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OTEC Thermal Resource Report for Mombasa

May 1979

Prepared for
U.S. Department of Energy
Assistant Secretary for Energy Technology
Division of Central Solar Technology

Under Contract No. ET-78-C-01-2898

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Division of Central Solar Technology
Washington, D.C. 20585

Prepared by
William Alan Wolff
Ocean Data Systems, Inc.
Monterey, California 93940

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INTRODUCTION

One of the basic environmental considerations in site selection for an Ocean Thermal Energy Conversion (OTEC) power plant is the availability of an adequate temperature difference resource. OTEC plants are designed to convert the potential energy in the temperature difference between the warm ocean surface water and the cold water existing at deeper depths into electricity. The turbines which produce the electricity must run on temperature differentials which are extremely small by the standards of conventional energy plants. Therefore, a definition of the most probable temperature structure for a site is most important.

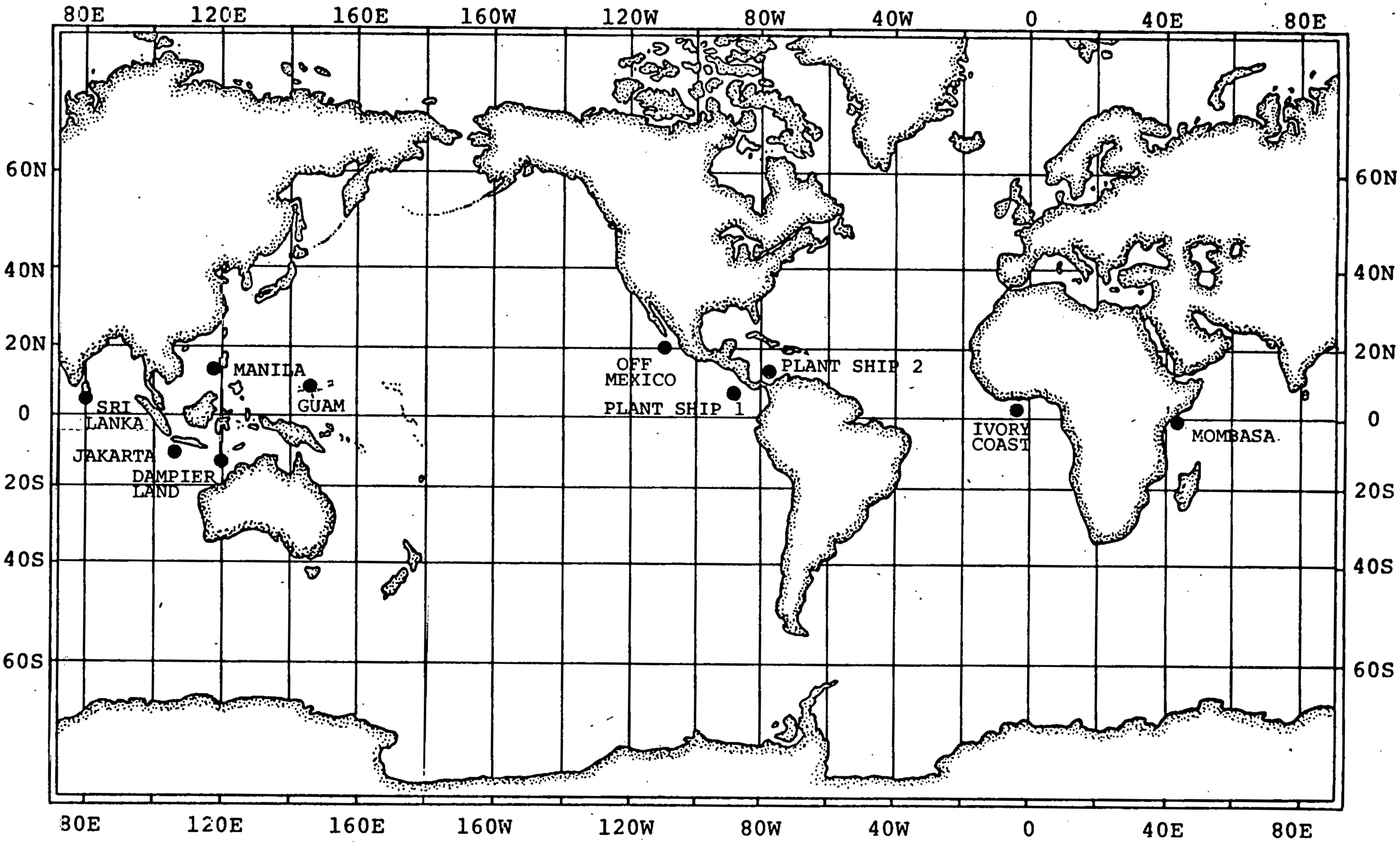
In order to define temperature structures for OTEC areas of interest, Ocean Data Systems, Inc. (ODSI) has developed computer data files of all unclassified soundings available. The primary sources for the data were NOAA's National Oceanographic Data Center, and the U.S. Navy's Fleet Numerical Weather Central. The files were updated in September 1978. Included in the data base were mechanical bathythermographs (MBT), expendable bathythermographs (XBT), salinity temperature depth systems (STD), and Nansen casts.

Under U.S. Department of Energy, Division of Solar Energy Contract No. EY-78-C-2989, ODSI has analyzed the monthly temperature structure for ten different geographical areas. The ten sites selected for study by the Department of Energy are:

			Latitude	Longitude
Bottom Mounted or Shore Plants:	Dampier Land		13-18°S	118-121°E
	Manila		14-16°N	118-120°E
	Guam		12-15°N	142-146°E
	Ivory Coast		3-6°N	3-8°W
	Jakarta		6-9°S	104-109°E
	Mexico		20-23°N	105-110°W
	Sri Lanka		5-10°N	78-83°E
	Mombasa		5°S-3°N	40-45°E
Ship Plants:	No. 1		5-10°N	90-95°W
	No. 2		13-15°N	75-80°W

The location of these sites is shown on the following map; a separate report was produced for each site.

For each area, the most probable temperature structures were determined. When the most probable temperature soundings were plotted, some month to month variability was present which was caused by the non-uniform data sample rather than by real changes in the ocean. These short-period time variations were removed by a filtering process described by Wolff, et al (1977), [44]. Availability of cold and warm water was examined at each site. In addition to warm and cold water availability, there are other requirements for the continuous operation of an OTEC plant. An adequate temperature differential (ΔT) is the primary need. A ΔT greater than 16.7°C (30°F) for the coldest month of the year would enable year round operation. The annual mean ΔT for



LOCATION OF THE TEN SELECTED SITES

a site should equal or exceed 20°C (36°F). Besides the thermal resource, there are other operational requirements. Bottom depth should be less than 1500 meters for mooring. Minimum distances offshore to 1000-meter depth is another important consideration for shore plants. Currents should be sufficient to guarantee good cold/warm water sources and to provide for dispersion of modified water. Desirable sites also have light winds, minimum sea and swell, and the lack of severe storms. These parameters have been examined for each site. The following tables summarize some of the key site parameters for each location.

SUMMARY OF SITE PARAMETERS

Site	Monthly Mean Temperature (°C) Surface Range	Monthly Mean Temperature (°C) 1000M	Annual Mean ΔT(°C) 500M	Annual Mean ΔT(°C) 1000M	Coldest Monthly Mean ΔT (°C) 500M	Coldest Monthly Mean ΔT (°C) 1000M
Sri Lanka	27.5-28.6	6.5-6.7	18.0	21.3	17.5	20.8
Mombasa N	25.4-28.7	7.2-7.5	17.0	19.5	15.6	18.2
Mombasa S	25.5-28.4	6.3-7.0	18.0	20.2	15.9	18.5
Jakarta	27.2-29.0	5.1-5.6	19.1	22.8	17.9	21.9
Dampier Land	25.6-28.2	4.9-5.0	19.1	22.6	17.4	20.7
Manila	27.1-29.5	4.4-4.6	20.0	24.0	18.6	22.6
Guam	27.7-29.2	4.3-4.4	21.1	24.1	20.4	23.4
Off Mexico	22.5-28.0	4.4-4.5	17.6	20.9	14.9	18.0
Plant Ship Pacific	27.1-28.5	4.6-4.8	19.4	22.8	18.1	21.7
Ivory Coast	24.3-28.1	4.5	19.2	22.1	16.8	19.7
Plant Ship Caribbean	26.4-28.4	5.0-5.3	18.1	22.4	17.2	21.3

SUMMARY OF SITE PARAMETERS

SITE	RANGE DISTANCE (IN KILOMETERS) TO SHORE FROM 1000 METERS	MONTHLY MEAN MIXED LAYER DEPTH METERS	MONTHLY MEAN SURFACE CURRENTS (CM/SEC)	SEA STATE MAX % OF TIME >3 METERS	NUMBER TROPICAL CYCLONES PER YEAR
SRI LANKA	22-55	30-80	25-62	3	0.2-1.2
MOMBASA	33-130	30-90	30-62	2	0.0-0.1
JAKARTA	18-60	55-80	25-52	2	0.0-0.1
DAMPIER LAND	265-417	30-80	25-47	4	0.4-1.2
MANILA	6-82	20-80	30-52	5	4.0-6.0
GUAM	7-18	60-120	30-47	5	2.0-3.0
OFF MEXICO	5-104	10-30	25-31	2	0.6-4.0
PLANT SHIP PACIFIC	-	0-30	30-52	2	0.0-2.0
IVORY COAST	33-52	0-30	25-31	2	0.0-0.1
PLANT SHIP CARIBBEAN	-	40-110	30-62	3	0.6-1.2

I. EXECUTIVE SUMMARY

The coastal waters off Mombassa, Kenya were selected for study for their potential for Ocean Thermal Energy Conversion (OTEC) use. The area examined is located in the southwestern equatorial region. The data file was searched between 40°-45° East longitude and between 5° South latitude and 3° North latitude. The area south of the equator was examined separately from the area north of the equator. A usable thermal resource exists for both the northern and southern sections examined.

