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ECOLOGICAL ANALYSIS OF SPATIAL AND TEMPORAL PATTERNS OF PELAGIC ECOSYSTEM COMPONENTS POTENTIALLY INTERACTING WITH AN OTEC PLANT NEAR PUNTA TUNA, PUERTO RICO

PHYSICAL CHARACTERISTICS

FINAL REPORT

Submitted to:

DOE/OHER

J.M. López and L.J. Tilly
Editors
Center for Energy and Environment Research
University of Puerto Rico
College Station
Mayaguez, Puerto Rico

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CENTER FOR ENERGY AND ENVIRONMENT RESEARCH
UNIVERSITY OF PUERTO RICO U.S. DEPARTMENT OF ENERGY

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

Submitted to:

DOE/OHER

by

John A. Fornshell
Center for Energy and Environment Research
Marine Ecology Division
Mayaguez, Puerto Rico 00708

FOREWORD

This document is part of the final report for the Department of Energy Project under Contract No. DE-AC05-760R01833, which includes five main sections: Physical Characterization, Plankton, Primary Productivity, Chemical Characterization, and Summary and Synthesis. The document is primarily organized as a collection of preprints of articles being submitted for journal publication. Once all sections are completed, the entire series will be combined as a five chapter volume dealing with the environmental aspects of the siting, construction and operation of an Ocean Thermal Energy Conversion Plant based off the south coast of Puerto Rico. Of prime concern in these studies, as suggested by the title, is the relationship among the scale of distribution of natural phenomena, the scientific detectability of pattern, and the alterations of pattern likely to be caused by the hypothetical 100 MWe power plant adopted as the design unit.

ABSTRACT

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

The Center for Energy and Environment Research has conducted hydrographic studies designed to characterize the Punta Tuna, Puerto Rico area as a potential site for an OTEC power plant. Seven cruises were conducted at approximately two month intervals. Each cruise included at least 22 hydrocast stations, six done as serial stations in a small area to reveal temporal and small scale variability. Two long-term serial occupations of the Benchmark Station were conducted with 17 hydrocasts on the first and 364 bathythermograph drops on the second.

The results of the analysis of these data so far indicate a bi-seasonality in the dynamics, Potential Energy Anomaly and Geostrophic Kinetic Energy. Mesoscale eddies and meanders are a common feature of the circulation pattern on Puerto Rico's southern coast. Our time series studies have shown the existence of a very energetic internal wave field with relatively large amplitude waves at the diurnal and semi-diurnal tidal frequencies. Our current meter work has shown the mean speed to be much larger than the mean flow, with no component of the flow accounting for more than 8% of the total signal.

INTRODUCTION

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

Introduction to the Area

The earliest organized and scientifically based study of the physical oceanography of the Caribbean Sea was published in 1837 by the Spanish Direction of Hydrography. This report was confined to surface water movements and in many ways anticipated the U.S. Navy's Pilot Charts in its content. Wust (1964) summarized and extended greatly our knowledge of the Caribbean. He held the wind to be the main driving force of the surface currents. His surface current charts which were largely based on "set and drift" observations show a westward drift on the southern side of Puerto Rico of .4 to .8 statute miles per hour. Wust (1964) and Morrison & Nowlin (1982) also categorized the various water masses present in the Caribbean as follows: 0-80/100 m Tropical Surface Water, $T^\circ C \geq 25^\circ C$ Salinity 33 to 36$^\circ/_{\circ\circ}$ 100-200 m Subtropical Underwater, $20^\circ C \leq T \leq 25^\circ$ and salinity 36.800-37.200$^\circ/_{\circ\circ}$; Sargassos Sea Water, 200-600 m, 7° T° 20°C and salinity 35$^\circ/_{\circ\circ}$ to 36.8$^\circ/_{\circ}$, Sub-Antarctic Intermediate Water 600-800 m, 6° T° 7° and salinity 34.9$^\circ/_{\circ\circ}$; Atlantic Deep Water or Venezuelan Basin Water $T^\circ < 6^\circ C$ salinity $>$34.9$^\circ/_{\circ\circ}$. The oxygen minimum is typically just above the Subantarctic Intermediate

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

Sturges (1965) made a volumetric analysis of the Caribbean Sea waters. He found more than half the water in the Caribbean Sea to be within .1° C and .02 °/₀₀ of 3.9° C and 34.98 °/₀₀. Sturges stated that the surface waters of the Caribbean Sea are formed by water flowing in through the eastern rim, the passages between the Lesser Antilles. This dominance, he contended, extended only to a depth of 800 to 1000 m. Sturges (1965) based on his water mass analyses of potential temperature and salinity relationships argued that the water at and below the 800 to 1000 meter level entered through the Windward Passage between Hispañiola and Cuba. Sturges concluded that a dynamic pressure gradient inhibited inward flow below this depth in the Jungfern-Anagada Passage. Morrison and Nowland (1982) have studied the formation of Caribbean Sea water masses using T° C, S °/₀₀, dissolved O_2, phosphates, nitrates and silicates as water mass indicators. They strongly amplify the work of Sturges (1965).

Ingham and Mahnken (1966) also observed indications of surface inflow in the passages between the Lesser Antilles and they saw evidence of turbulent vertical mixing in a cyclonic eddies resulting from the surface flow around the island of St.

Vincent, Febres-Ortega, et al. (1976) also observed an eddy in the lee of St. Vincent Island. Fett and Rabe (1976) saw evidence of eddies in the lee of Granada Island in satellite data.

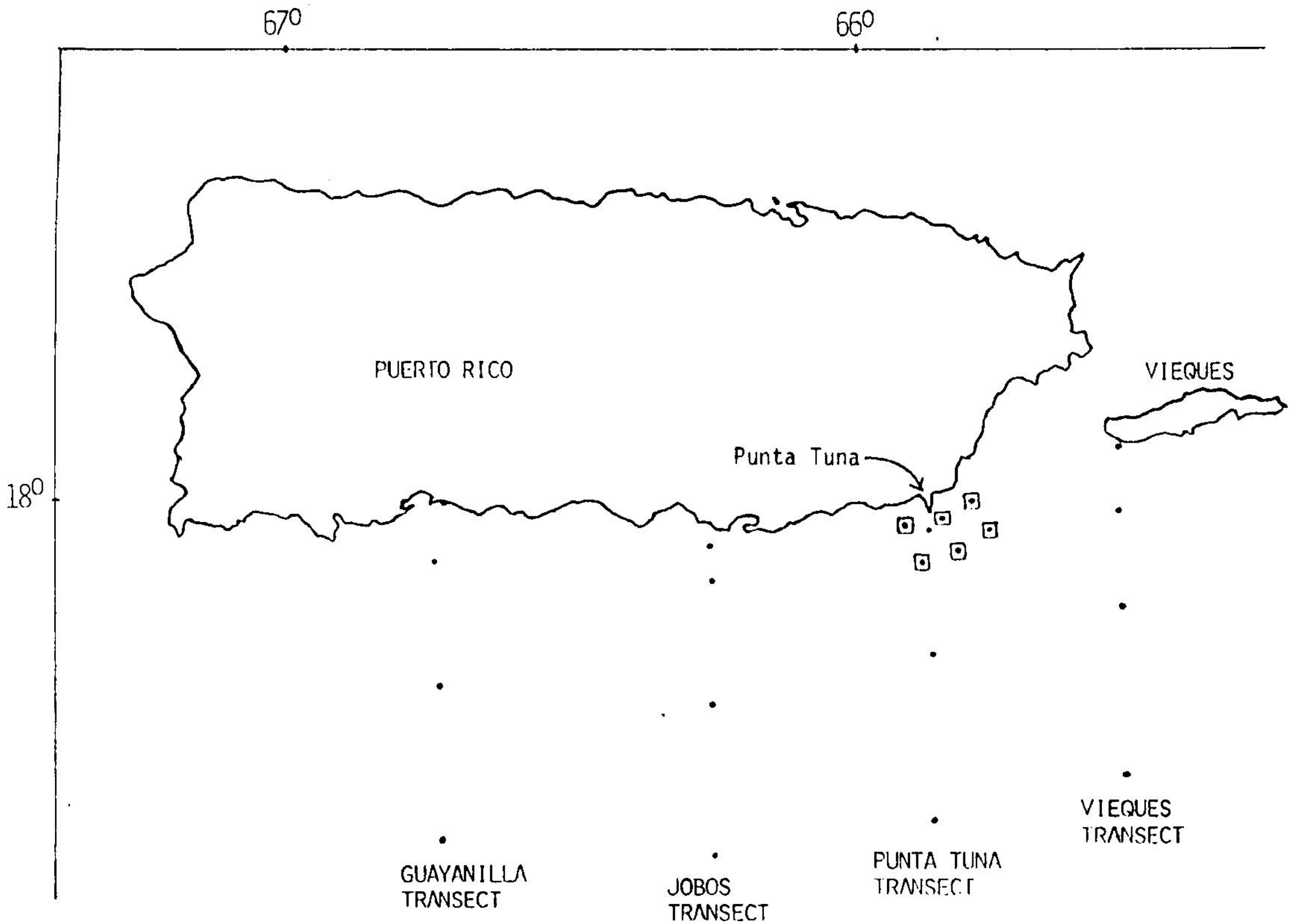
Gordon (1967) extended the earlier work of Wust (1969) and Sturges (1965) on the general circulation in the Caribbean. He based his study on baroclinic geostrophic current calculations using data from several transects across the Caribbean Sea and one across the Straits of Yucatan. The westward flowing current has its axis in the southern third of the Caribbean, though the western flow was found all the way up to the Greater Antilles. Gordon found the level of zero-zonal velocity to vary from $\leq$800 m to $\geq$1700 with the shallowest levels being along the southern and eastern boundaries, north coast of South America and the Lesser Antilles. Because the zero velocity level was found to be shallower than the sill depths for many of the inter-island passages, outflow into the Atlantic seemed possible. In his current calculations just west of the Antilles, Gordon found local areas of eastward flow. These may have been similar to the eddies found by Ingham et al. (1966).

