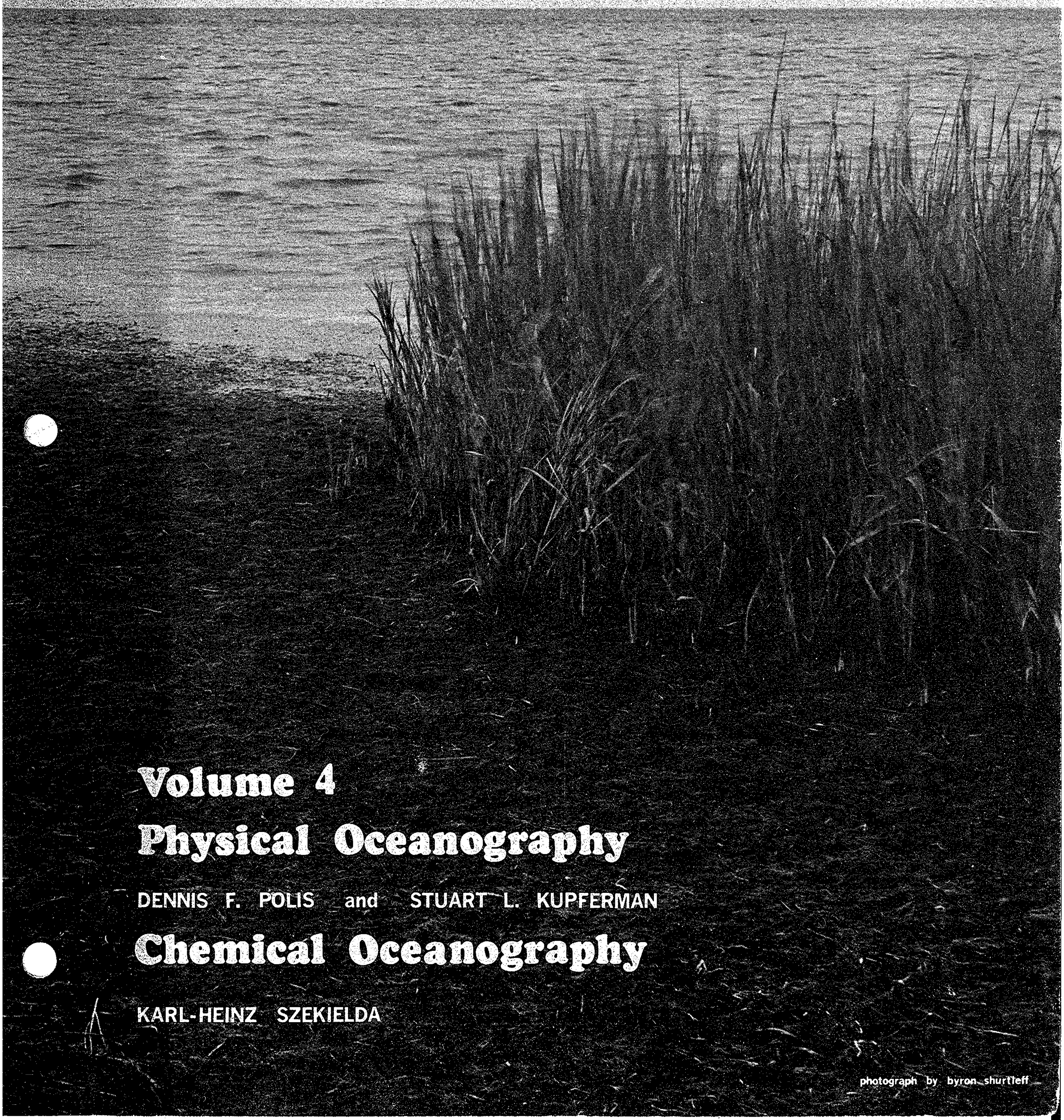
DELAWARE BAY REPORT SERIES



Volume 4

Physical Oceanography

DENNIS F. POLIS and STUART L. KUPFERMAN

Chemical Oceanography

KARL-HEINZ SZEKIELDA

photograph by byron shurtleff

DELAWARE BAY REPORT SERIES

Volume 4

PHYSICAL OCEANOGRAPHY

by

Dennis F. Polis and Stuart L. Kupferman

CHEMICAL OCEANOGRAPHY

by

Karl-Heinz Szekielda

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Dennis F. Polis

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College of Marine Studies
University of Delaware
Newark, Delaware
19711

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PHYSICAL OCEANOGRAPHY

by

Dennis F. Polis and Stuart L. Kupferman

Physical oceanography is the quantitative description of oceanographic phenomena based on physical and mathematical principles. It deals with the three-dimensional structure, movements, materials, and energy characteristics of the hydrosphere. This report discusses the physical oceanography of Delaware Bay, which is a part of the Delaware Estuary System.