The Mombassa site compares unfavorably with most of the other 10 sites studied under this contract if ΔT is used as the only criteria. An annual average ΔT of 20°C is not reached until a depth of 1100 meters in the northern section, and at 1000 meters in the southern section. The average of the monthly mean ΔTs at 500 meters is 17.0°C in the north section and 17.6°C in the southern section. The thermal resource is definitely better in the southern position.

There is a mixed layer throughout the year that is advantageous for OTEC development. Winds and storms are not a problem for the site. Low sea and swell conditions are characteristic. Surface current conditions are fairly complicated. The distance from shore to the 1000 meter depth varies, depending on what latitude is chosen for the site. One thousand meter depths are between 30 and 130 kilometers (≈ 18 and 70 nautical miles) from land. Off the city of Mombassa itself, the distance is 111 kilometers (60 nautical miles). Thus, although the thermal resource is better in the southern section, access to shore is better for the northern section.

II. BATHYMETRY

The general location of the prospective site is shown in Figure II-1. Figure II-2 provides the rough bathymetry of the area taken the U.S Naval Oceanographic Office, 1974, [39]. The width of the continental shelf is more uniform in the northern section than the southern. The steepness of the continental slope is also less variable for the area north of the equator. Off most of the coast in consideration the continental shelf is neither extremely wide as in possible OTEC sites in the Gulf of Mexico nor very narrow as the shelf is off Puerto Rico for example. The shelf is most narrow for this East African site near the equator. The steepest continental slope for this site is also near the equator. South of 2°S latitude the shelf becomes more extensive and the slope less steep. Thus the distance from the port city of Mombasa, Kenya at 04° 02'S latitude and 39° 37'E longitude to the outer limit of the continental shelf is 38 kilometers (20.5 nautical miles), and the distance to water 1000 meters deep is approximately 111 kilometers (60 nautical miles).

The extreme distances for each section from shore to depths of interest are shown in Table II-1.

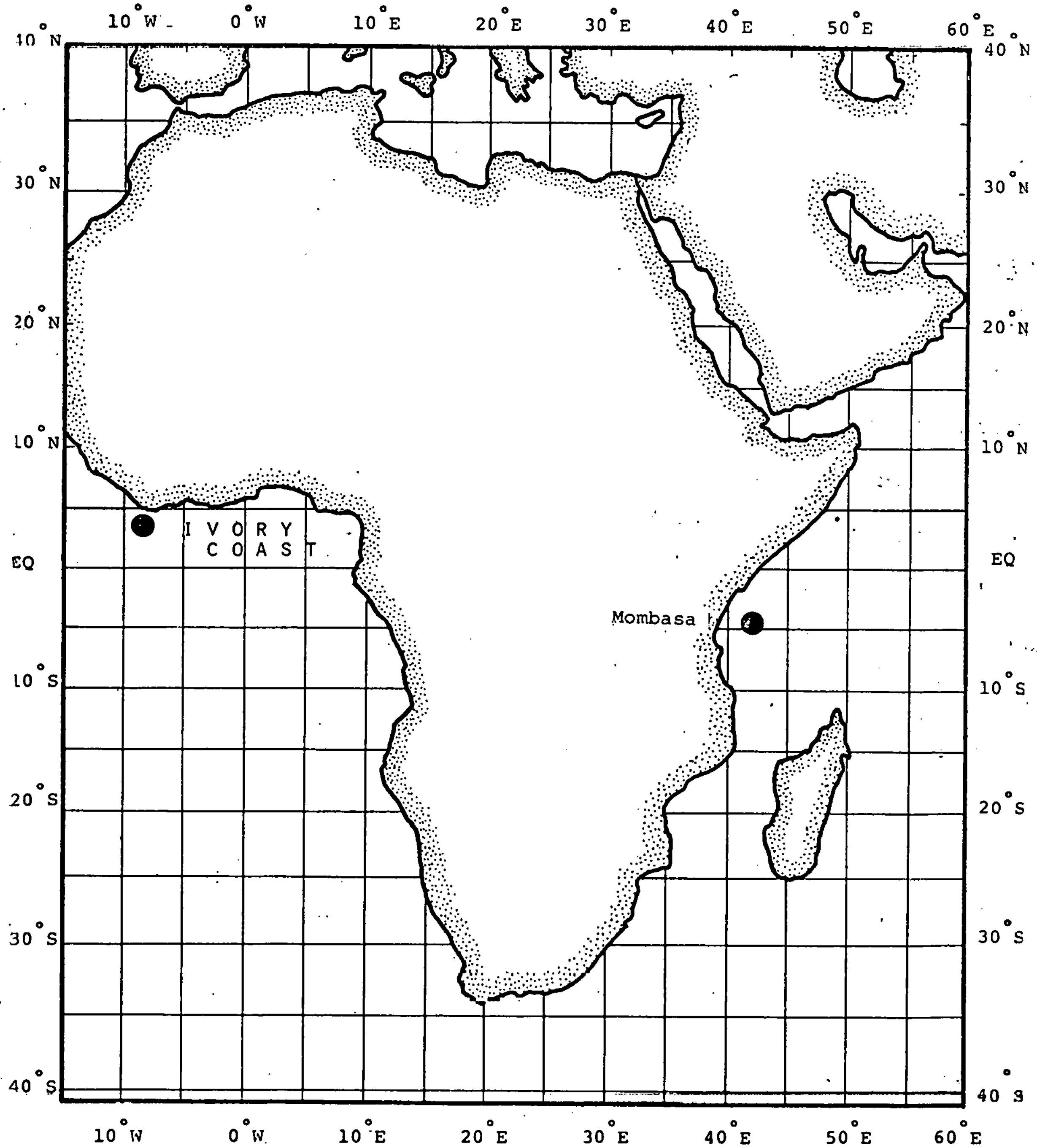


FIGURE II-1: LOCATOR CHART SHOWING THE LOCATION OF THE MOMBASA SITE

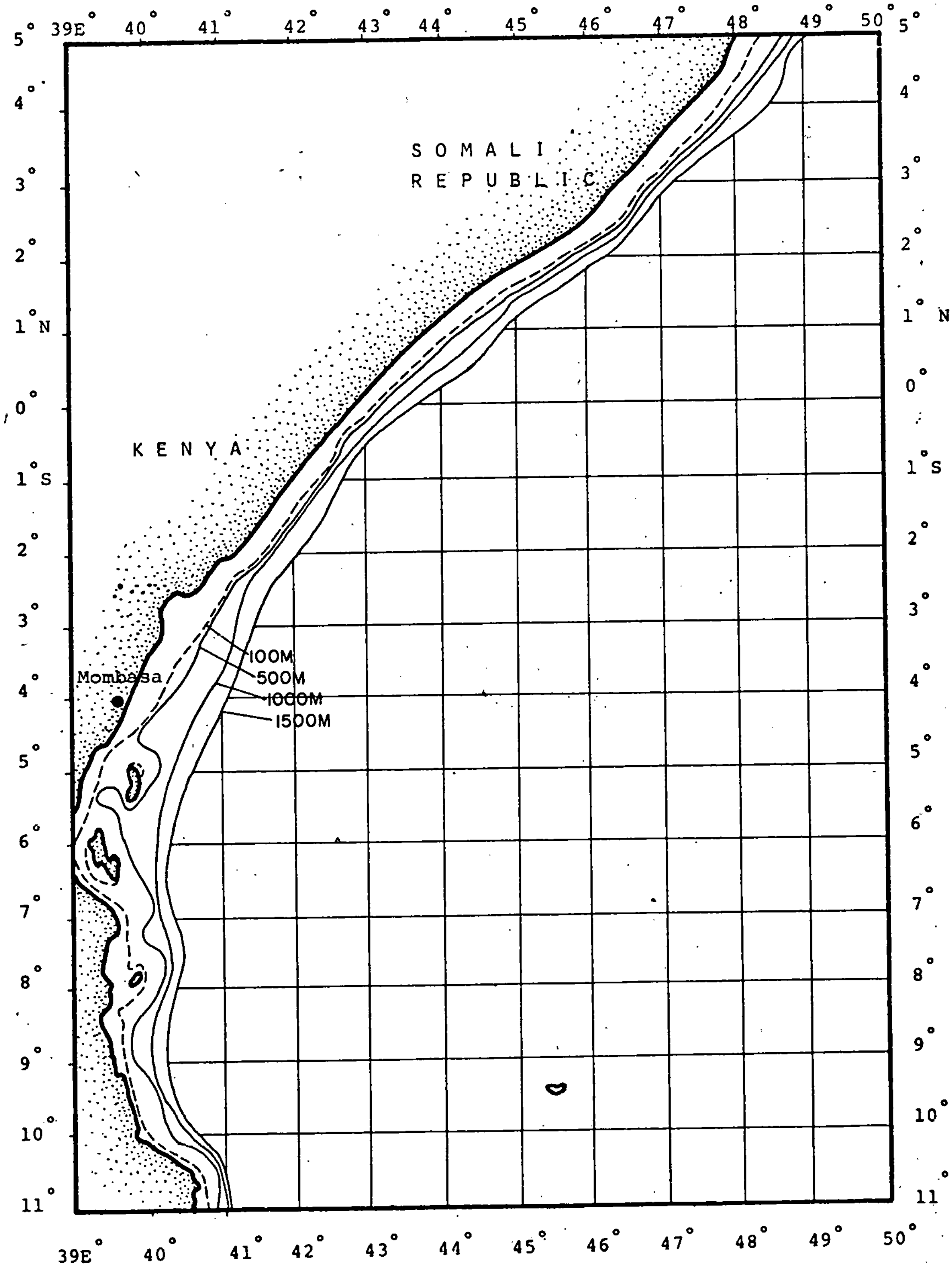


FIGURE II-2: CHART SHOWING ROUGH BATHYMETRY TO 1500 METERS OFF MOMBASA. (From U.S. Naval Oceanographic Office, 1974, [39].)