Gordon extended Wust's hypothesis of trade wind dominance of the surface currents by modelling the Ekman Mass Transport in the Caribbean Sea. His calculations resulted in a baroclinic field extending vertically to a depth of between 1000 and 1500 m. This was sufficient to produce the westward moving current throughout the Caribbean so persistently described. The agreement between the model's predicted baroclinic field and the observed field was very good. Gordon's modeling efforts also predicted a deepening of isotherms and isohalines towards the northern boundary. Again the agreement between observation and theory was reasonable.

Sturges (1970) made a five-day current meter study of the bottom flow through Anegada-Jungfern Passage. He found the flow to be oscillatory with a predominantly tidal frequency and a net inflow into the Caribbean of $6X10^3$ m S^{-1} for brief periods of a few hours. This was in contradiction to his earlier work (Sturges, 1966). Metcalf (1976) used hydrographic sections on the Atlantic and Caribbean sides of the passages between the Lesser Antilles to study water exchanges between the two bodies. In addition, direct current meter measurements were also made. His results are summarized as follows: Inflow of water through Grenada Passage 10 Sv, St. Vincent Passage 10 Sv, St. Lucia Passage 6 Sv and Dominica Channel less than 1 Sv. Metcalf moored two current meters near the bottom in the Anegada-Jungfern Passage. They confirmed the hydrographic data of Ca. 1.39 Sv into the Caribbean above 700 m and Ca. .7 Sv out of the Caribbean below 700 m. The direct measurement showed the flow to be unsteady with reversals showing diurnal and semi-diurnal tidal frequencies, seiche frequencies and storm surge effects.

SCOPE OF RESULTS

The Marine Ecology Division of the Center for Energy and Environment Reseach has collected a large amount of physical oceanographic data in the Caribbean Sea south of Puerto Rico and Vieques. This data set includes a large volume of data of many different forms: (1) 154 hydrographic stations, a 22 station grid occupied seven times at two month intervals for 13 months (Fig. 1). This is a larger hydrographic data base than that used by


67°
66°
18°
PUERTO RICO
VIEQUES
Punta Tuna
GUAYANILLA TRANSECT
JOBOS TRANSECT
PUNTA TUNA TRANSECT
VIEQUES TRANSECT

Wust, 1964; Sturges,1966; Gordon,1967 or Morrison and Nowlin, 1982 and represents the first regional quasi seasonal physical study of this part of the Caribbean Sea. (2) The data set also includes two 8-day and five 1-day studies of variability at one point. These data include mechanical BTs (360) a single 8-day study with one drop each 30 minutes and 18 hydrocasts over an eight day period 12 hr intervals with XBTs in between, (3) a 131 day current meter record from Benchmark including speed, direction and temperature at 20 m and 200 m has also been made.

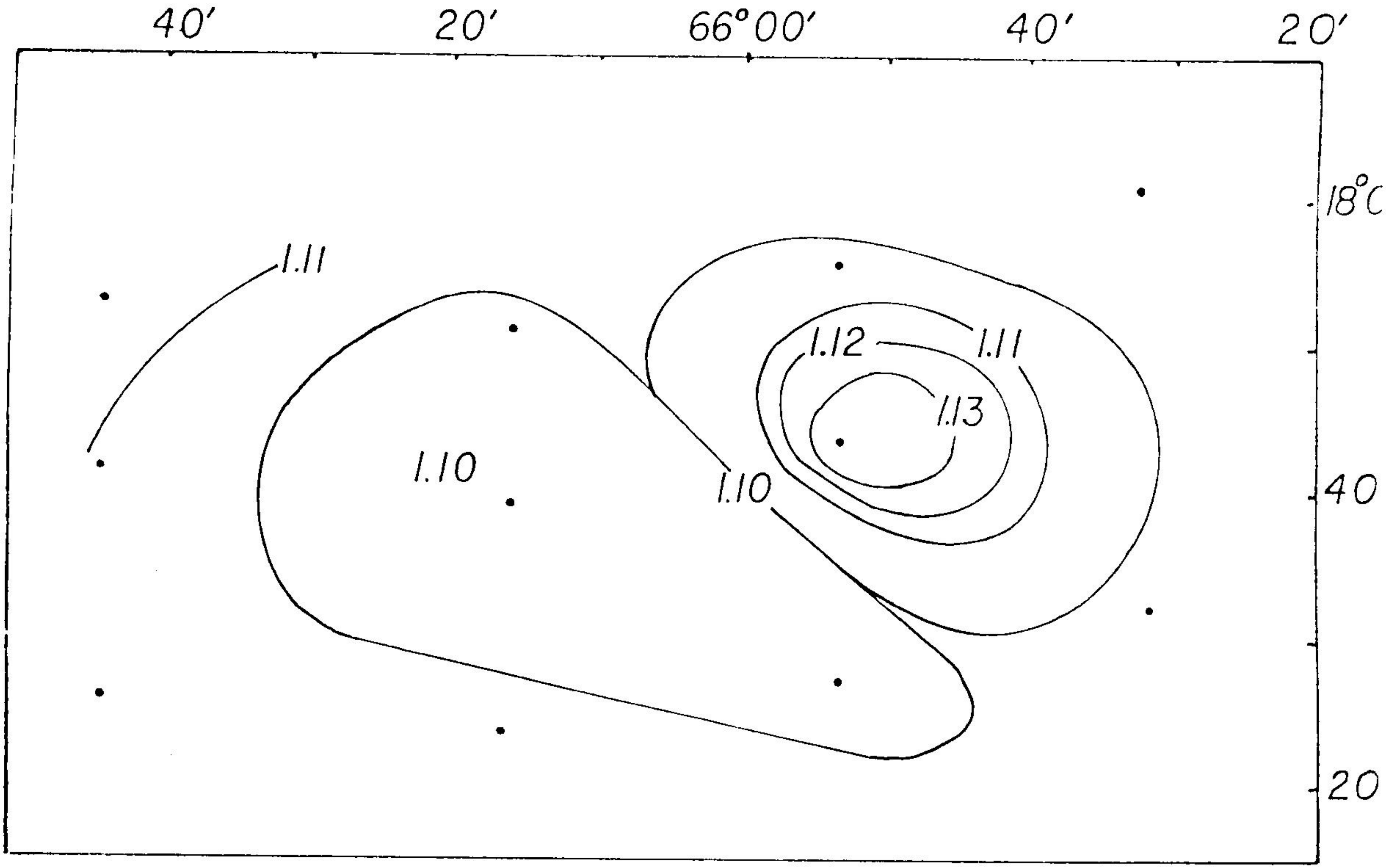
Data reduction of the hydrographic and bathythermographic data to geophysical numbers has been completed. The results are not fully analyzed but preliminary work has shown that small eddy-like features are common. These eddies have a horizontal length scale on the order of 10's of miles and appear to be island wake phenomena, not like the small eddies recently reported from POLYMODE work (Dugan et al., 1982). Examples of these eddies and meanders are shown in Figures 2,3,4 & 5. La Fond's method for determining the reference level was used (in Newman and Pierson, 1966). Using this method we found the 500 dB level to be the reference level.