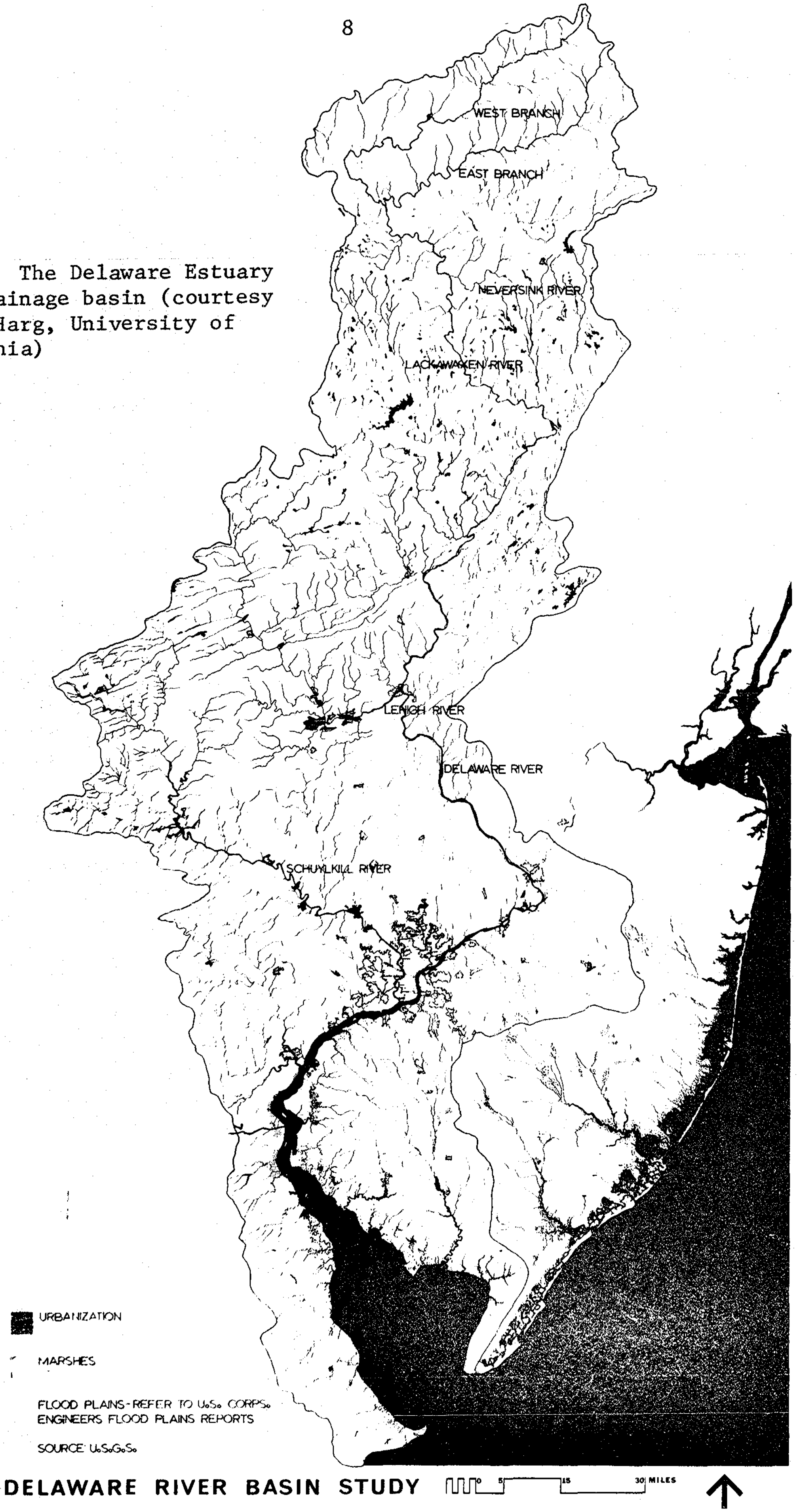
GENERAL BACKGROUND

The Delaware River Estuary System drains a basin of 12,765 square miles; it includes parts of Delaware, New Jersey, Pennsylvania, and New York, and eight square miles in Maryland. (See Figure 1.)

Of this area, the greater part (about 9,700 sq. mi.) consists of Appalachian Highlands with consolidated rock aquifers of generally low capacity, with the exception of certain valleys containing glacial outwashes from the pleistocene. The importance of these formations is that most of the basin tends to drain very quickly, with highly fluctuating discharges into the estuary at Trenton, New Jersey.

The mean annual precipitation in the basin (1921-50) is 44 inches, with a runoff of 21 inches or 4.7×10^{12} gallons per year. The flow of the Delaware River at Trenton averaged over this same period was 11,810 cubic feet per second (Parker *et al.*, 1964). Augmentation of this flow by fresh water drainage into the river below Trenton has

Figure 1. The Delaware Estuary system drainage basin (courtesy of Ian McHarg, University of Pennsylvania)



been discussed by Ketchum, (1953). (See Table 1.)

Before proceeding to a discussion of the bay and estuary, there are some terminological difficulties to be dealt with.

Table I*

Drainage Areas and Gaged River Flow of Various Streams Tributary to Delaware River and Bay, Having Drainage Areas Greater Than 50 Square Miles.

River or Stream	Drainage Area sq. miles	Average Discharge ft^3/sec	Average Discharge ft^3/sec/sq. mi.
Delaware at Trenton	6,780	11,710	1.73
Crosswicks Creek	84	152	1.82
Neshminy	210	265	1.26
Rancocos, N. Branch	111	162	1.46
Schuylkill - At. Phila.	1,893	2,715	1.44
Chester Creek	61	78	1.27
Brandywine Creek	287	378	1.32
White Clay Creek	88	119	1.36
Maurice River	113	176	1.56
Total gaged (69.25%)	9,627	15,755	1.64
Ungaged area (30.75%)	4,273	7,010**	(1.64)
Total drainage area	13,900	22,765	(1.64)

* Ketchum (1953)

** Ungaged area times 1.64 (average ft^3/sec/sq. mi.)

NOMENCLATURE

Estuarine nomenclature is extremely inconsistent and therefore confusing to those who are not familiar with the variant usages. Biologists tend to define an estuary as a body of water in which sea water is measureably diluted with river water (Reid, 1961). Under this definition, even offshore areas such as the New York Bight are classed as estuaries. Physical oceanographers generally follow Pritchard's (1967a) definition:

> An estuary is a semi-enclosed coastal body of water having free connection with the open sea and dilution of sea water by land drainage.

In this usage the region of the Delaware system from between Capes May and Henlopen up to some location between New Castle, Delaware and Philadelphia, Pennsylvania (which varies mainly with river flow) constitutes the Delaware Estuary. The U. S. Army Corps of Engineers (1956b) apparently considers semi-enclosure and tidal action to be the essential notes of an estuary, for it defines the Delaware Estuary to be that area of water between the capes and the head of tide at Trenton, New Jersey. The Delaware River Basin Commission (1966) considers the water between Liston Point, Delaware (which is legally the upper limit of Delaware Bay) and Trenton to be the estuary.

A similar, but less pronounced confusion exists over the definition of the bay, for while the legal definition of the bay takes it up to Liston Point, some previous workers (Shuster, 1959) have used the Smyrna River or (Zeskind and Le Lacheur, 1926) the southern tip of Artificial Island as the upstream limit of the bay. Clearly, there is need for some agreed-upon terminology in dealing with the Delaware estuarine system. The following terms provide a fixed geographical basis for discussion:

Delaware Estuary: The entire water area from Capes May and Henlopen to Trenton (Figure 2).

Delaware Bay: The water area from Capes May and Henlopen to a line between the stone markers at Liston Point, Delaware and Hope Creek, New Jersey.

Tidal River: The portion of the Delaware Estuary above the Delaware Bay.