TABLE II-1: DISTANCES TO SELECTED DEPTHS OFF MOMBASA.

North Section 0°-3°N/40-45°E

DEPTH (Meters)	CLOSEST DISTANCE (Kilometers)	FARTHEST DISTANCE (Kilometers)
100	16.7	37
500	25.9	50
1000	33.3	56
1500	52.0	78

South Section 0°-5°S/40-45°E

DEPTH (Meters)	CLOSEST DISTANCE (Kilometers)	FARTHEST DISTANCE (Kilometers)
100	12.9	65
500	22.2	70
1000	33.3	130
1500	41.7	163

City of Mombasa

DEPTH (Meters)	CLOSEST DISTANCE (Kilometers)	FARTHEST DISTANCE (Kilometers)
100	38.0	--
500	43.5	--
1000	111.0	--
1500	146.0	--

III. THERMAL RESOURCE

Tables III-1 and III-2 provide the monthly most probable temperature profiles as a function of depth for the northern and southern sections. Tables III-3 and III-4 shows the same data tabulated in terms of ΔT, the surface temperature minus the temperature at depth differential (°C) by month. There is data coverage for all the standard depths for both the northern and southern sections studied. The main sources for the temperature data were NOAA's National Oceanographic Data Center, and the U.S. Navy's Fleet Numerical Weather Central, although soundings from other sources were added when available. There is also data for each month of the year, although not at each depth. When the available data was plotted some month-to-month variability was present which was caused by the sparse and non-uniform data sample rather than by real variations in the ocean. These short-period time variations were removed by a filtering process described by Wolff, et al (1977), [44]. This historical oceanographic data shows that the temperature profile off Mombassa is usable for OTEC exploitation. The thermocline of this area is shallower and thinner than the thermocline in areas south or east of this site. The temperature differences are less within the thermocline in the western Indian Ocean.

The temperatures at depths for the western Indian Ocean are generally warmer than those in the Atlantic or Pacific. The mean annual temperatures for the southern and northern

TABLE III-1: MONTHLY MOST PROBABLE TEMPERATURE (°C) PROFILE

MOMBASA (NORTH SECTION) 0-3°N/40-45°E

Depth	Month 1	2	3	4	5	6	7	8	9	10	11	12	Annual Average
0	26.7	27.2	28.2	28.7	28.4	27.4	26.2	25.4	25.7	26.0	26.6	26.0	26.9
50	26.2	26.6	27.8	27.7	27.5	26.5	26.0	25.2	24.9	25.2	25.9	25.1	26.2
100	24.7	24.7	25.0	23.0	20.9	19.9	20.8	21.4	21.1	20.5	20.8	19.1	21.8
150	18.5	17.5	18.6	18.0	16.9	16.0	16.4	16.5	16.4	16.0	16.0	15.3	16.8
200	14.7	15.6	14.9	14.6	14.3	13.7	13.9	14.2	14.2	14.0	13.7	13.2	14.3
250	12.7	12.4	13.1	13.1	13.3	12.7	12.8	12.8	12.7	12.7	12.5	12.3	12.8
300	12.0	11.6	12.0	12.0	12.1	11.9	11.9	12.0	11.8	11.9	11.7	11.6	11.9
350	11.3	10.9	11.2	11.3	11.6	11.4	11.4	11.2	11.0	10.9	10.6	10.6	11.1
400	10.6	10.5	10.8	10.8	11.2	10.8	10.8	10.5	10.6	10.5	10.5	10.5	10.7
450	10.4	10.1	10.3	10.1	10.3	10.0	10.3	10.2	10.1	10.0	10.0	10.0	10.2
500	10.0	10.0	10.3	10.0	9.9	9.6	9.9	9.8	9.7	9.7	9.7	9.8	9.9
550	9.8	9.9	10.1	9.8	9.7	9.4	9.7	9.6	9.5	9.5	9.5	9.6	9.7
600	9.6	9.7	10.0	9.6	9.5	9.2	9.5	9.3	9.3	9.3	9.4	9.3	9.5
650	9.4	9.5	9.7	9.3	9.2	9.0	9.3	9.1	9.1	9.0	9.2	9.1	9.2
700	9.1	9.2	9.5	9.1	8.9	8.7	8.9	8.8	8.8	8.8	8.9	8.8	9.0
750	8.9	9.0	9.3	8.9	8.7	8.4	8.6	8.4	8.4	8.5	8.7	8.5	8.7
800	8.6	8.8	9.1	8.8	8.6	8.2	8.3	8.2	8.2	8.2	8.4	8.2	8.5
850	8.3	8.5	8.9	8.6	8.3	7.9	8.0	7.9	7.9	7.9	8.0	7.9	8.2
900	7.9	8.1	8.5	8.3	8.1	7.7	7.8	7.7	7.7	7.7	7.8	7.7	7.9
950	7.7	7.8	8.1	7.9	7.7	7.5	7.5	7.4	7.5	7.5	7.6	7.5	7.6
1000	7.5	7.5	7.7	7.6	7.4	7.2	7.2	7.2	7.3	7.3	7.3	7.2	7.4
1050	7.2	7.2	7.4	7.2	7.1	7.0	7.0	6.9	7.0	7.0	7.1	7.0	7.1
1100	7.0	6.9	7.0	6.9	6.9	6.8	6.7	6.6	6.6	6.7	6.8	6.7	6.8
1150	6.7	6.7	6.7	6.6	6.5	6.4	6.4	6.3	6.2	6.3	6.4	6.5	6.5
1200	6.4	6.4	6.3	6.2	6.2	6.1	6.0	6.0	6.0	6.1	6.2	6.2	6.2
1250	6.2	6.1	6.1	6.1	5.9	5.8	5.7	5.7	5.7	5.8	5.8	5.9	5.9
1300	5.8	5.8	5.8	5.7	5.7	5.6	5.5	5.5	5.5	5.6	5.6	5.7	5.7
1350	5.6	5.6	5.5	5.5	5.4	5.4	5.3	5.3	5.3	5.4	5.3	5.4	5.4
1400	5.3	5.3	5.2	5.2	5.2	5.1	5.1	5.1	5.1	5.2	5.2	5.1	5.2
1450	4.9	4.9	4.9	4.9	4.8	4.7	4.7	4.8	4.8	4.8	4.8	4.8	4.8
1500	4.7	4.6	4.6	4.7	4.7	4.6	4.6	4.6	4.7	4.7	4.7	4.7	4.7