Hydrography

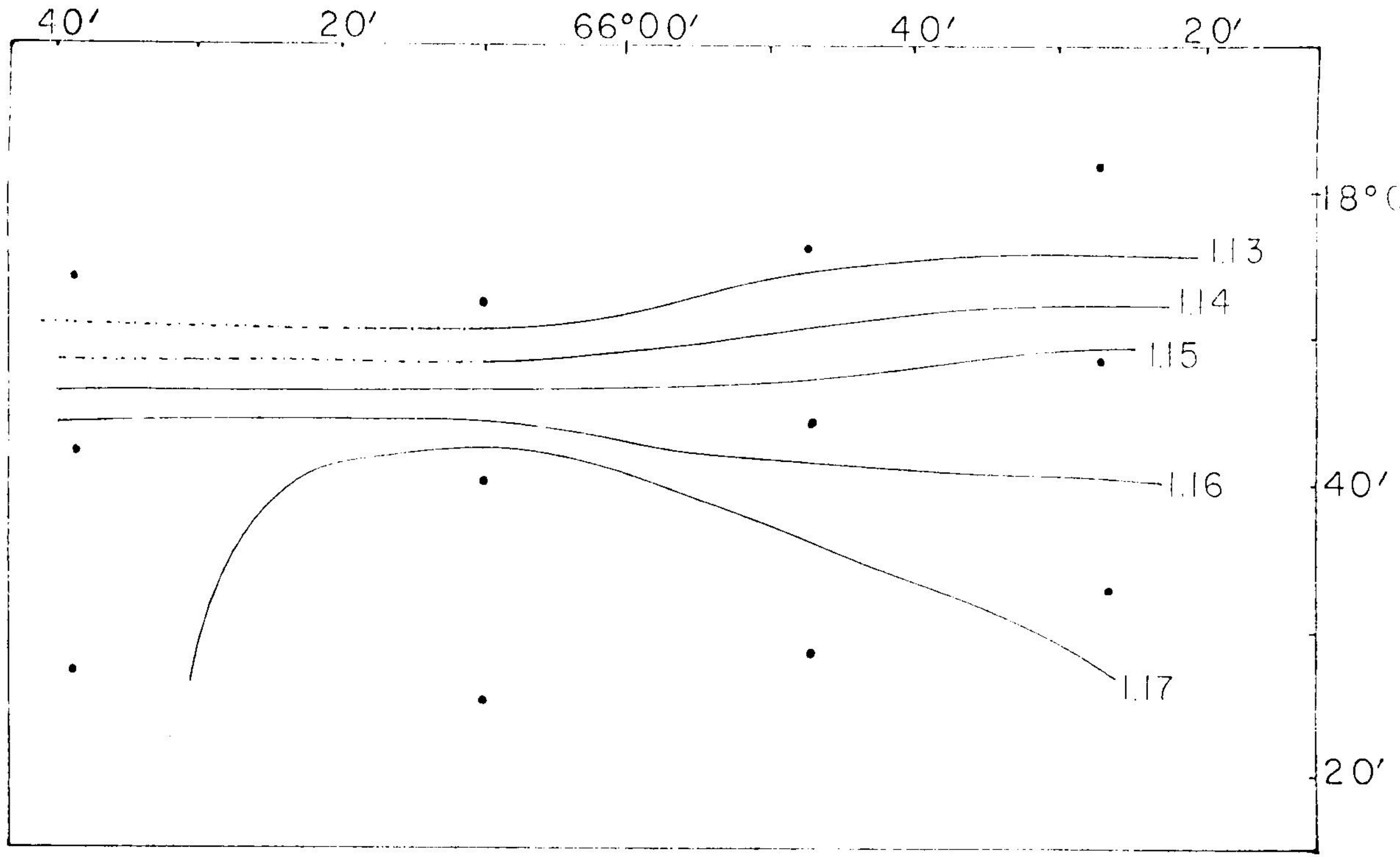
The January cruise results showed the surface baroclinic currents to be weak and variable with an average speed of 8 cm/sec. Below 100 m the flow was well organized to the west. A 10 to 15 cm per second maximum was found at 200 m. The March cruise results again showed weak and disorganized surface baroclinic currents with maxima of 5 to 10 cm/sec occurring below 100 m and a well organized westward current. South of Guayanilla

Bay there was a small anticyclonic eddy extending to at least 400 m with a radius of about 10 nmi. The May cruise results show two eddies embedded in the mean westward flow. One of these eddies, south of Punta Tuna was anticyclonic and extended to a depth of 400 m. The other, south of Jobos Bay, was cyclonic and extended to a depth of more than 600 m when referenced to the 1000 dB level. In July a well organized eastward flow dominated the surface flow, but became westward below 200 m. September's results showed what appears to be a strong, but small, anticyclonic eddy south of Vieques. This meander or eddy extends to at least 400 m. The November cruise results showed again westward flow below 200 m with a poorly organized weak surface pattern. Finally, in February 1981, there were indications of a subsurface anticyclonic eddy south of Vieques with maximum currents at 200 m and a vertical range extending from 100 to 400 m depth. The eddies observed in the results from the seven cruises are either subsurface or extend well below the Ekman layer depth; hence, they are probably not wind-generated. They are not associated with water mass anomalies as in the case of POLYMODE eddies (Dugan, et al., 1982). Their length scale, 10s of nmi, is the same order of magnitude as the Windward Islands located upstream to the east of our survey area. Hence, it appears that they are an island wake phenomenon physically analogous to a Von Karmen vortex street. Such eddies have not been reported from the northeastern Caribbean Sea before. This survey is the first with a station spacing on a grid scale fine enough in space and time to adequately define these meso scale features. The surface dynamics height fields for May, July, September 1980 and February 1981 are shown in Figures 2-6.