The following terms are based on dynamical considerations and are more useful for physical oceanographic discussions:

Lower Estuary: That portion of the Delaware Estuary to the furthest upstream influence of oceanic salinity. This upstream limit is defined as the point where the chloride content of the water drops below 250 parts per million. Chloride is the ion found in greatest concentration in seawater. 250 PPM chloride is the commonly accepted maximum for potable water. The location at which this chloride level is found varies with river flow and tidal stage. It is normally found in the region between Wilmington and Philadelphia.

Upper Estuary: That portion of the Delaware Estuary upstream of the Lower Estuary.

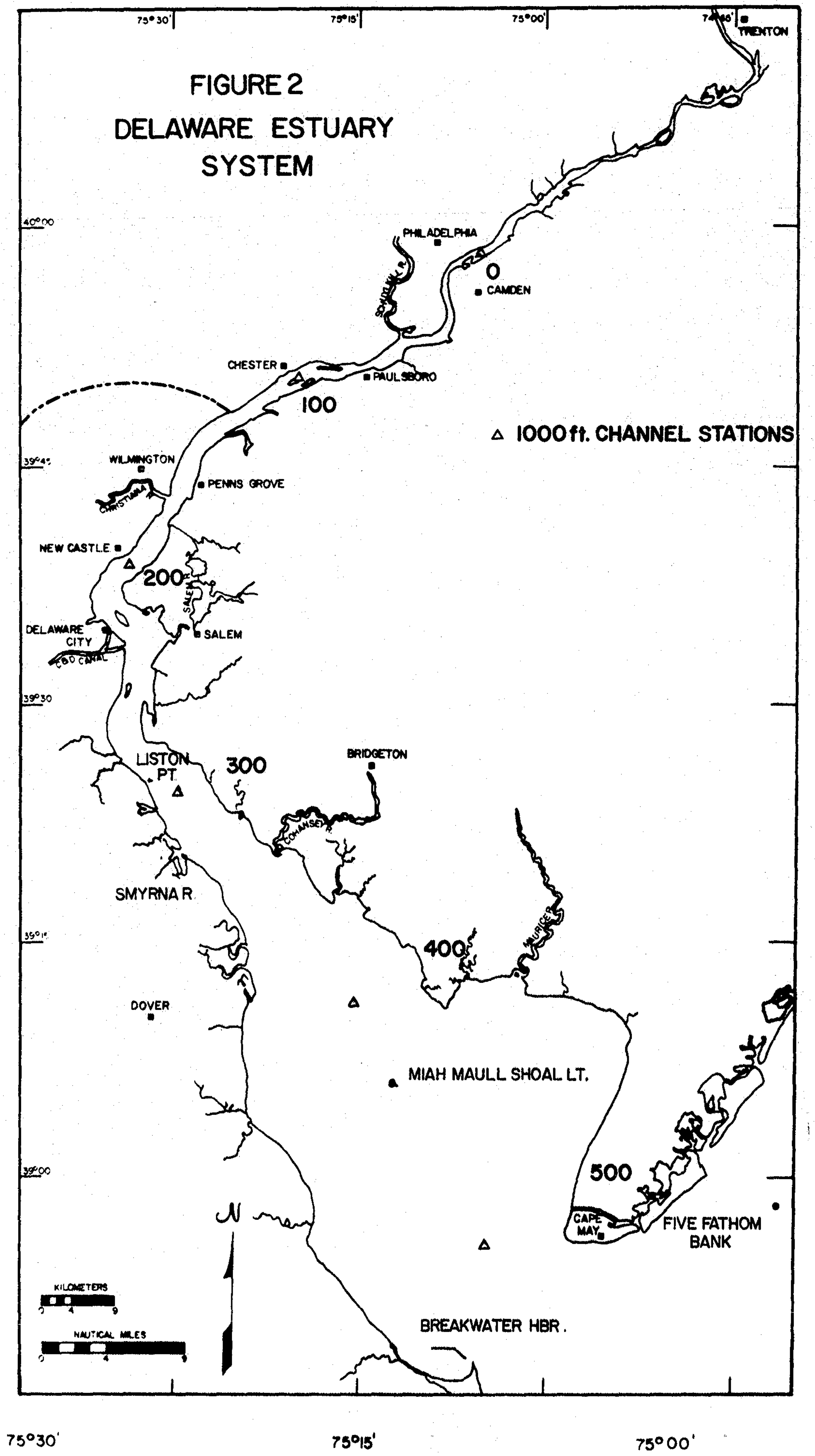


FIGURE 2
DELAWARE ESTUARY
SYSTEM
TRENTON
PHILADELPHIA
CAMDEN
0
SCHUYLKILL R.
CHESTER
PAULSBORO
100
△ 1000 ft. CHANNEL STATIONS
WILMINGTON
PENNS GROVE
CHRISTIANA R.
NEW CASTLE
200
SALEM R.
SALEM
DELAWARE
CITY
C & D CANAL
LISTON
PT.
300
BRIDGETON
COHANSEY R.
SMYRNA R.
400
MAURICE R.
DOVER
MIAH MAULL SHOAL LT.
500
CAPE
MAY
FIVE FATHOM
BANK
BREAKWATER HBR.
KILOMETERS
NAUTICAL MILES
75°30'
75°15'
75°00'
40°00
39°30
39°00

MORPHOLOGY AND BATHYMETRY OF THE DELAWARE BAY

The estuary is 132 statute miles long and varies in width from about 11 miles at the capes to about 27 miles at the widest point of the bay, after which it decreases in a very nearly exponential fashion from the vicinity of Miah Maull Shoal to Trenton, where its width is 1000 feet. A navigation channel passes from the deep water inside the entrance of the bay to Trenton, New Jersey. The authorized depth of this channel is 40 feet below mean low water up to the Philadelphia Navy Yard and then 25 feet to Trenton.

The morphology of Delaware Bay has been described by Schuster (1959). He has referred to the bay as having "the shape... of a flattened funnel with a more extensive shallow water area in its eastern side." The bay is basically divided into three regions: a shallow storage area on the New Jersey side, a center channel, and an area on the Delaware side characterized by alternating shoals and fingers of deep water. (See Figure 3.) Schuster's morphological calculations are summarized in Table II. The hypsographic curve (total area above a given depth plotted against depth) from his report is reproduced here as Figure 4.

The dimensions necessary to complete the description of the lower estuary have been estimated, using National Ocean Survey Charts 1218, 294, and 295, and are summarized in Table IIa. These dimensions have been determined assuming that the chlorinity limit of 250 parts per million lies on the Delaware-Pennsylvania border.