TABLE III-2: MONTHLY MOST PROBABLE TEMPERATURE (°C) PROFILE

MOMBASA (SOUTH SECTION) 0-5°S/40-45°E

Depth	Month 1	2	3	4	5	6	7	8	9	10	11	12	Annual Mean
0	27.0	27.3	27.7	28.4	28.0	27.2	26.2	25.5	25.6	26.0	26.8	27.1	26.9
50	26.2	26.3	26.6	26.9	26.9	26.5	25.8	25.1	25.0	25.2	25.7	26.0	26.0
100	21.7	22.6	22.8	22.0	21.2	20.8	21.5	21.5	22.1	22.1	21.9	21.5	21.8
150	16.9	17.7	18.1	17.0	16.2	15.8	16.3	16.5	16.6	16.6	16.4	16.3	16.7
200	13.7	13.9	14.2	14.0	13.6	13.4	13.7	14.2	14.2	14.2	13.9	13.8	13.9
250	12.3	12.3	12.6	12.4	12.2	12.0	12.3	12.8	12.7	12.7	12.4	12.4	12.4
300	11.3	11.3	11.5	11.4	11.2	11.2	11.4	11.8	11.7	11.6	11.4	11.3	11.4
350	10.7	10.7	10.9	10.8	10.5	10.5	10.7	10.9	10.8	10.6	10.6	10.5	10.7
400	10.1	10.1	10.3	10.2	10.1	10.1	10.2	10.3	10.3	9.9	9.9	9.8	10.1
450	9.8	9.8	9.9	9.8	9.7	9.6	9.7	9.8	9.8	9.4	9.5	9.4	9.7
500	9.4	9.3	9.2	9.2	9.2	9.2	9.4	9.5	9.7	9.1	9.1	8.9	9.3
550	9.2	9.2	9.1	9.0	8.9	8.8	9.0	9.1	9.2	8.6	8.6	8.7	9.0
600	8.9	9.0	8.9	8.8	8.6	8.6	8.8	8.9	8.9	8.3	8.3	8.3	8.7
650	8.7	8.8	8.7	8.6	8.4	8.4	8.5	8.6	8.7	8.2	8.2	8.1	8.5
700	8.4	8.4	8.3	8.2	8.2	8.3	8.3	8.4	8.4	8.0	7.9	8.0	8.2
750	8.1	8.1	8.0	7.9	7.9	8.1	8.2	8.2	8.1	7.8	7.0	8.1	8.0
800	7.9	7.9	7.7	7.7	7.6	7.8	7.8	7.9	7.8	7.9	7.5	7.6	7.8
850	7.7	7.8	7.5	7.4	7.4	7.6	7.6	7.7	7.6	7.4	7.3	7.7	7.6
900	7.2	7.3	7.3	7.0	6.8	7.2	7.4	7.5	7.4	7.2	7.1	7.0	7.2
950	7.2	7.2	6.8	6.6	6.6	7.0	7.2	7.3	7.1	6.9	6.8	7.0	7.0
1000	6.9	6.9	6.5	6.4	6.3	6.7	6.9	7.0	6.9	6.7	6.6	6.8	6.7
1050	6.7	6.7	6.3	6.1	6.0	6.4	6.7	6.8	6.7	6.4	6.4	6.5	6.5
1100	6.5	6.1	6.1	5.9	5.8	6.2	6.4	6.6	6.4	6.2	6.1	6.3	6.2
1150	6.3	6.3	5.9	5.6	5.5	5.9	6.2	6.4	6.1	5.9	5.8	6.0	6.0
1200	5.9	5.9	5.6	5.4	5.4	5.7	5.9	6.1	5.9	5.6	5.5	5.7	5.7
1250	5.7	5.7	5.4	5.2	5.1	5.5	5.7	5.8	5.6	5.4	5.3	5.4	5.5
1300	5.4	5.4	5.2	5.0	5.0	5.2	5.4	5.5	5.3	5.1	5.1	5.2	5.2
1350	5.2	5.2	5.0	4.8	4.7	5.0	5.1	5.2	5.0	4.9	4.9	5.0	5.0
1400	4.9	4.9	4.8	4.7	4.7	4.7	4.8	4.8	4.7	4.6	4.6	4.7	4.7
1450	4.5	4.6	4.5	4.5	4.5	4.5	4.6	4.6	4.5	4.4	4.3	4.4	4.5
1500	4.4	4.3	4.2	4.2	4.2	4.3	4.3	4.2	4.2	4.1	4.2	4.3	4.2

TABLE III-3: SURFACE TEMPERATURE - TEMPERATURE AT DEPTH

DIFFERENTIAL (°C) BY MONTHS MOMBASA (NORTH SECTION) 0-3°N/40-45°E

Depth	Month												Annual
	1	2	3	4	5	6	7	8	9	10	11	12	Mean
50	0.5	0.6	0.4	1.0	0.9	0.9	0.2	0.2	0.8	0.8	0.7	0.9	0.6
100	2.0	2.5	3.2	5.7	7.5	7.5	5.4	4.0	4.6	5.5	5.8	6.9	5.1
150	8.2	9.7	9.6	10.7	11.5	11.4	9.8	8.9	9.3	10.0	10.6	10.7	10.0
200	12.0	11.6	13.3	14.1	14.1	13.7	12.3	11.2	11.5	12.0	12.9	12.8	12.6
250	14.0	14.8	15.1	15.6	15.1	14.7	13.4	12,6	13.0	13.3	14.1	13.7	14.1
300	14.7	15.6	16.2	16.7	16.3	15.5	14.3	13.4	13.9	14.1	14.9	14.4	15.0
350	15.4	16.3	17.0	17.4	16.8	16.0	14.8	14.2	14.7	15.1	16.0	15.4	15.8
400	16.1	16.7	17.4	17.9	17.2	16.6	15.4	14.9	15.1	15.5	16.1	15.5	16.2
450	16.3	17.1	17.9	18.6	18.1	17.4	15.9	15.2	15.6	16.0	16.6	16.0	16.7
500	16.7	17.2	17.9	18.7	18.5	17.8	16.3	15.6	16.0	16.3	16.9	16.2	17.0
550	16.9	17.3	18.1	18.9	18.7	18.0	16.5	15.8	16.2	16.5	17.1	16.4	17.2
600	17.1	17.5	18.2	19.1	18.9	18.2	16.7	16.1	16.4	16.7	17.2	16.7	17.4
650	17.3	17.7	18.5	19.4	19.2	18.4	16.9	16.3	16.6	17.0	17.4	16.9	17.6
700	17.6	18.0	18.7	19.6	19.5	18.7	17.3	16.6	16.9	17.2	17.7	17.2	17.9
750	17.8	18.2	18.9	19.8	19.7	19.0	17.6	17.0	17.3	17.5	17.9	17.5	18.2
800	18.1	18.4	19.1	19.9	19.8	19.2	17.9	17.2	17.5	17.8	18.2	17.8	18.4
850	18.4	18.7	19.3	20.1	20.1	19.5	18.2	17.5	17.8	18.1	18.6	18.1	18.7
900	18.8	19.1	19.7	20.4	20.3	19.7	18.4	17.7	18.0	18.3	18.8	18.3	19.0
950	19.0	19.4	20.1	20.8	20.7	19.9	18.7	18.0	18.2	18.5	19.0	18.5	19.2
1000	19.2	19.7	20.5	21.1	21.0	20.2	19.0	18.2	18.4	18.7	19.3	18.8	19.5
1050	19.5	20.0	20.8	21.5	21.3	20.4	19.2	18.5	18.7	19.0	19.5	19.0	19.8
1100	19.7	20.3	21.2	21.8	21.5	20.6	19.5	18.8	19.1	19.3	19.8	19.3	20.1
1150	20.0	20.5	21.5	22.1	21.9	21.0	19.8	19.1	19.5	19.7	20.2	19.5	20.4
1200	20.3	20.8	21.9	22.5	22.2	21.3	20.2	19.4	19.7	19.9	20.4	19.8	20.7
1250	20.5	21.1	22.1	22.6	22.5	21.6	20.5	19.7	20.0	20.2	20.8	20.1	21.0
1300	20.9	21.4	22.4	23.0	22.7	21.8	20.7	19.9	20.2	20.4	21.0	20.3	21.2
1350	21.1	21.6	22.7	23.2	23.0	22.0	20.9	20.1	20.4	20.6	21.3	20.6	21.5
1400	21.4	21.9	23.0	23.5	23.2	22.3	22.1	20.3	20.6	20.8	21.4	20.9	21.8
1450	21.8	22.3	23.3	23.8	23.6	22.7	21.5	20.6	20.9	21.2	21.8	21.2	22.0
1500	22.0	22.6	23.6	24.0	23.7	22.8	21.6	20.8	21.0	21.3	21.9	21.3	22.2

TABLE III-4: SURFACE TEMPERATURE - TEMPERATURE AT DEPTH DIFFERENTIAL (°C) BY MONTHS MOMBASA (SOUTH SECTION) 0-5°S/40-45°E

Depth	Month												Annual
	1	2	3	4	5	6	7	8	9	10	11	12	Mean
50	0.8	1.0	1.1	1.5	1.1	0.7	0.4	0.4	0.6	0.8	1.1	1.1	0.9
100	5.3	4.7	4.9	6.4	6.8	6.4	4.7	4.0	3.5	3.9	4.9	5.6	5.1
150	10.1	9.6	9.6	11.4	11.8	11.4	9.9	9.0	9.0	9.4	10.4	10.8	10.2
200	13.3	13.4	13.5	14.4	14.4	13.8	12.5	11.3	11.4	11.8	12.9	13.3	11.9
250	14.7	15.0	15.1	16.0	15.8	15.2	13.9	12.7	12.9	13.3	14.4	14.7	14.5
300	15.7	16.0	16.2	17.0	16.8	16.0	14.8	13.7	13.9	14.4	15.4	15.8	15.5
350	16.3	16.6	16.8	17.6	17.5	16.7	15.5	14.6	14.8	15.4	16.2	16.6	16.2
400	16.9	17.2	17.4	18.2	17.9	17.1	16.0	15.2	15.3	16.1	16.9	17.3	16.8
450	17.2	17.5	17.8	18.6	18.3	17.6	16.5	15.7	15.8	16.6	17.3	17.7	17.2
500	17.6	18.0	18.5	19.2	18.8	18.0	16.8	16.0	15.9	16.9	17.7	18.2	17.6
550	17.8	18.1	18.6	19.4	19.1	18.4	17.2	16.4	16.4	17.4	18.2	18.4	18.0
600	18.1	18.3	18.8	19.6	19.4	18.6	17.4	16.6	16.7	17.7	18.5	18.8	18.2
650	18.3	18.5	19.0	19.8	19.6	18.8	17.7	16.9	16.9	17.8	18.6	19.0	18.4
700	18.6	18.9	19.4	20.2	19.8	18.9	17.9	17.1	17.2	18.0	18.9	19.1	18.7
750	18.9	19.2	19.7	20.5	20.1	19.1	18.0	17.3	17.5	18.2	19.1	19.2	18.9
800	19.1	19.4	20.0	20.7	20.4	19.4	18.4	17.6	17.8	18.1	19.3	19.5	19.1
850	19.3	19.5	20.2	21.0	20.6	19.6	18.6	17.8	18.0	18.6	19.5	19.6	19.4
900	19.8	20.0	20.4	21.4	21.2	20.0	18.8	18.0	18.2	18.8	19.7	20.1	19.7
950	19.8	20.1	20.9	21.8	21.4	20.2	19.0	18.2	18.5	19.1	20.0	20.1	19.9
1000	20.1	20.4	21.2	22.0	21.7	20.5	19.3	18.5	18.7	19.3	20.2	20.3	20.2
1050	20.3	20.6	21.4	22.3	22.0	20.8	19.5	18.7	18.9	19.6	20.4	20.6	20.4
1100	20.5	21.2	21.6	22.5	22.2	21.0	19.8	18.9	19.2	19.8	20.7	20.8	20.7
1150	20.7	21.0	21.8	22.8	22.5	21.3	20.0	19.1	19.5	20.1	21.0	21.1	20.9
1200	21.1	21.4	22.1	23.0	22.6	21.5	20.3	19.4	19.7	20.4	21.3	21.4	21.2
1250	21.3	21.6	22.3	23.2	22.9	21.7	20.5	19.7	20.0	20.6	21.5	21.7	21.4
1300	21.6	21.9	22.5	23.4	23.0	22.0	20.8	20.0	20.3	20.9	21.7	21.9	21.7
1350	21.8	22.1	22.7	23.6	23.3	22.2	21.1	20.3	20.6	21.1	21.9	22.1	21.9
1400	22.1	22.4	22.9	23.7	23.3	22.5	21.4	20.7	20.9	21.4	22.2	22.4	22.2
1450	22.5	22.7	23.2	23.9	23.5	22.7	21.6	20.9	21.1	21.6	22.5	22.7	22.4
1500	22.6	23.0	23.5	24.2	23.8	22.9	21.9	21.3	21.4	21.9	22.6	22.8	22.7