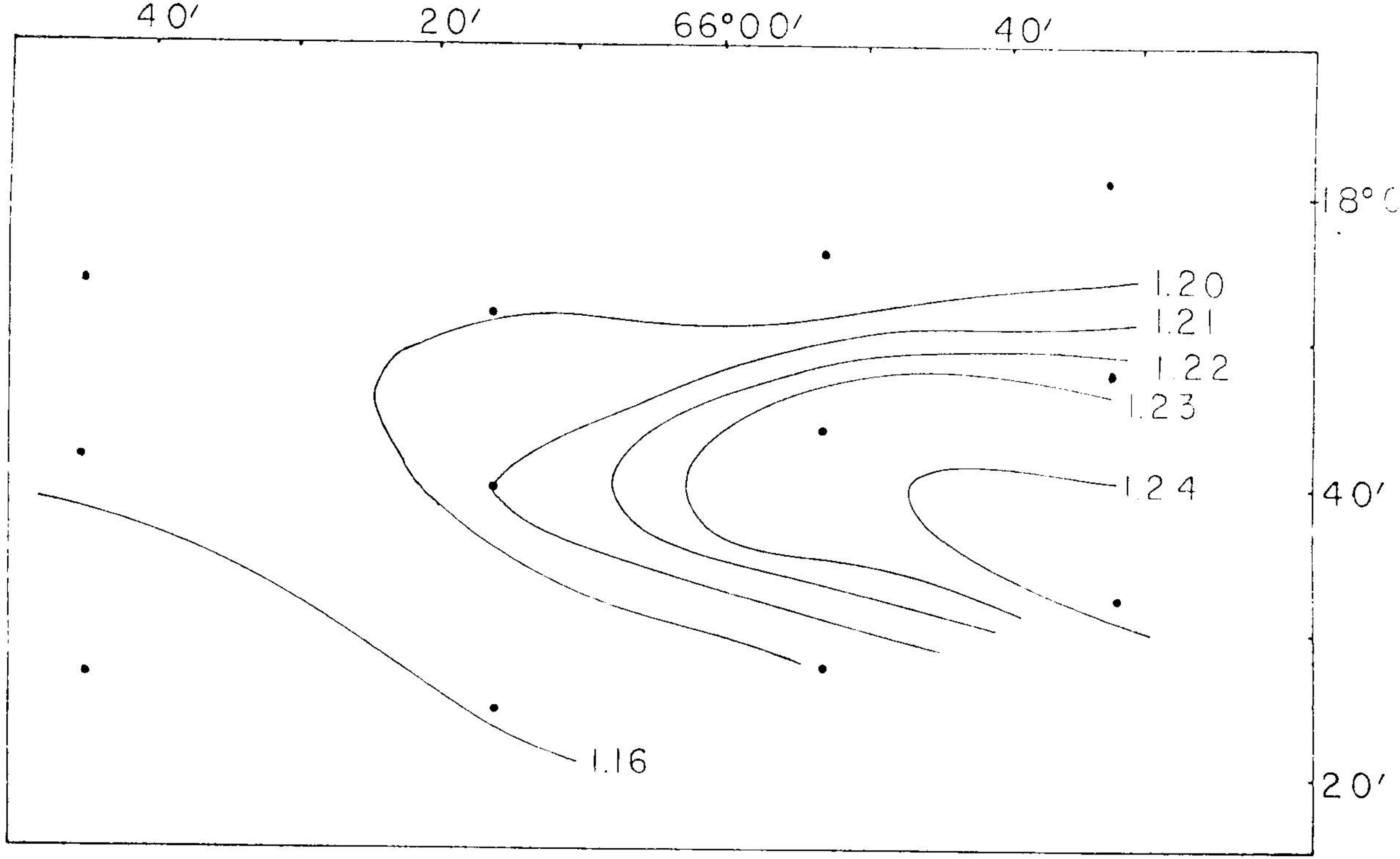
May 1980 0/500



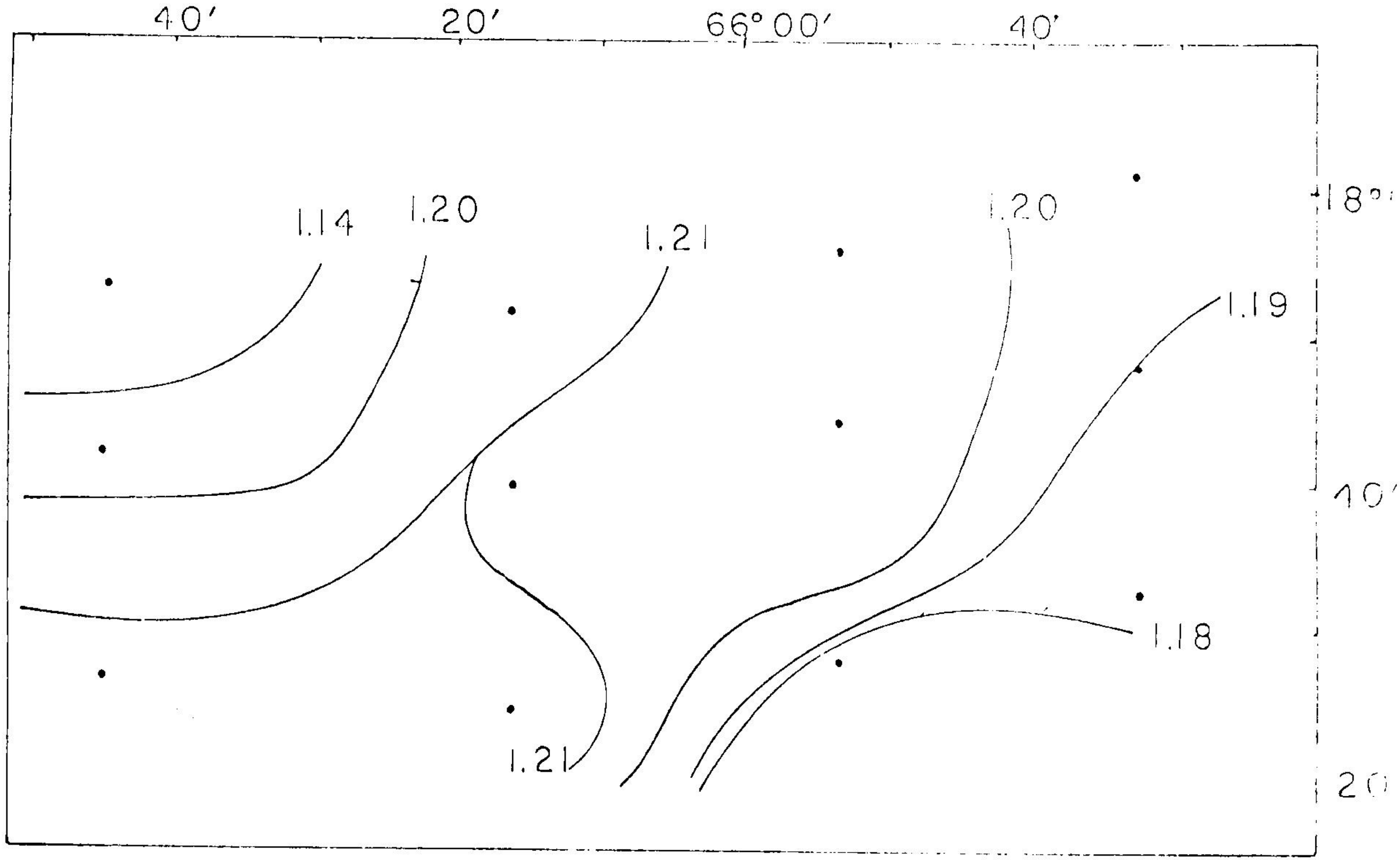
July 1980 0/500



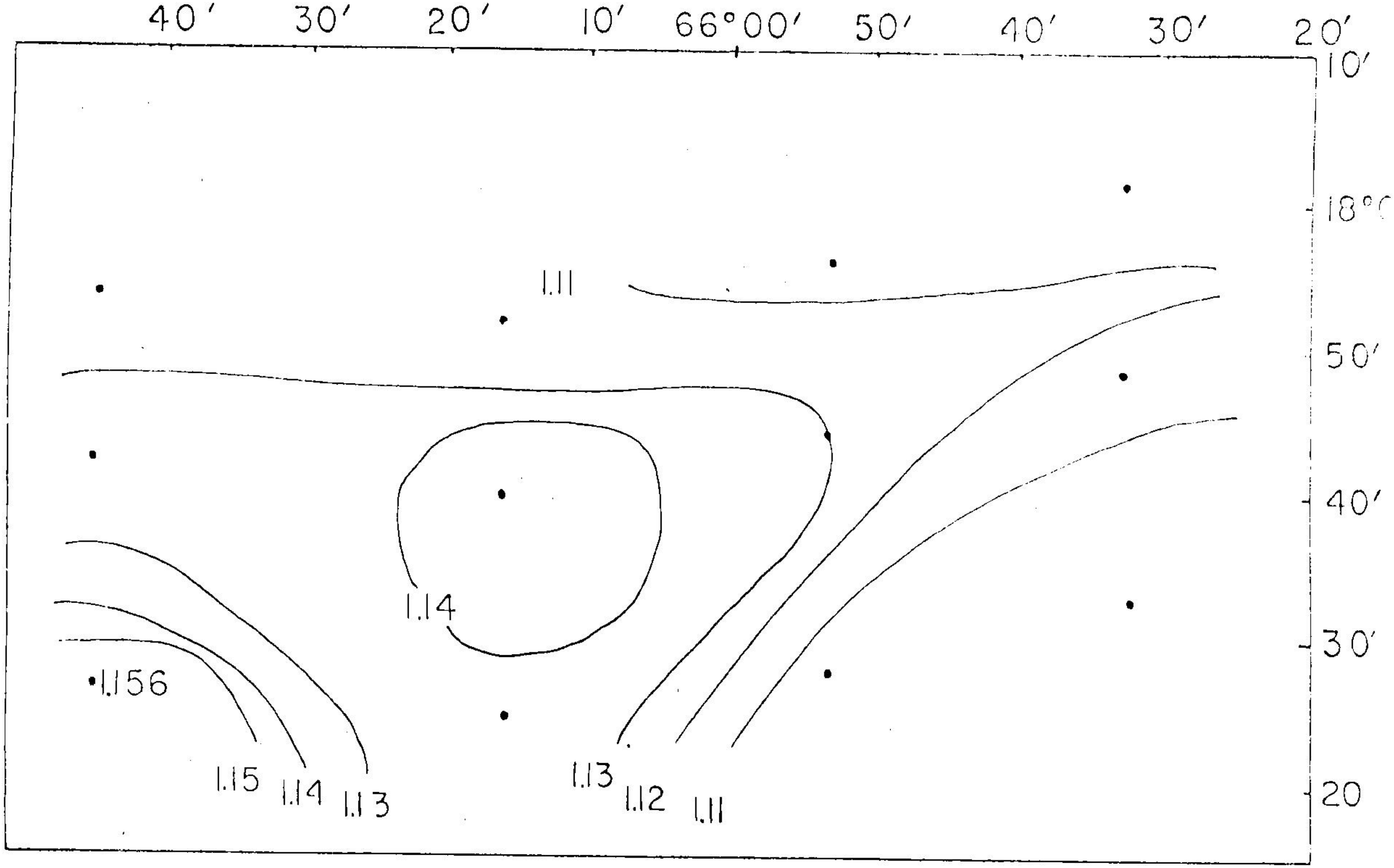
Sept. 1980 0/ 500



Nov. 1980 0/500



Fab. 1981 0/500

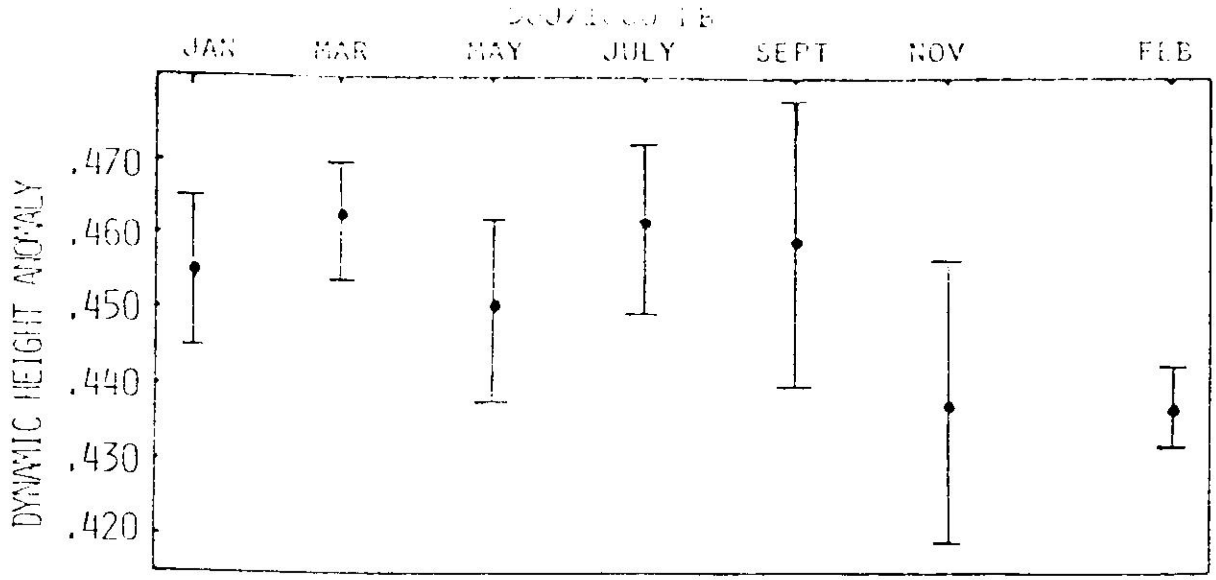


There is another feature observed clearly for the first time here. There appears to be a significant seasonality in the northeastern Caribbean. The mean dynamic height anomaly increases by 5 to 10 cm relative to the 500 dB level. This increase is such that the range of dynamic heights within cruises does not overlap (Fig. 7). The observed increase in dynamic heights produces an increase in the potential energy anomaly. This change was recorded in July, September and November of 1981 and was restricted to the upper 500 m. The increase in mean dynamic height and potential energy anomaly was associated with lowered salinities and elevated temperatures in the upper ocean at this time.

Time Series Studies

On each of the seven cruises one station called, Benchmark, (Figure 1) was occupied for a period of 24 to 48 hours during which hydrocast to 1000 m and XBT drops to 750 m were conducted. In addition, two