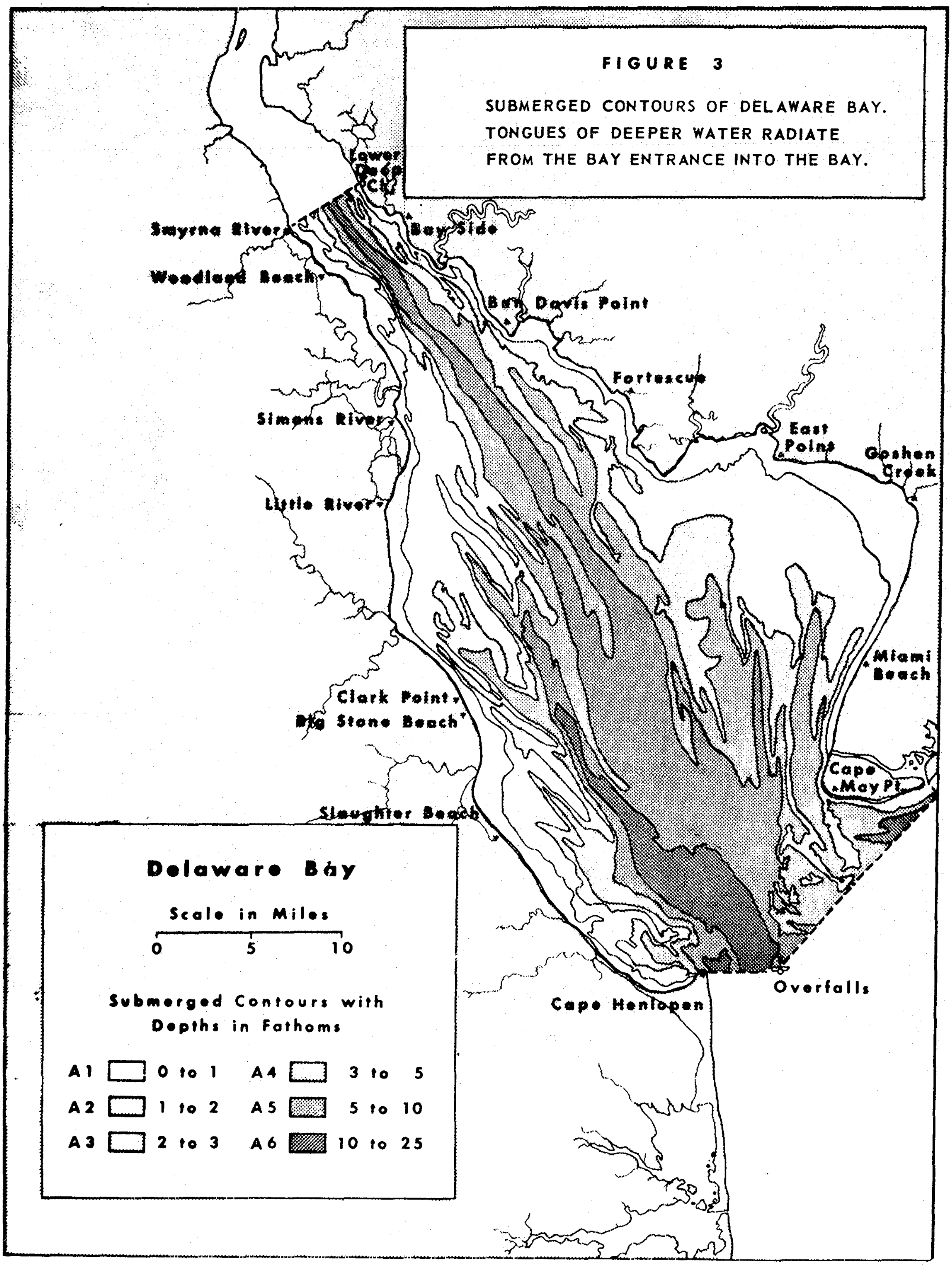


FIGURE 3

SUBMERGED CONTOURS OF DELAWARE BAY. TONGUES OF DEEPER WATER RADIATE FROM THE BAY ENTRANCE INTO THE BAY.

