and 1600 on 19 July, 1900 on 21 July, and 2000 on 22 July. As most of these correlates appear during the weaker, semi-diurnal portion of the Galveston (or Caribbean) system, it might be surmised that the North Atlantic systen, as seen in San Juan, may be the dominant in the Punta ?Tuna area.

It is fairly certain, using the information available, that both the Tropical Surface Water, the upper water mass, containing the upper mixed layer, and its lower counterpart, the Subtropical Underwater, are moving southwesterly past the test area during the time of this cruise.

3.8.3. INTERPRETATIONS

Although the 100 meter deep water clearly moved southwesterly, confirmed by both the drogue and the current meter, the speed again is in doubt due to the differences between the two instruments. Although the drogue was not observed to move over the shallow shelf that extends southward of Jobos, the reduction to only a singledaily observation may have prevented observing such motion. The current meter indicated more tidal correlation than did the drogue. Furthermore, the current meter displayed two strong easterly excursions that may be related to non-tidal forcing such as internal waves, or possible atmospheric pressure forcing. These easterly movenents occurred at times the drogue motion was not being monitored.

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3.9 OVERALL RESULTS

This section is included to summarize all the results of the drogue data collected during this program.

The results will be evaluated on a total basis as well as seasonally.

There were a total of 421.6 hours of monitoring the arifting of 100 meter deep drogues (although some of this tine actually was devoted to following drogues with a mich shallower depth due to breakage).

There were eight cruises during the period from Novenber 1979 until July 1980, Table 30 contains the information as to the dates, elapsed data time, and generalized results. Overall, there were 192 observations during the 422 hours, yielding an observation about every two hours. At least one drogue was in the water over a total of 22 days over the nine months, with a total of thirteen actually useable drogue deployments, sone running concurrently, and some extending over many days. The average number of useable drogue tracking hours was slightly more than 30 hours/drogue, with a range of from 4 to 102 hours.

?The overall speed

n throughout the program at 100 meters

aepth was 12 on/sec, with the cruise averages ranging from

5-23 cm/sec. Table 31 shows the speed and directional data in

a summary form for all the cruises combined. This table

weighs each of the 192 observations as to the actual elapsed

time between each observation. The overall tine-weightea

average speed was 13 cm/sec, with the observed values ranging

from 0-56 cm/sec (the 40-90 cm/sec values that were observed

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TABLE 31

SUMMARY OF ALL DROGUE WATER MOTION MEASUREMENTS

SPEED ?TIME CUMMULATIVE DIRECTION TIME

(cm/sec) oy TIME (Deg-1) @

o- 2 4 4 315 ~ 344

3-5 9 1 345 - 014 4 10-North

6-8 28 42 01s ~ 044

9-1 7 48 045 - 074

2-14 20 58 075 ~ 104 4 l6-rast,

as - 17 12 70 105 ~ 134

1s - 20 6 16 135 ~ 164

al 23 3 90 165 - 194 2 18-South

24 - 26 7 7 195 ~ 224

27 - 29 O05 98 225 - 254 24

30 - 32 O58 98 255 - 284 26 Sé-West:

33 - 35 0.2 98 285 - 314

36 - 38 Os 99

39-41 0.3 99

42 - 56 0.2 200

Average Speed = 13 cn/sec

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when the drogue panel was definitely not at 100 meters were not included in this average). The speed with the greatest

?time of observation was 6-8 cm/sec, with 28% of the time, compared to 21-23 cm/sec and 15-17 cm/sec following with 138

and 128 of the time, respectively. Ninety percent of ?the

time the speed was 23 cm/sec or less.

?This table also shows the great amount of time that the rogues spent moving westward (225 - 314 deg-r), 568. However, a significant portion of the time, 16%, was spent moving east- ward, and 108 of the time the drogues moved northward.

Table 32 shows the summary of the directional data expressed as either easterly (015 - 164 deg-T) or westerly (195 - 344 deg-7) for each day that the drogue was drifting under observa- tion, Although the greater numbers of days showed a westerly rift, numerous days also showed an easterly drift. Also

shown on this table are the surface water direction for each

day (where observed), the wind direction, and the future

atmospheric pressure (the pressure change within the next two-

three days). One or more of these three observations were

looked at as to a possible correlation with the eastward moving

100 meter deep water.

?he wind direction had a correlation coefficient of zero,

when compared to the 100 meter deep water direction. The wind

was out of the east, moving westerly, during every day, regard~

less of the water direction.

?The surface water direction was seen to occasionally change

direction, as seen historically, however, the correlation

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TABLE 32

POSSIBLE CORRELATES WITH 100M DEEP WATER SOUTHEAST OF PUERTO RICO

CRUISE DATE WESTWARD EASTWARD = SUPACE «WIND

195-344 DegT OLS16S Doge? DIRECTION DIRECIION AMOSMIERIC

® @ {TORRD) (TOWARD) _ PRESSURE,

November 9 54 46 west Low

Total = 54 46

Jan/Feb 28 12 982 Low

29 0 100 Low

30 50 29 Low

31 100 0 High

1 100 0 High

Total 50 42

February 18 190 ° West, High

1s oo 0 West, High

20 72 28 West High

21 190 0 West High

Total 91 9

March 24 75 ° West High

25 100 ° West High

Total 88 0

May 7 94 3 East West High

8 75 a7 East ?West High

9 78 22 East West High

10 60 31 East West High

in 30 60 Bast West High

Total 60. 30

gJune-10 10 33 58 Bi High

i 4 83 Ei High

12 100 ° East High

Total 19 59

June-25 25 100 ° West West High

26 88 6 West West High

Total 92 4

guly 1s 87 13 West Low

20 100 0 West low

a1 oo ° West High

Total 98 2

?TOTALS 65 29

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coefficient between the surface water direction and that at

100 meters was only 0.2.