of the stations in the small scale grid were also occupied. This sampling scheme was designed to reveal temporal and spatial variability on a time scale of less than one day and a length scale of less than ten kilometers. The results of four of these surveys are shown in Figures 8-10. The results show internal waves with an amplitude of 50 to 80 m at 700 m and a period approximating an M_2 tide.

To more precisely study the internal wave field a study employing hydrocasts to 150 m at 12 hour intervals was conducted. Internal waves were again observed in the upper ocean isotherms and isohalines (Figures 11 and 12). These internal waves have a diurnal periodicity, M_1, and appear to be superimposed on a


JAN
MAR
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DYNAMIC HEIGHT ANOMALY
.470
.460
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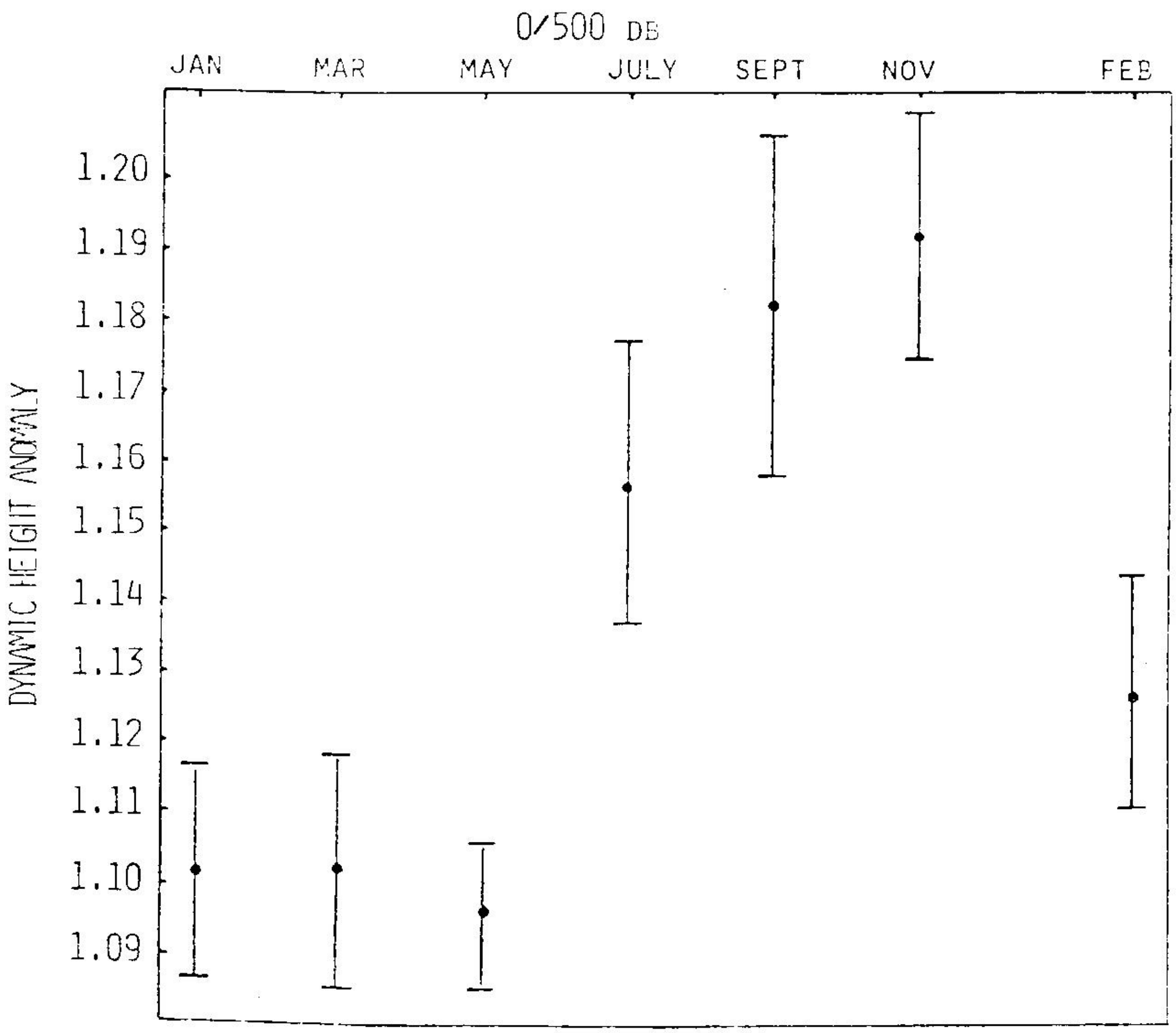
.430
.420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1.20
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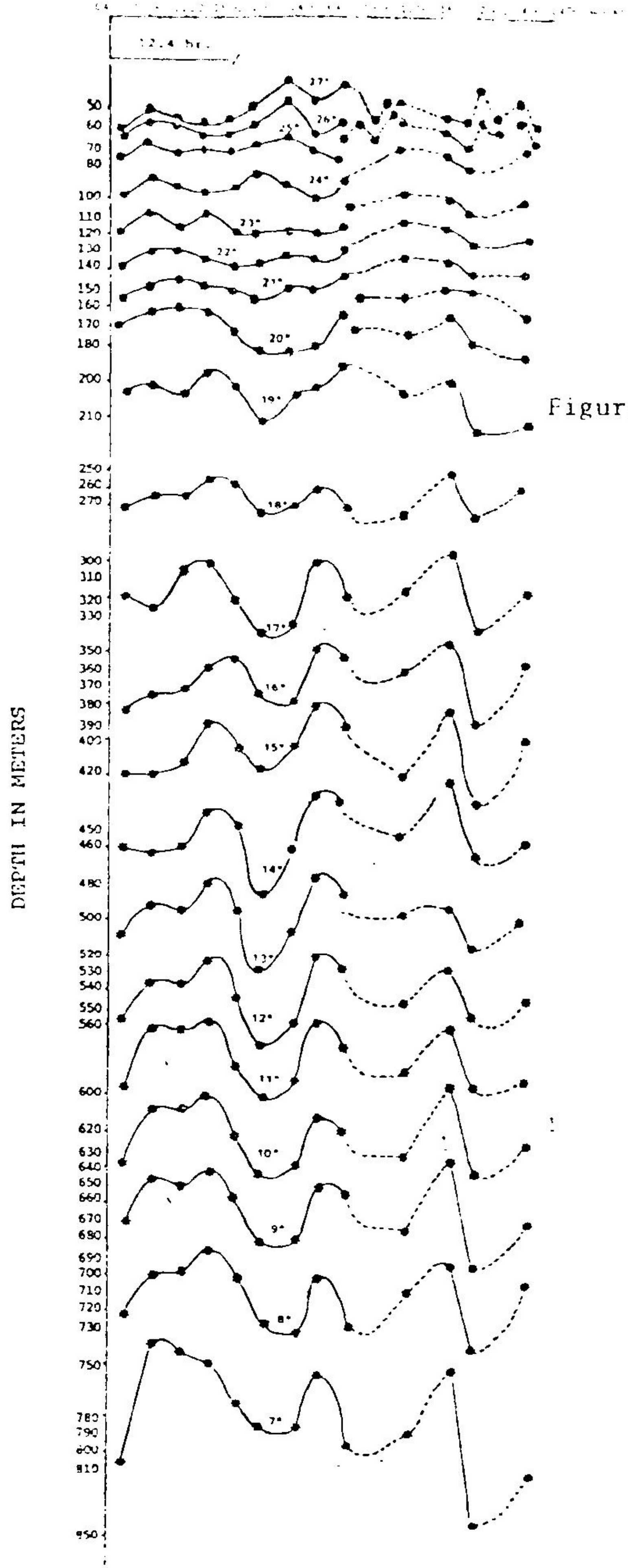


Figure 8. Vertical distribution of isotherms at Benchmark station during May 25 through May 27, 1980.