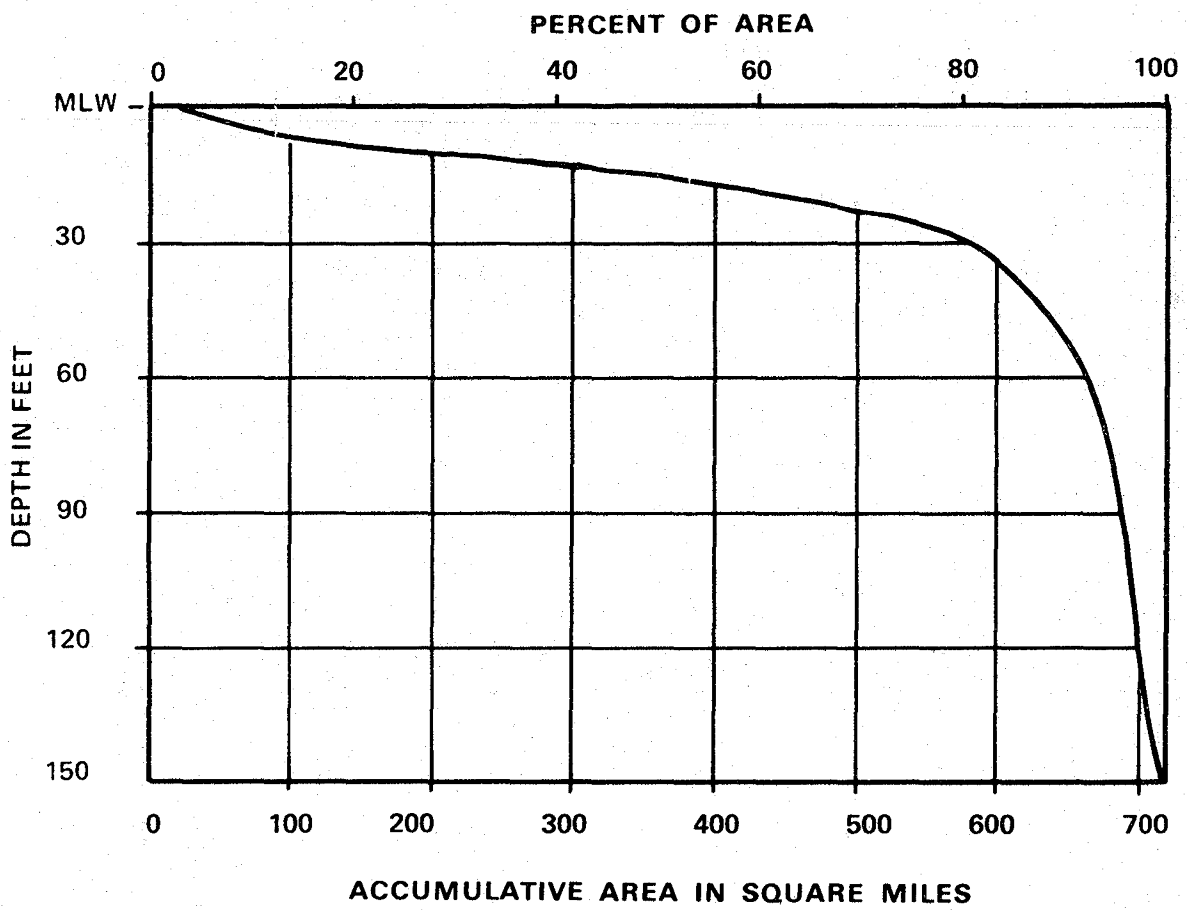


Figure 4. This hypsographic curve shows the area within Delaware Bay that is above or below any given depth (See Table II). For example, slightly over 80% of the bay is less than 30 feet deep (from Schuster, 1959).

Table II*

Morphology of the Delaware Bay below the Smyrna River

Maximum Length	46.7 statute miles
Maximum Width	27.1 statute miles
Mean Width	15.3 statute miles
Maximum Depth	151 feet
Mean Depth	31.7 feet
Total Surface Area	720 square miles (statute)
Length of Shoreline	
Delaware	55.1 statute miles
New Jersey	73.2 statute miles
Total:	128.3 statute miles
Total Volume	633,800,000,000 cubic feet
	(4,734,400,000,000 gallons)

*Schuster (1959)

Table IIa

Morphology of the Lower Estuary above the Smyrna River

Length (to Del. - Pa. border)	33 statute miles
Maximum Width	4.6 statute miles
Average Width	2.2 statute miles
Maximum Depth	40 feet
Average Depth	17 feet

The foregoing morphological summaries have been generated on the basis of data collected by the National Ocean Survey (formerly Coast and Geodetic Survey). These data are well worth considering.

The situation as regards detailed bathymetry is unsatisfactory, but is being corrected. Figures 5a through 5h show the location and extent of historical surveys of the bay's bathymetry, while Table III provides the survey dates. A study of these will indicate that there are areas of the bay (e.g., Joe Flogger Shoal) which have not been systematically surveyed since 1880. For this reason it is not surprising that the presently used navigation chart (#1218) has areas in which the depths are off by a factor of 2 (Robert Sheridan, private communication). This presents a considerable difficulty to anyone attempting to model the hydrodynamics of the bay, as accurate depth information is essential to all state-of-the-art computer and physical models. This situation is being remedied by NOS, which is presently engaged in a five-year project to resurvey the bay. At present (1972) only the area around the entrance of the bay has been resurveyed (See Figure 5h).

TIDES

The tide in the Delaware Estuary is dominated by the main lunar (semidiurnal) constituant having a period of 12.42 hours. The mean range of the tide at the Capes is about 4.3 feet. The range generally increases through the estuary to about 6.7 feet at Trenton (See Table IV). The time of high water at Trenton is almost eight hours

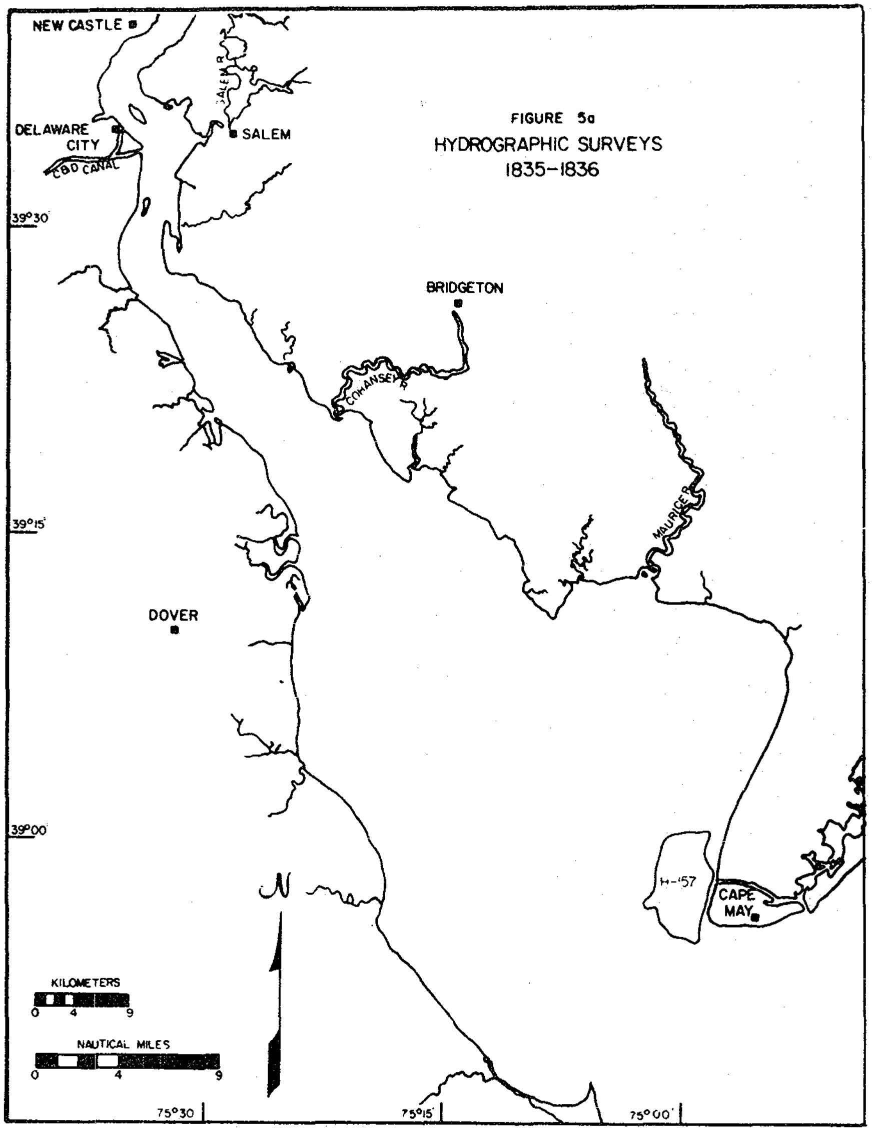


FIGURE 5a
HYDROGRAPHIC SURVEYS
1835–1836
NEW CASTLE
DELAWARE CITY
C&D CANAL
SALEM R.
SALEM
BRIDGETON
COHANSEY R.
MAURICE R.
DOVER
H-157
CAPE MAY
39°30'
39°15'
39°00'
KILOMETERS
0 4 9
NAUTICAL MILES
0 4 9
75°30
75°15'
75°00'