sections of the Mombassa region at 1000 meters are 6.7°C and 7.4°C, respectively. For representative sites in the Pacific and Atlantic such as Manila and the Ivory Coast, the mean annual temperature at 1000 meters is 4.5°C. The monthly mean surface temperatures, however, are not any warmer than sites in other oceans, for either Mombassa section, ranging between 25.1°C and 29.1°C. Annual average ΔTs are therefore somewhat less than most of the other sites being examined, under this contract. This is particularly true of the northern site where the annual mean ΔT at 1000 meters is 19.5°C. At 1000 meters, the annual mean ΔT for the southern site is 20.2°C. At 500 meters, the annual average of monthly mean ΔTs is 17.0°C for the northern site and 17.6°C for the southern section with a monthly mean temperature as low as 15.6°C during the coldest month.

Figure III-1 shows monthly ΔT contours plotted versus depth for the northern section. Figure III-2 provides a plot of monthly ΔT coutours for the southern section.

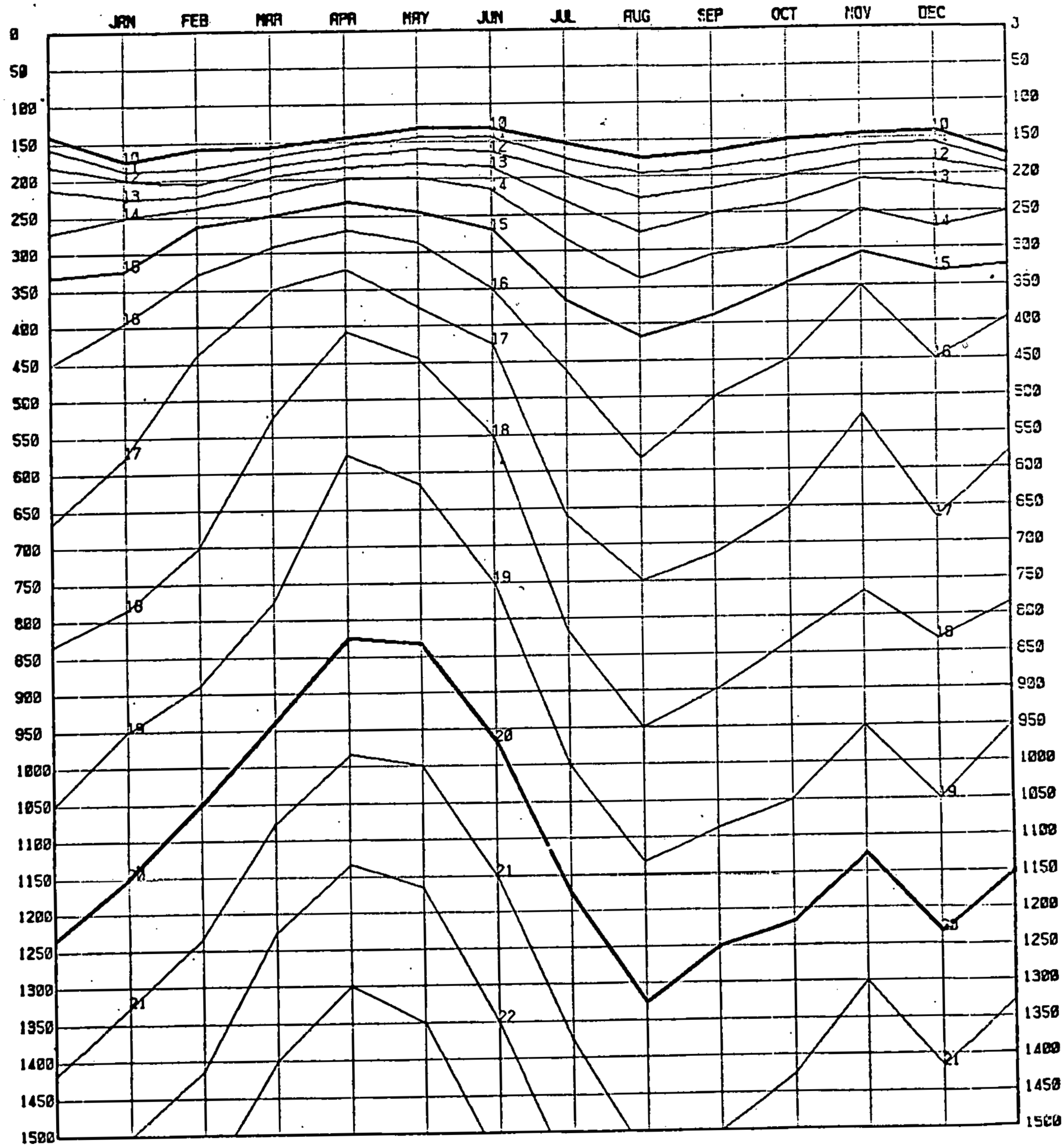


FIGURE III-1: CHART SHOWING MONTHLY ΔT CONTOURS (C°) AT A DEPTH RESOLUTION OF 50 METERS FOR MOMBASA (NORTH SECTION) 0-3N/40-45E

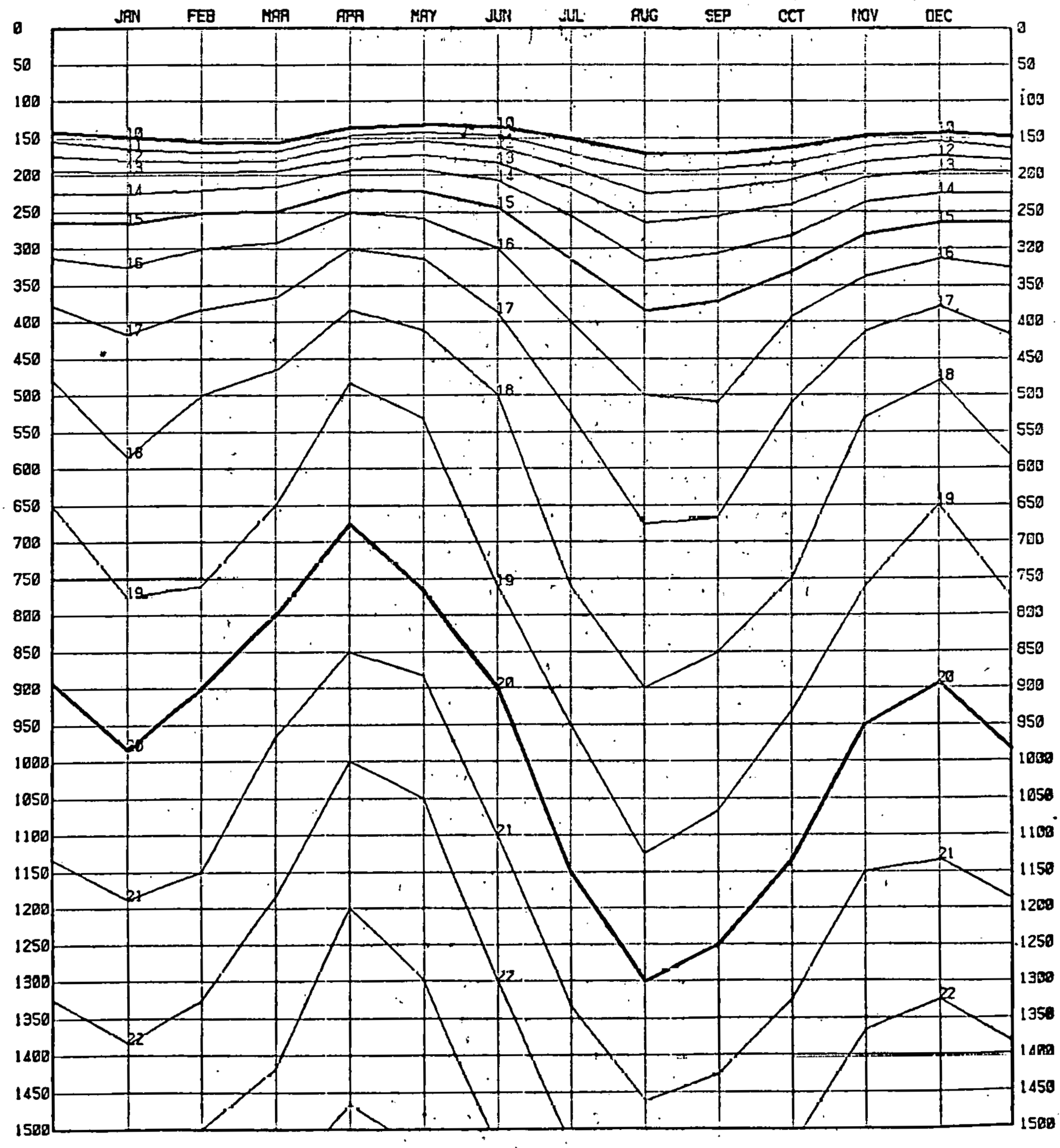


FIGURE III-2: CHART SHOWING MONTHLY ΔT CONTOURS (°C) AT A DEPTH RESOLUTION OF 50 METERS FOR MOMBASA (SOUTH SECTION) 0-5S/40-45°E