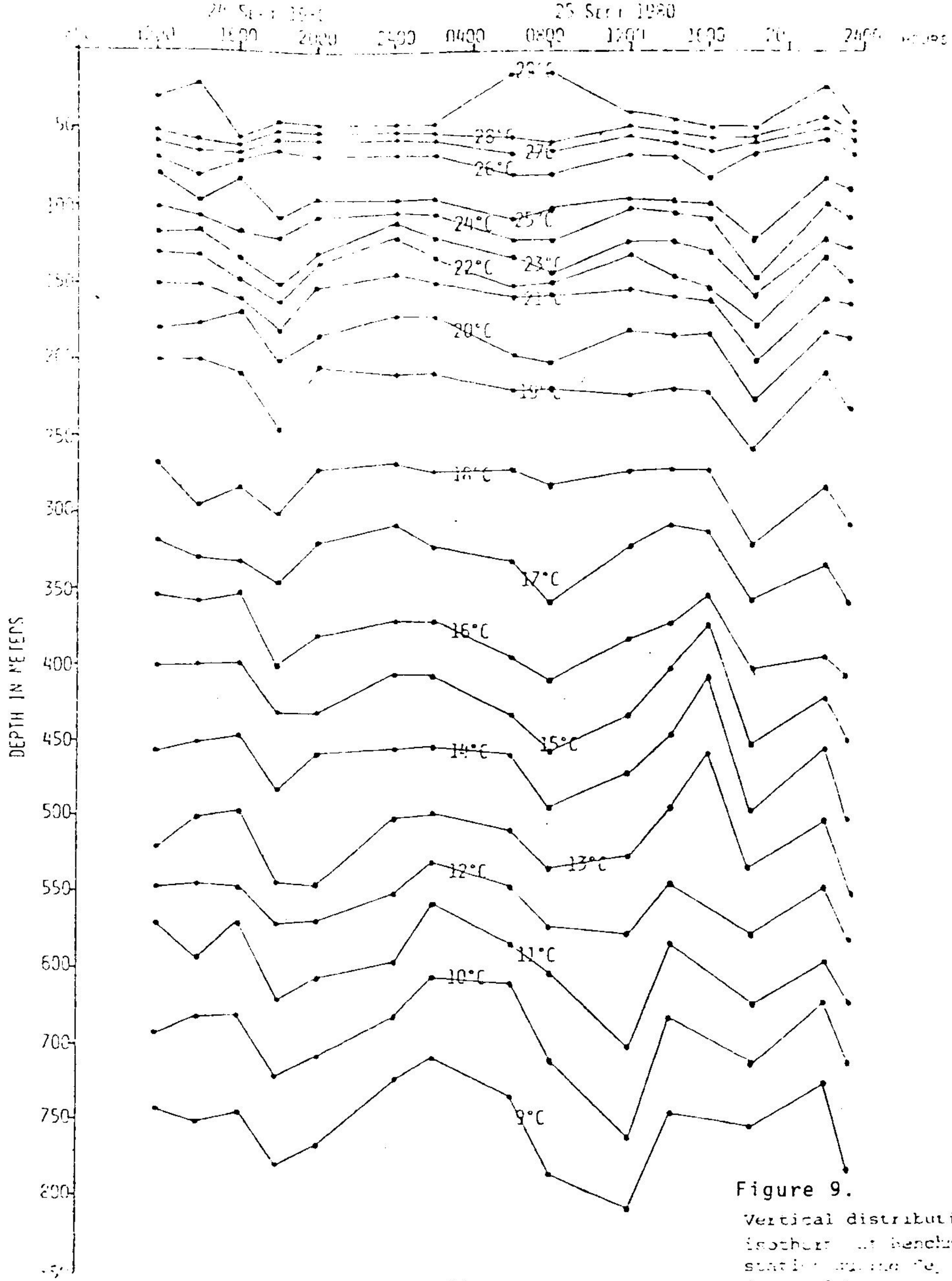


Figure 9.

Vertical distribution of isotherms at benchmark station ...

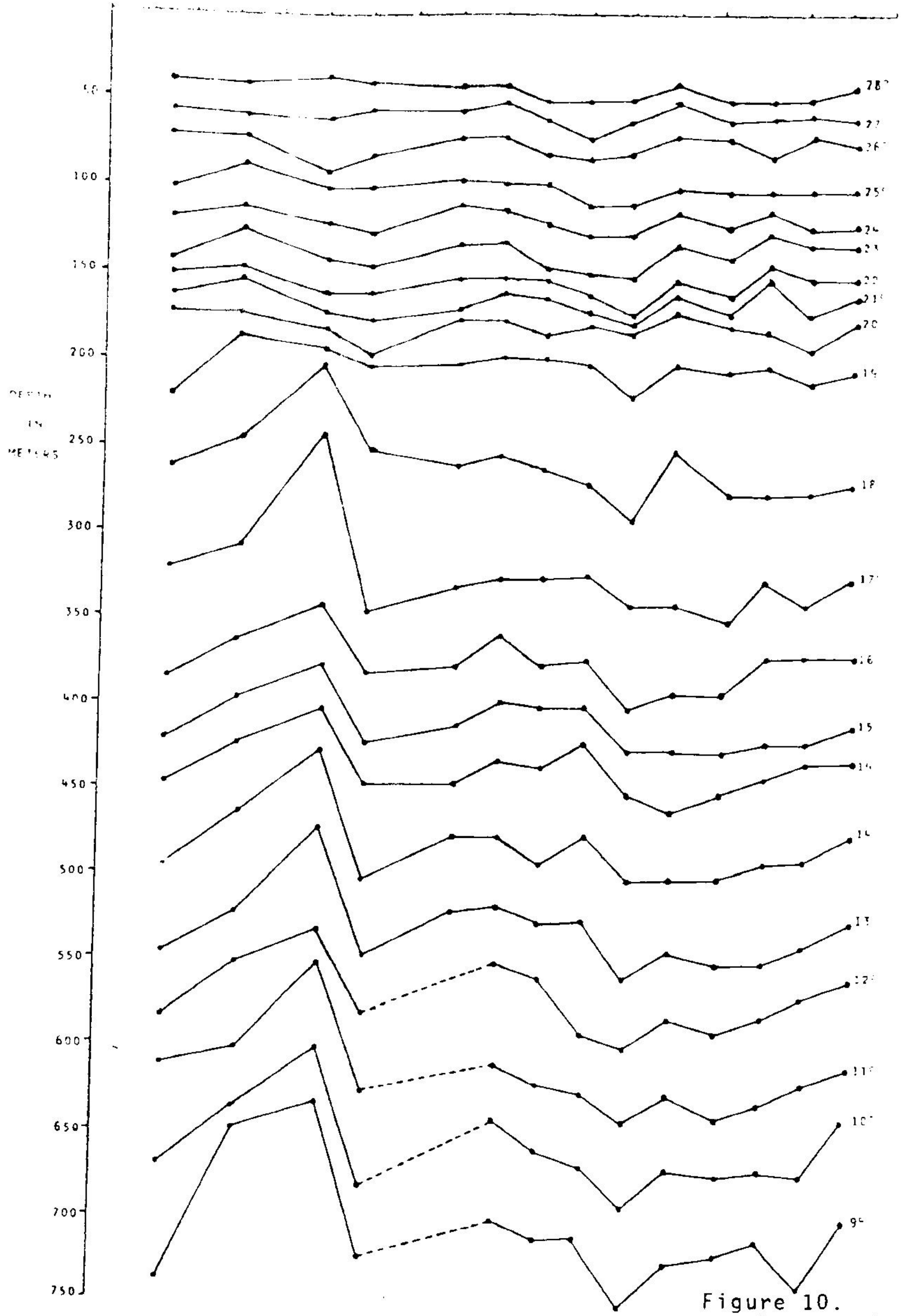
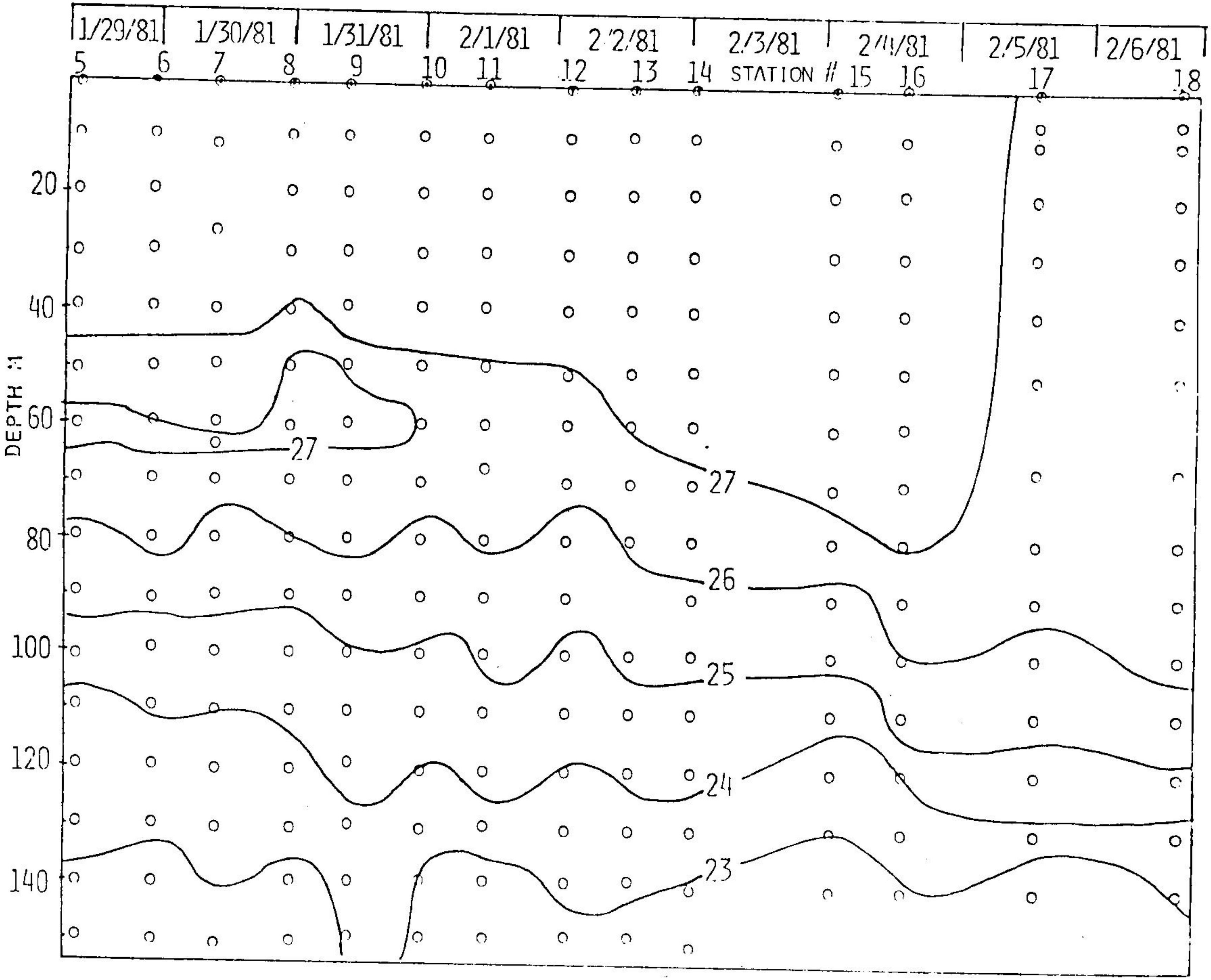