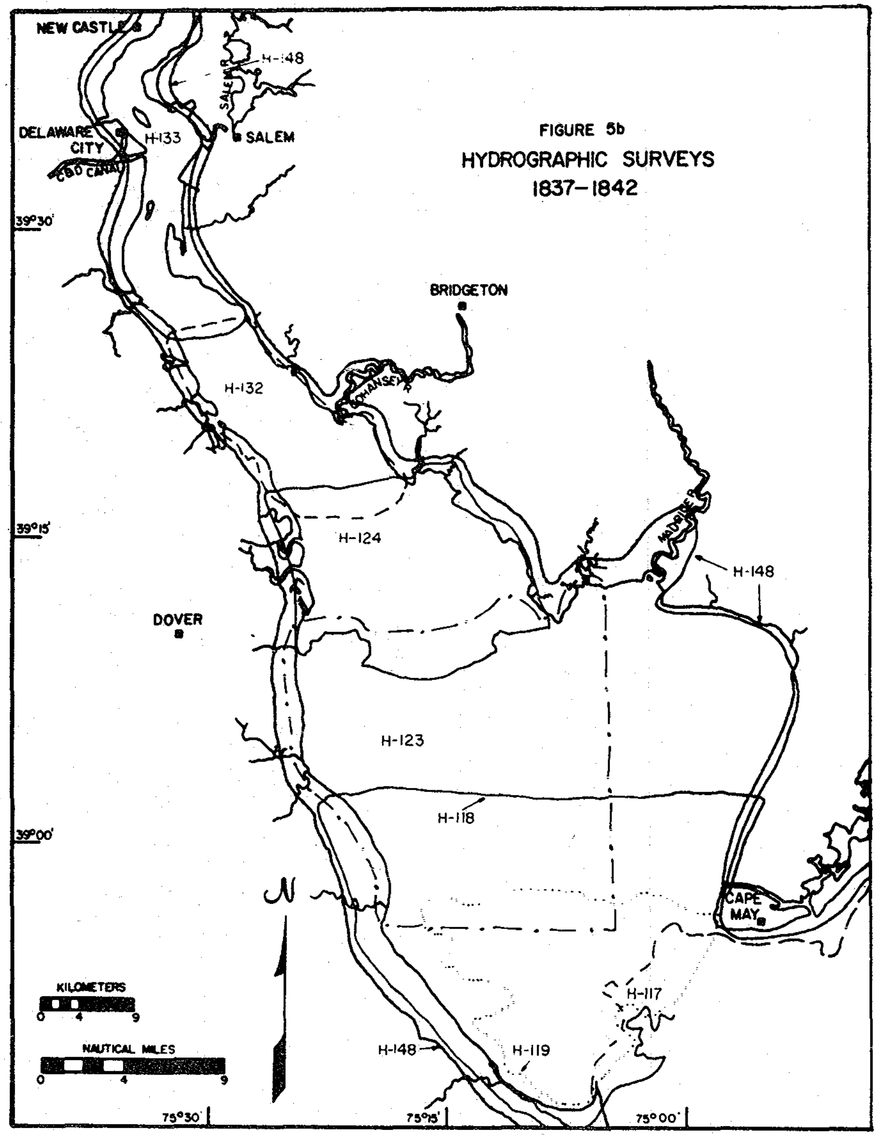


FIGURE 5b
HYDROGRAPHIC SURVEYS
1837–1842
NEW CASTLE
DELAWARE CITY
C&D CANAL
SALEM R.
SALEM
H-148
H-133
BRIDGETON
COHANSEY R.
H-132
H-124
MAURICE R.
H-148
DOVER
H-123
H-118
CAPE MAY
H-117
H-148
H-119
39°30'
39°15'
39°00'
KILOMETERS
0 4 9
NAUTICAL MILES
0 4 9
75°30'
75°15'
75°00'