IV. MIXED LAYER DEPTH

For OTEC purposes, the upper mixed layer is defined as the depth at which the temperature is first 1°C colder than the sea surface temperature. There is an upper mixed layer depth (MLD) throughout the year both north and south of the equator. The mixed layer depth has a mean of about 50 meters. The values of the MLD range between 30 meters and 90 meters. There is some variation between the northern section and the southern section. Representative values for the mixed layer depth determined from Colburn's The Thermal Structure of the Indian Ocean (1974), [6], and our own temperature data file are shown in Table IV-1.

TABLE IV-1: TYPICAL MIXED LAYER DEPTHS (METERS) OFF MOMBASA.

	JAN-FEB	MAR-APR	MAY-JUN	JUL-AUG	SEP-OCT	NOV-DEC
Southern Section	40	40	70	90	70	55
Northern Section	80	50	30	70	70	35

A mixed layer depth is helpful for ideal OTEC operating conditions. The MLD off Kenya is deep enough to assure an intake of uniformly warm water. The northern section's MLD during the May-June and November-December periods is not as deep as would be ideal. This MLD is not so deep that recirculation of the mixed exhaust should be a major problem.

V. WINDS AND STORMS

The northeast monsoons govern the region beginning in November. The transition to the southwest monsoon begins during April and continues in May. Relatively weak winds of 15 knots or less are characteristic of the region. Southeast of Mombasa, there is an offshore wind maxima with occasional observations up to 10.3 meters/second. Still winds over 10.3 meters/second occur infrequently. Typical winds for the region are:

	JAN-FEB	MAR-APR	MAY-JUN	JUL-AUG	SEP-OCT	NOV-DEC
Resultant wind direction in degrees from N	60 ↓	110 ↖	190 ↑	170 ↑	170 ↖	120 ↑
Resultant wind speed in meters per second	5.7	2.6	5.7	5.7	6.7	3.1
Wind steadiness in percent	89	72	91	84	93	83

The source of this information is the Meteorological Atlas of the International Indian Ocean Expedition, (1972), [26].

Table V-1, taken from the U.S. Naval Weather Service (1974), [35] shows basic climatic information for the vicinity of Mombasa, Kenya.

Tables V-2 through V-5 with data from the U.S. Weather Bureau (1938), [31] provides information on the winds for each of the ten sites examined under this contract.

Figure V-1 adapted from H.L. Crutcher and R.G. Quayle (1974), [7] shows the preferred annual storm tracks for this region. Figure V-2 from the same source provides the average number of tropical cyclones per 5° square per year. As these figures show tropical storms and hurricanes are not a problem for this site, less than 0.1 storms per year affect either of the Mombasa sites.

TABLE V-1: CLIMATIC SUMMARY FOR MOMBASA, KENYA (Elevation 54.6 meters)
Latitude 04° 02's, Longitude 39° 37' E.
From U.S. Naval Weather Service (1974) [35].

PARAMETER	MONTH											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ABSOLUTE MAX TEMP (°C)	35	36	35	36	33	32	33	31	32	33	34	36
AVERAGE MAX TEMP (°C)	33	33	34	32	30	29	29	29	30	31	32	33
MEAN TEMP (°C)	28	28	29	28	27	26	25	25	26	26	28	28
AVERAGE MIN TEMP (°C)	24	24	24	24	23	22	21	22	22	23	24	24
ABSOLUTE MIN TEMP (°C)	21	21	22	21	19	16	18	17	18	18	20	21
AVERAGE RAINFALL (MM)	28	15	69	191	318	119	94	61	66	84	99	64
MEAN NO. DAYS RAIN	4	2	6	17	19	14	16	15	12	12	11	9
MEAN NO.DAYS THUNDERSTORM	<1	1	4	4	<1	0	0	0	0	<1	2	3
MEAN NO. DAYS FOG	0	0	<0	1	1	0	0	0	<1	0	0	0
MEAN RELATIVE HUMIDITY (%)	69	70	71	69	67	61	64	62	64	64	68	69
PREVAILING WIND SPEED	NE	E	SE	S	S	S	S	S	SE	SE	SE	NE
MEAN WIND SPEED (M/S)	3.6	3.6	3.6	3.6	4.1	4.6	4.1	4.1	4.1	4.1	3.1	3.1

TABLE V-2

RESULTANT WINDS

Average Wind Velocity in Meters per Second

Location	Dec-Jan-Feb	Mar-Apr-May	Jun-Jul-Aug	Sep-Oct-Nov
Ivory Coast	3.1-4.1	3.1-4.1	4.1-5.1	4.1-5.1
Mombasa	5.1-6.2	4.1-5.1	6.2-7.2	4.1-5.1
Sri Lanka	4.1-5.1W 5.1-6.2E	4.1-5.1	6.2-7.2W 7.2-8.2E	5.1-6.2
Jakarta	4.1	3.1-4.1	5.1-6.2	5.1-6.2
Dampier Land	4.1-5.1	4.1-6.2	5.1-6.2	4.1-5.1
Philippines	5.1-6.2	3.1-4.1	4.1	6.2-7.2
Guam	5.1-6.2	4.1-5.1	4.1-5.1	4.1-5.1
Off Mexico	3.1-4.1	2.1-4.1	2.1-4.1	4.1-5.1
Plant Ship Pacific	3.1-4.1	3.1-4.1	4.1-5.1	4.1-6.2
Plant Ship Caribbean	6.2-7.2	5.1-6.2	6.2-8.2	4.1-5.1

TABLE V-3

FREQUENCY AND PERCENTAGE OF MODERATE GALES AND STRONGER WINDS,

BEAUFORT FORCE 7 AND HIGHER

($\geq$ 14.4 meters per second)

MONTH	IVORY COAST	MOMBASA	SRI LANKA	JAKARTA	DAMPIER LAND	PHILLIPINES	GUAM	OFF MEXICO	PLANT SHIP (PACIFIC)	PLANT SHIP (CARIBN)
JAN	0*	0-1	0	0	0	1-5	1-5	1-5	0	5
FEB	0	0	1	1-5	1-5	5	1-2	1-2	0	5
MAR	1-2	0	0	1-2	1-2	1	0	1-2	0	1-5
APR	0	0	0	1-2	0	1	1-5	1	0	1-5
MAY	0	1	1-5	1	0	1-5	0	0	0	1
JUN	0	5-10	5-10	1-5	0	1-5	0	1	0	1-5
JUL	0	5-10N 10-20S	1-5	1-5	1-5	5	0	0	0	1-5
AUG	0	1-5S 5-15N	1-5	0	0	1-5	1-5	1-5	0	1-5
SEP	0	0	1-5	1-5	0	5	1-5	0	0	1
OCT	0	0	0W 1-5E	1-5	0	1-5	1-2	1	1	1-5
NOV	0	0	1-5	1-5	0	10-15N 1-10S	5-15	1-5	0-5	1-5
DEC	0	1-2	0W 1-5E	1-5	0	10-15N 5-10S	1-5	1-5	0	1-5

* 0 = few or none.