Figure 10.
Vertical distribution of isotherms at Benchmark station during Nov. 12-13, 198[illegible]


1/29/81
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STATION #
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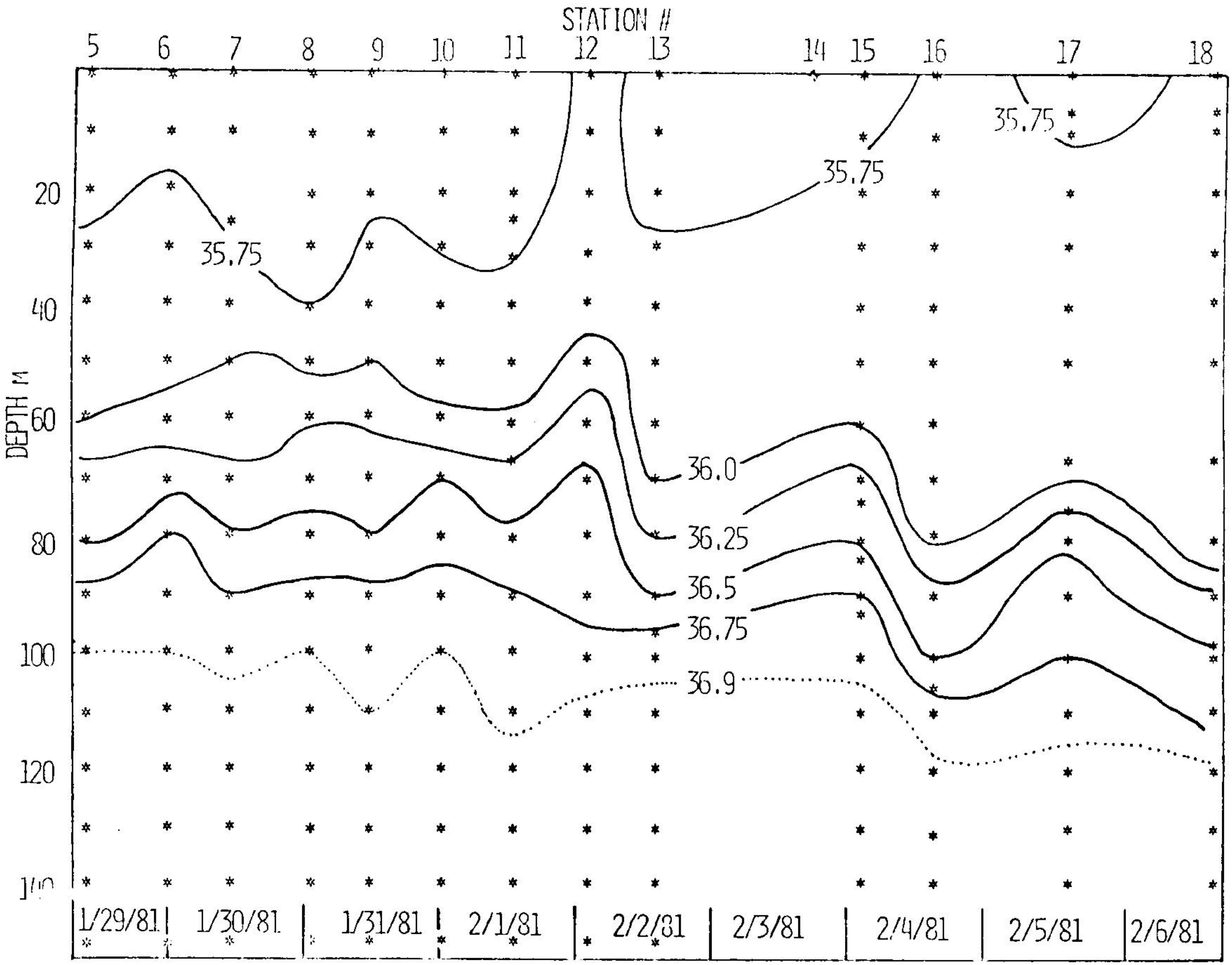

STATION #
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DEPTH M
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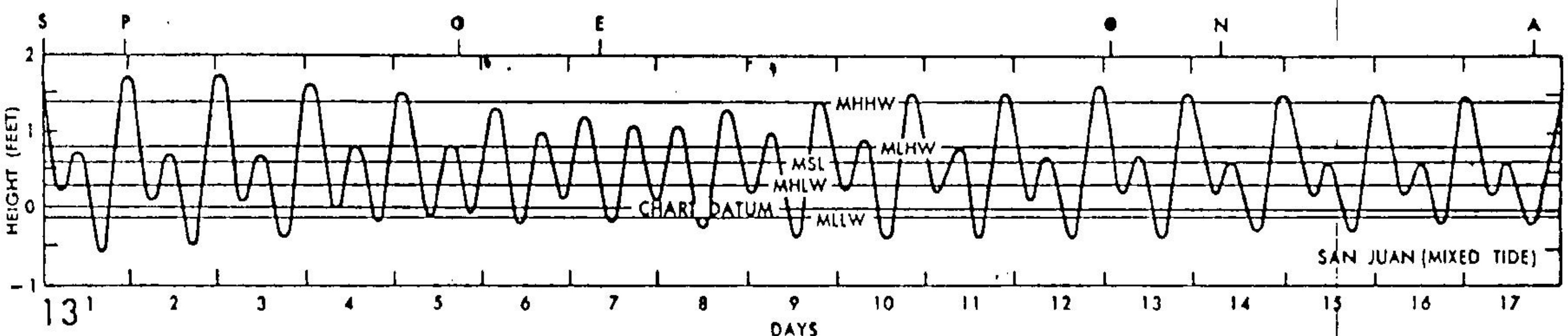
35.75
36.0
36.25
36.5
36.75
36.9
1/29/81
1/30/81
1/31/81
2/1/81
2/2/81
2/3/81
2/4/81
2/5/81
2/6/81

general deepening of the isotherms and isohalines. The apparent deviation in the main internal wave periodicity from an M_2 to an M_1 tidal period may be an artifact of the sampling interval and the fortnightly variability of the tidal cycle. Looking at the tides in San Juan on the north side of the island, one sees the fortnightly tidal cycle varying from no semi-diurnal inequality to a very pronounced semi-diurnal inequality (Fig. 13). If this tide were sampled on a 12 hour basis for eight days, it would be difficult to discern the true semi-diurnal nature over much of the cycle. Similar variations are possible in the internal tidal waves at Punta Tuna (Benchmark Station) on the south coast. If the internal tides develop a strong inequality in amplitude during the fortnightly cycle, a twelve hour sampling interval for only eight days could miss the presence of the minor semi-diurnal component.