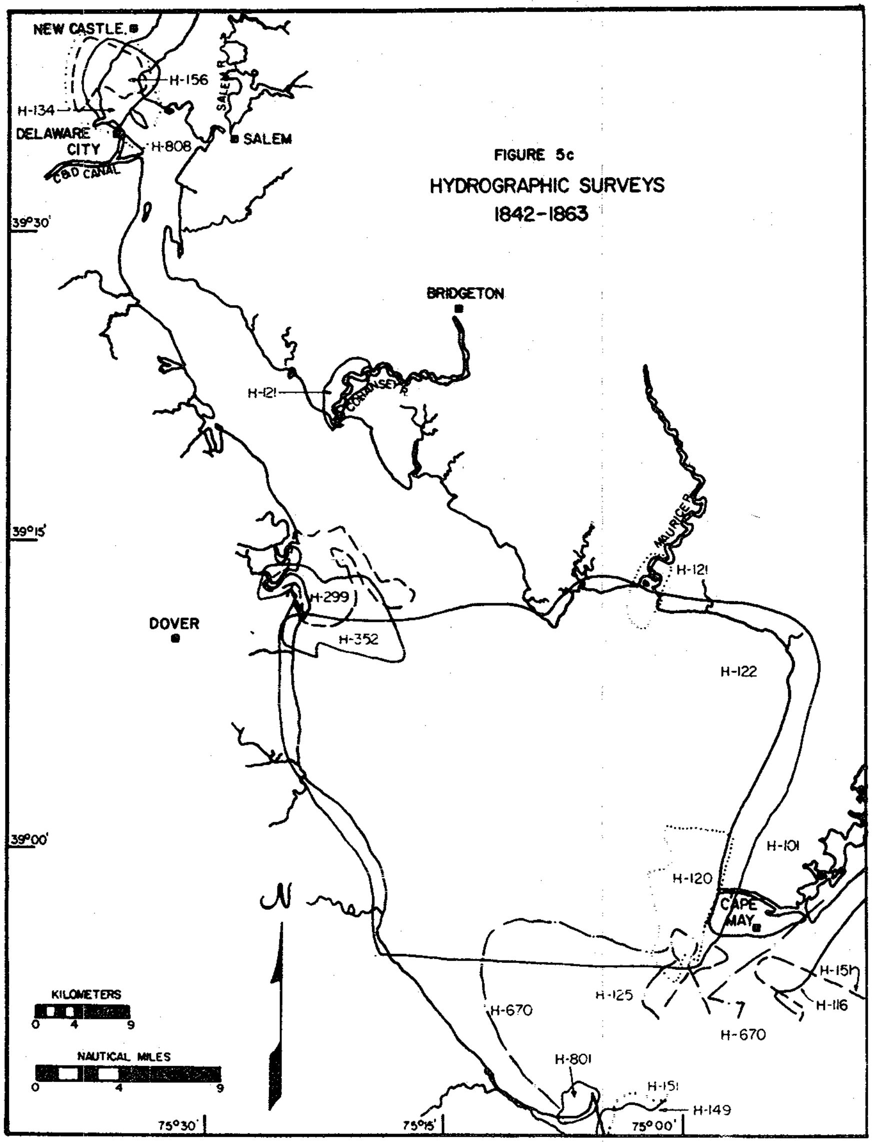


FIGURE 5c
HYDROGRAPHIC SURVEYS
1842-1863

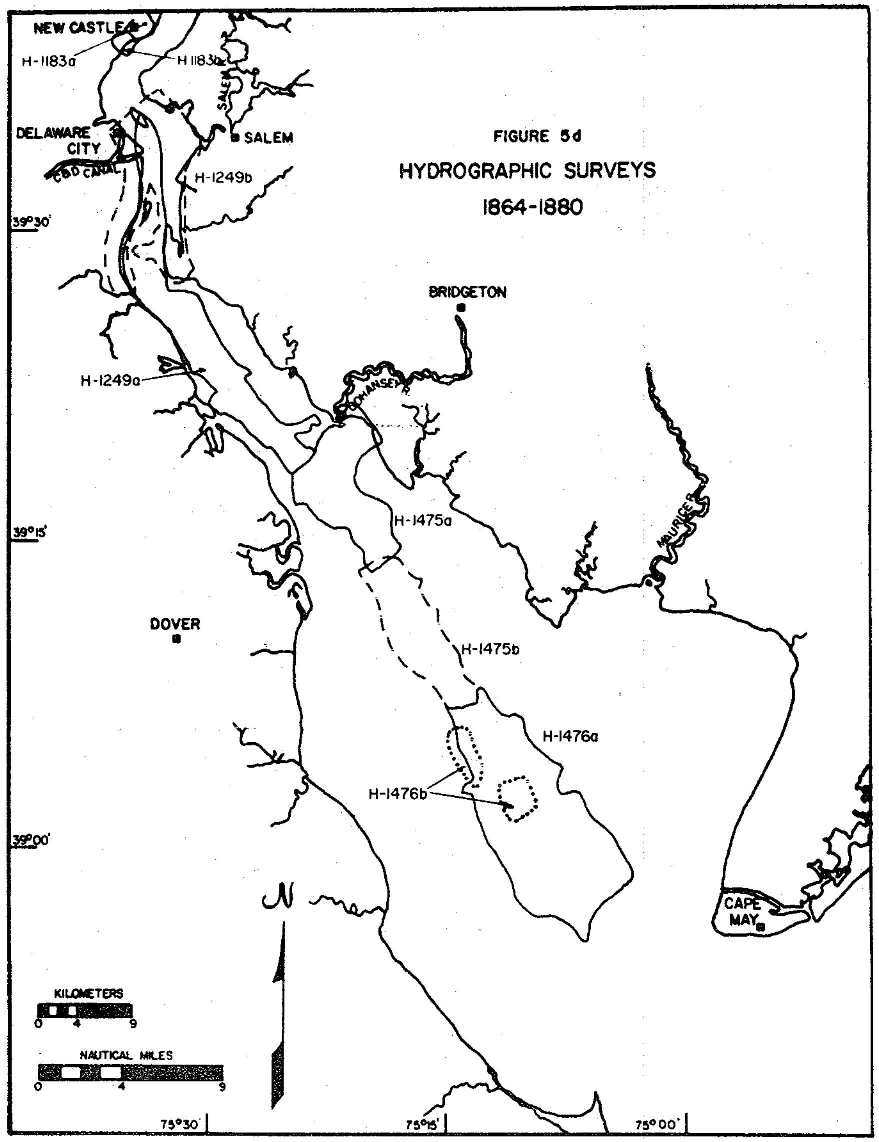


FIGURE 5d
HYDROGRAPHIC SURVEYS
1864-1880

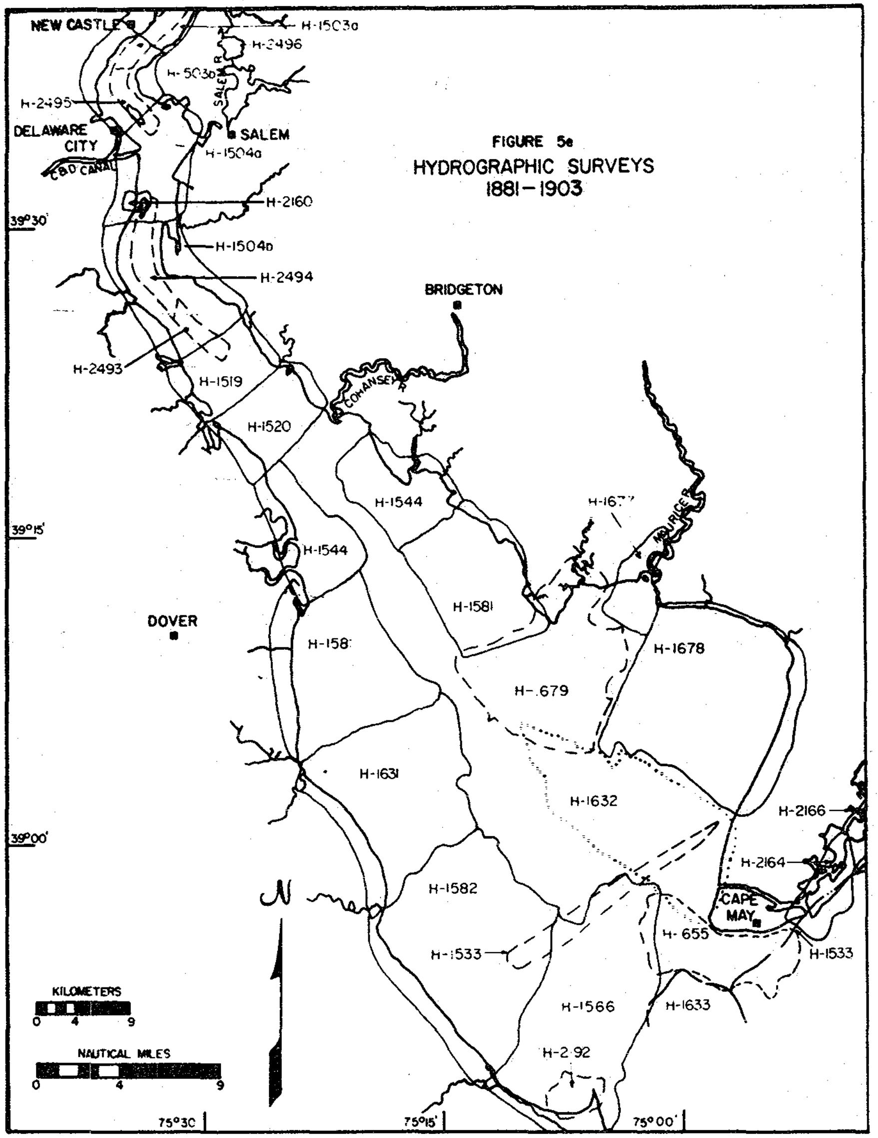


FIGURE 5e
HYDROGRAPHIC SURVEYS
1881-1903
NEW CASTLE
DELAWARE CITY
C&D CANAL
SALEM
SALEM R.
BRIDGETON
COHANSEY
MAURICE R.
DOVER
CAPE MAY
H-1503a
H-2496
H-2495
H-1504a
H-2160
H-1504b
H-2494
H-2493
H-1519
H-1520
H-1544
H-1581