TABLE V-4

PERCENTAGE OF WINDS WITH BEAUFORT FORCE 8 AND HIGHER

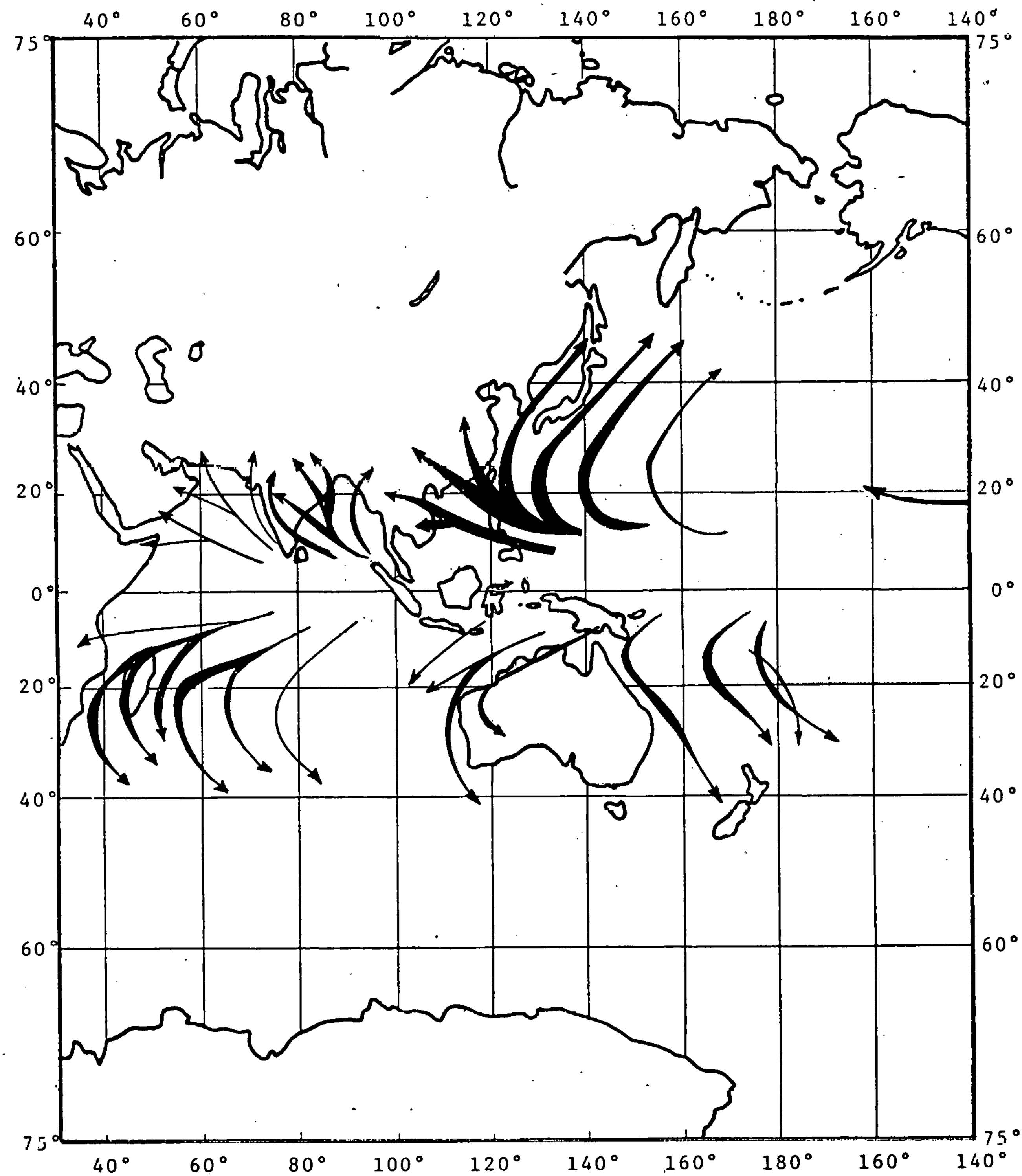
($\geq$ 17.5 meters per second)

LOCATION	Dec-Jan-Feb	Mar-Apr-May	Jun-Jul-Aug	Sep-Oct-Nov
Ivory Coast	0	1	0	0
Mombasa	N 1 S 0	0	0	0
Sri Lanka	0	0	1	0
Jakarta	1	1	0	1
Dampier Land	1	1	0	0
Philippines	5	0	1	1-5
Guam	0	1	1	1-5
Off Mexico	1	1	0	1
Plant Ship Pacific	0	1	0	0
Plant Ship Caribbean	1	0	1	0

TABLE V-5

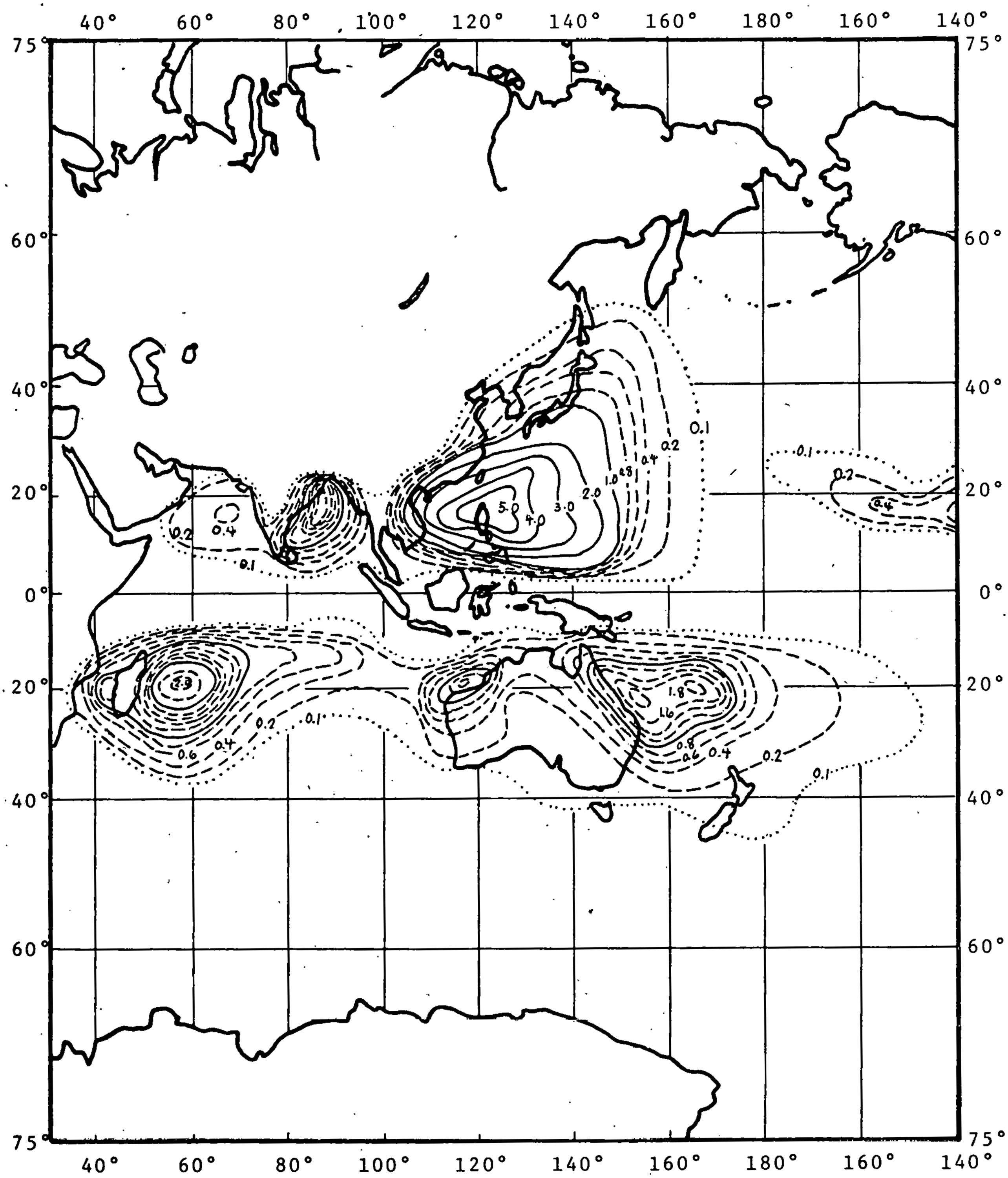
PREDOMINANT SURFACE WIND DIRECTION

MONTH	MOMBASA	SRI LANKA	DAMPIER LAND	JAKARTA	MANILA	GUAM	OFF MEXICO	PLANT SHIP (PACIFIC)	PLANT SHIP (CARIBN)	IVORY COAST
JAN	↓ ↓	↙	↗ ↗	↘	↙	↙	↘	↙	↙	↑ ↗
FEB	↓	↙	↗	→	↙	↙	↓	↙	↙	↑
MAR	↙	↓ O ↙ ↓	↘ ↗	→	↙	↙	↘	↙	←	↑
APR	O° ↙ ↖	O ↗	↖ ↖	↖	↓	↙	↘	↙	←	↑
MAY	↑ ↑	↗	↖	↖	↙ ↖	↙	↘	↖	←	↑
JUN	↑	↗	↖	↖	↗	←	↘	↘ ↙ ↑	←	↑
JUL	↑	↗	↖	↖	↗	↑ ↑ ←	↘	↑	←	↑
AUG	↑	↗	↖	↖	↗	← ↖	↓	→ ↗ ↑	←	↗
SEP	↑	→ O ↗	↖	↖	↙ ↗	←	↘	↗	←	↑
OCT	↖	→	↖	↖	↙	↙	↘	↑	←	↑
NOV	↙ ↖	→ O ↗	↖ ↗	↘ ↖	↙	↙	↓	↙ ↓ ↖ ↖	←	↑
DEC	↙	↙	↗	↗	↓	↙	↓	↙	↙	↗



ANNUAL PERFERRED STORM TRACKS FOR TROPICAL STORMS

FIGURE V-1



AVERAGE NUMBER OF
TROPICAL CYCLONES PER 5°
SQUARE PER YEAR

FIGURE V- 2

VI. SEA AND SWELL CHARACTERISTICS

Sea and swell conditions are generally a response to wind conditions. Since winds off Mombassa are consistently light, it would be expected that high sea and swell conditions are rare. This is indeed the case for the waters off Mombassa. Tables VI-1 and Table VI-2 present sea and swell data taken from U.S. Hydrographic Office Wind Waves at Sea (1947, [5]).

TABLE VI-1: PERCENTAGE OF VARIOUS SEA CONDITIONS.