The deepening of the isotherms and isohalines may be related to the advection of an eddy through the survey area. The February 1981 cruise in the seven cruise sequence was conducted three weeks after the 8-day serial occupation. As can be seen in Figure 6 we see the surface dynamic height field at the time of the cruise. In the upper 200 m the flow through Benchmark was eastward. South of Vieques there was a cyclonic eddy between 100 and 400 m. If this eddy had been advected through the Benchmark site this would have produced the observed deepening of the isotherms and isohalines.

The Benchmark station was again occupied between July 11 and July 18, 1981. On this occasion mechanical BTs were dropped at 30 minute intervals for eight days. The results of this sampling effort showed an internal wave field with peaks in the spectrum


S
P
O
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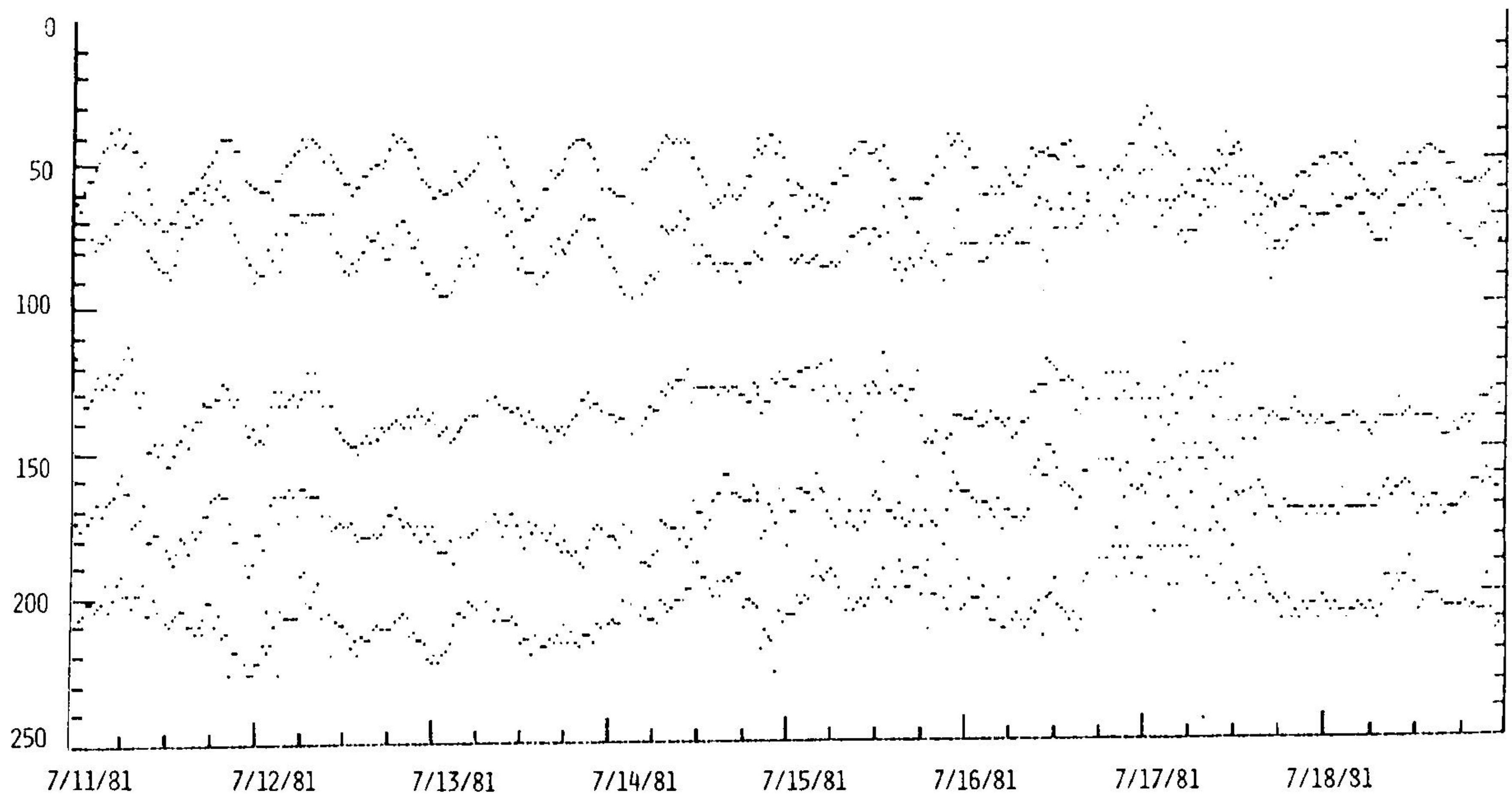
A
MHHW
MLHW
MSL
MHLW
CHART DATUM
MLLW
SAN JUAN (MIXED TIDE)
HEIGHT (FEET)
2
1
0
-1
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
DAYS

at 0.08 CPH and 0.6 CPH (Figure 14). The semi-diurnal variation in the thermocline was between 30 and 40 m at the maximum. Such variation is as large as that observed in the mean depth of the thermocline, seasonally. Superimposed on the M_2 period internal waves are smaller waves of amplitude less than 5 m and a period of 0.6 CPH (Figure 14).

<u>Current Meter Work</u>

At the start of the second 8 day serial occupation of the Benchmark station, 11 July 1981, a current meter deployment was initiated from a ship anchored at this station. The current meters were deployed at 20 m from 11 July 1981 until 17 November 1981 and 200 m 29 July 1981 until 17 November 1981. Both meters were equipped to measure temperature as well as current speed and direction. The data tapes have all been visually examined (by Fornshell) and appear to contain a good record over the 131 days of the current meter deployment. The format of the data record is an analog chart of speed direction and temperature. These must be read manually in order to generate a digital data format which can be fed into a computer for automatic data processing.

The current meter data for the month of October have been reduced to geophysical numbers and Fourier analyzed by Jorge Capella. These data show a mean current of 4.98 cm/sec at 241° T. The mean speed is 14.79 cm/sec. The Fourier analysis showed that the variability was fairly evenly distributed with no more than 7% of the variability being accounted for by any time period between 14 days and twenty minutes. This work is both a part of the Marine Ecology Division's OTEC/OHER research and part of a Master's Thesis by Jorge Capella.


0
50
100
150
200
250
7/11/81
7/12/81
7/13/81
7/14/81
7/15/81
7/16/81
7/17/81
7/18/81

SUMMARY

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

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

1. The flow pattern most often observed is westward flow.
2. Mesoscale eddies appear to be common features in this area.
3. The hydrography of these mesoscale eddies indicate an origin as vortices shed by islands in the windward chain.
4. There is a pronounced seasonality in the dynamic height field which is confined to the upper 500 m.
5. Internal waves are a significant source of temporal variability in our survey area.
6. The largest internal waves are internal tides.
7. The internal waves may account for as much as 75% of the temporal variability in the dynamic heights.

These results have implications for the possible operation of an OTEC power plant in this area. First, our results show that there is a year round 20°C+ thermal gradient between the surface and 1000 m at Punta Tuna. At times it is near 25°C. The ambient flow pattern is characterized by a mean flow towards the west at about .1 knots. Superimposed on this is a mesoscale turbulence composed of meanders and eddies. These appear at this time to be von Karmen vortex - like eddies being generated by the Virgin Islands to the east of our survey area. Against the background of such turbulence the effects of an OTEC plant on the mean flow will be undetectable.

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

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

2. Internal waves of M_2 and M_1 period at Punta Tuna, Puerto Rico. J. Geophysical Research. J.A. Fornshell and J. Capella.

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

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

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

6. Dissolved oxygen distribution in the northeastern Caribbean Sea. J. Capella. No journal selected as yet.

7. Tidal currents at Punta Tuna. J. Physical Oceanography. J. A. Fornshell.

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