Finally, as the rising and falling of the atmospheric Pressure is known to cause a local upwelling, it was considered that this ?down stream" upwelling may help to draw the deeper

water upward, under the lower pressure ar

As the weather path through the Caribbean is from east to west at about 5-7 om/sec, a 2-3 day anticipatory tine period may be expected between an effect at Punta Tuna to be seen and the causing low Pressure to make itself felt in the air at Punta Tuna. There~ fore, a correlation coefficient was computed between the direc~ tion of the water at Punta and the atmospheric pressure 2-3 days after the water motion observation was made. ?The pressure was considered low if it was less than two standard deviations below the mean pressure over the prior 14 days. If this cor- relation were high, it was hoped that such an upstream pressure change could be used as a prediction aid for future plant operations. The actual anticipatory pressure could be monitored in the Lesser Antilles. ?The correlation coefficient was only 0.3 which shows little, if any, relationship.

On at least one, and possibly two, different occasions, the 100 meter deep drogue panels were apparently swept into

the shallow waters of the south-central island shelf.

From Table 30, there is no apparent temporal pattern to

the speed values, as the valu

were all close to the average

Of 12 cm/sec, with the exception of the highly inaccurate

November 1979 cruise and the certainly damaged panel occurrence

of duly 1980.

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There appears to be no seasonality to the easterly flow,

as it appeared during late January, late May and June. The

winter occurrence most probably had a very deep Mixed Layer

Depth, whereas the MLD in the summer months usually decreases

considerably.

?There were frequent occurrences of tidal oscillations,

however, these events usually only acted as temporary perturbations in the predominant direction. certainly no tidal motion seemed to dominate the motion. The tidal system, centered in the North Atlantic (San Juan), with its associated semi-diurnal oscillations, appeared to be the stronger influence than the Caribbean system, with its predictive times indicated as "Galveston."

On at least one occasion clear evidence of inertial motion was seen. This was manifested as a clockwise gyre occurring

while the predominant motion was taking precedence.

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4.0 concLustons

?The significant conclusions resulting from this study

are as follows:

?The drogues used during the program did follow the

100 meter deep water. This was confirmed both theoretically

and experimentally by comparison with a current meter

at the same depth.

?The speeds of the 100 meter deep water were less

?than 24 cm/sec 908 of the time, (The percentage would

probably increase if better estimates of the time of

panel tears and breaks could be made.)

The speed of the 100 meter deep water was about

one-quarter that of the surface water during the few

occaisions that comparisons were possible.

--Usually the 100 meter deep water followed the

bathymetric contours, moving northeast or southwest from the drop-off site, The southwest direction was

most frequently seen. Historical records are similiar.

--Occaisionally the trajectory showed strong northerly excursions, but only after the trajectory had moved eastward, past the eastern coast of the island,

--Virtually no southward trajectory was seen.

"As no direct northward motion was seen immediately adjacent to the drop-off site, there may be little danger of the 100 meter deep water(OTEC effluent?) reaching the reef environment directly offshore at Punta Tuna,

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--There is a real probability that the 100 meter deep water (OTEC effluent?) may encounter the steep bathymetric rise off the central south coast of the island, thereby impinging onto the reef system in that area.

--There is no obvious seasonality in the motion at the 100 meter depth.

"Inertial motion is visible at 100 meters, however, this does not seriously alter the prevailing direction of flow.

--There are weak tidal influence:

which show an extremely minor influence on the prevailing direction of flow.

"Sone relationship may exist between easterly flow at the 100 meter depth and decreasing atmospheric pressure, but the predictability is poor.

-~There is no clear correlation between the direction of the water at 100 meters depth and that at the surface.

-~There is no predictive correlation between the

@irection of the water at 100 meters depth and the sea

surface wind direction.

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5.0 RECOMMENDATIONS

?The following are the most important recommendations

resulting from the activities, results, and conclusions

of this program:

Determine the plant design configuration in order

to allow a more precise effluent characteristics and depth prediction.

Develop modeling capabilities in anticipation of plant

design characteristics and more complete water flow patterns.

w-As the observed trajectory at 100 meters depth aia

impinge upon the south-central reef area, separate effluent

systems for both the cold and warm water from the plant may

be advantageous, if this separation would avoid effluent/

reef interaction.

?Increase the time scale of the ocean measurement

Programs to extend over many years so as to allow long-term

temporal patterns to develop.

~-Look for clear, definable, and discernible predictive

correlates to anticipate short-term effluent direction

changes during plant operation.

~-Combine eulerian and Lagrangian measurements to

develop a better spatial and tenporal understanding of the potential effluent flow pattern.

--Use a constant density (rather than-constant depth) lagrangian follower to determine changes in density with

depth near the deep-sea boundaries

14s,

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Measure both the dispersion and diffusion characteristics of the suspect water column to estimate the decreasing concentration of an effluent as both a function of time

and distance from the plant.

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