	Low Seas (0.3-0.9 meters)	High Seas (2.4 meters or higher)
JAN-FEB Northern Section	20-40%	0-10%
JAN-FEB Southern Section	40-80%	0-10%
JUL-AUG Northern Section	40-60%	0-10%
JUL-AUG Southern Section	40-60%	0-10%

TABLE VI-2: PERCENTAGE OF VARIOUS SWELL CONDITIONS.

	Low Swell (0.3-1.8 meters)	High Swell (3.6 meters or higher)
JAN-FEB Northern Section	40-60%	0-10%
JAN-FEB Southern Section	60-80%	0-10%
JUL-AUG Northern Section	40-60%	10-20%
JUL-AUG Southern Section	40-60%	0-10%

Table VI-3, taken from Ocean Wave Statistics, (1967, [19]), presents a statistical breakdown showing the number of observations in various wave heights versus period categories. These statistics represent actual observations from ships. The observations are from an area somewhat larger than the area chosen for site analysis, but the conditions over the area are represented as being homogeneous. Figure VI-1 provides a graph of the relative frequency of various wave heights for the Mombasa site.

Table VI-4 summarizes mean wave data for the Mombasa site from Climatic Summaries For Major Indian Ocean Ports (1974, [35]).

TABLE VI-3: STATISTICAL BREAKDOWN SHOWING NUMBER OF SHIPS OBSERVATIONS OFF MOMBASA REPORTING VARIOUS HEIGHT/PERIOD COMBINATIONS (ALL SEASONS). From Ocean Wave Statistics (1967), [19].

Wave Height (meters)	Calm	Wave Period (Seconds) <5	6-7	8-9	10-11	12-13	14-15	16-17	18-19	20-21	over 21	Total	Percent of Grand Total
0.25	471	1530	5	6	2					5	3	1022	10
0.5	28	1437	136	22	5	2		1			29	1660	17
1.0	51	2181	838	131	35	13	6	2		1	19	3277	33
1.5	24	726	1225	273	73	17	5	3			1	2347	24
2.0	2	121	463	300	98	16	4	1				1005	10
2.5	1	48	136	127	57	23	5	1				398	4
3.0	2	9	55	50	24	5	1	1				147	1
3.5		4	20	21	11	2						58	<1
4.0		3	7	9	5	6	1					31	<1
4.5		2	4	6	5	4						21	<1
5.0		1	1			1						3	<1
5.5	1	3										4	<1
6.0	1											1	<1
6.5	2											2	<1
7.5		1										1	<1
8.0	1											1	<1
TOTAL	582	5068	2890	945	315	89	22	9		6	52	9978	
Percent of Grand Total	6	51	29	9	3	<1	<1	<1	<1	<1	<1		

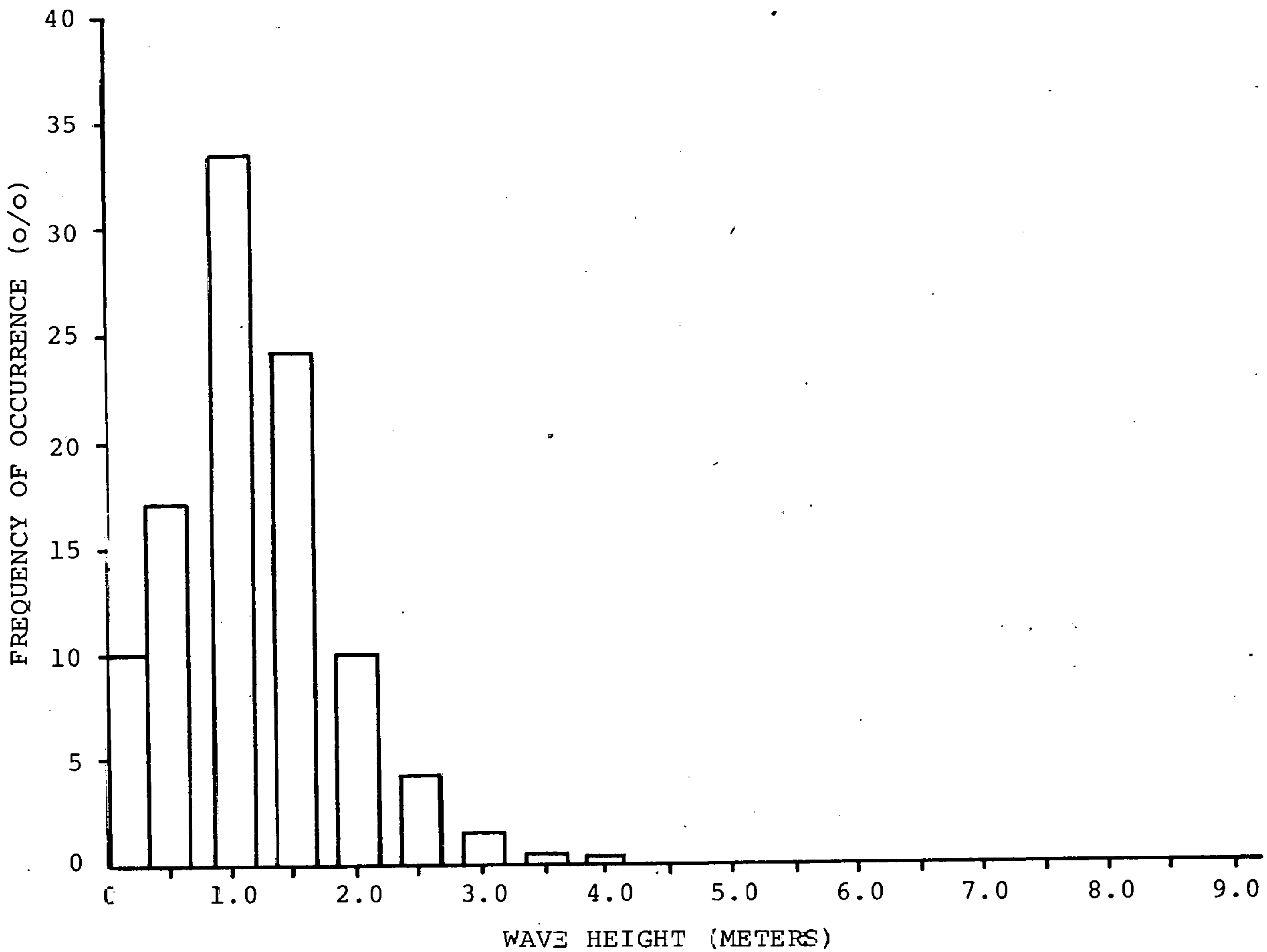


FIGURE VI-1

WAVE HEIGHT FREQUENCIES (MOMBASA)

TABLE VI-4: MONTHLY MEAN WAVE HEIGHTS IN METERS.

Northern Section	JAN	FEB	MAR	APR	MAY	JUN
	1.2-1.5	1.2-1.5	0.6-0.9	0.6-0.9	1.2-1.5	1.8-2.1
	JUL	AUG	SEP	OCT	NOV	DEC
	1.8-2.1	1.2-1.5	1.2-1.5	0.6-1.5	0.6-0.9	0.6-1.5
Southern Section	JAN	FEB	MAR	APR	MAY	JUN
	1.2-1.5	0.6-1.5	0.6-0.9	0.6-0.9	1.2-1.5	1.2-2.1
	JUL	AUG	SEP	OCT	NOV	DEC
	1.2-2.1	1.2-1.5	1.2-1.5	1.2-1.5	0.6-0.9	0.6-1.5

VII. CURRENTS

The circulation pattern of the area responds to seasonal shifts in the monsoons. The surface currents during the summer and winter seasons have definite characteristics. During the Northeast Monsoon, water north of the equator is carried westward by the Northeast Monsoon current. This water flows southward along Somalia; west of Madagascar the south equatorial current branches into the northward-flowing East African Coast Current. This East African Coast Current converges with the southward-flowing Somalia Current. From the convergence zone, the eastward-flowing Equatorial Counter-current begins in November-December.

During the Southwest Monsoon, most of the South Equatorial Current proceeds into the Somali Current moving northward along Kenya and Somalia. Unlike the weak southward-flowing Somali Current during the Northwest Monsoon, this Somali Current is quite strong. North of the equator, it turns eastward into the Southwest Monsoon Current. The reversal to the Southwest Monsoon region begins in April-May, usually in April south of the equator.

Like mean wind speeds during the Northeast Monsoon, currents during this period are generally weak and variable. Only in the southernmost part of the section off the city of Mombasa are the surface currents of strength, generally about 50 cm/sec, but occasionally near 100 cm/sec. The currents due east of the city of Mombasa at a surface station where the bottom is 1000 meters deep show very consistent flow toward the northeast at all depths. This station is in the East African Coast Current. The surface flow is around 50 cm/sec with little variability in speed and direction between January and July. The speeds of the currents decrease further north along the coast. Off Somalia, surface current speeds are generally closer to 10 cm/sec, between January and June. During the summer conditions, surface current speeds of 50 cm/sec or greater occur in the entire region. This current information is from Düing and Schott, 1978, [15].

The rare hurricane which occurs in this region will affect surface currents. Leipper, 1967 [21] showed that a current had developed in the area transversed by Hurricane Hilda. Analysis of temperature - depth data showed a current of approximately 50 cm/sec. A theoretical study by O'Brien and Reid, 1967 [27], states that hurricanes will cause currents with a speed of approximately one meter per second.

The passage of hurricanes can induce upwelling of subsurface water for a temporary period. This upwelling will cause anomalous vertical current shears. Strong vertical and horizontal current shears are also observed in association with major current systems. This site is in the source region of the Somali current, so there may be strong current shears off Mombasa.

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