H-1678
H-1631
H-1632
H-2166
H-2164
H-1582
H-1533
H-1566
H-1633
39°30'
39°15'
39°00'
75°30'
75°15'
75°00'
KILOMETERS
NAUTICAL MILES

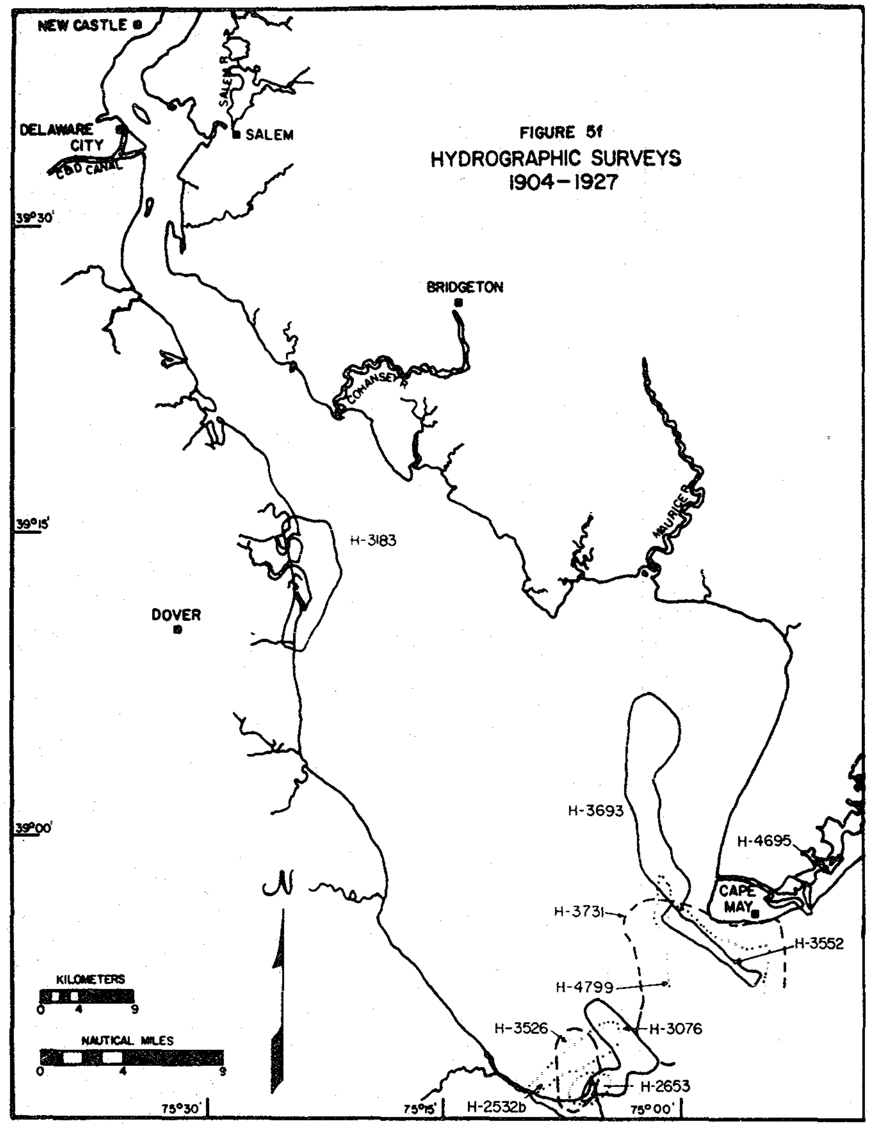


FIGURE 5f
HYDROGRAPHIC SURVEYS
1904-1927
NEW CASTLE
DELAWARE CITY
C&D CANAL
SALEM
BRIDGETON
COHANSEY
DOVER
CAPE MAY
H-3183
H-3693
H-4695
H-3731
H-3552
H-4799
H-3526
H-3076
H-2653
H-2532b
39°30'
39°15'
39°00'
75°30'
75°15'
75°00'
KILOMETERS
NAUTICAL MILES

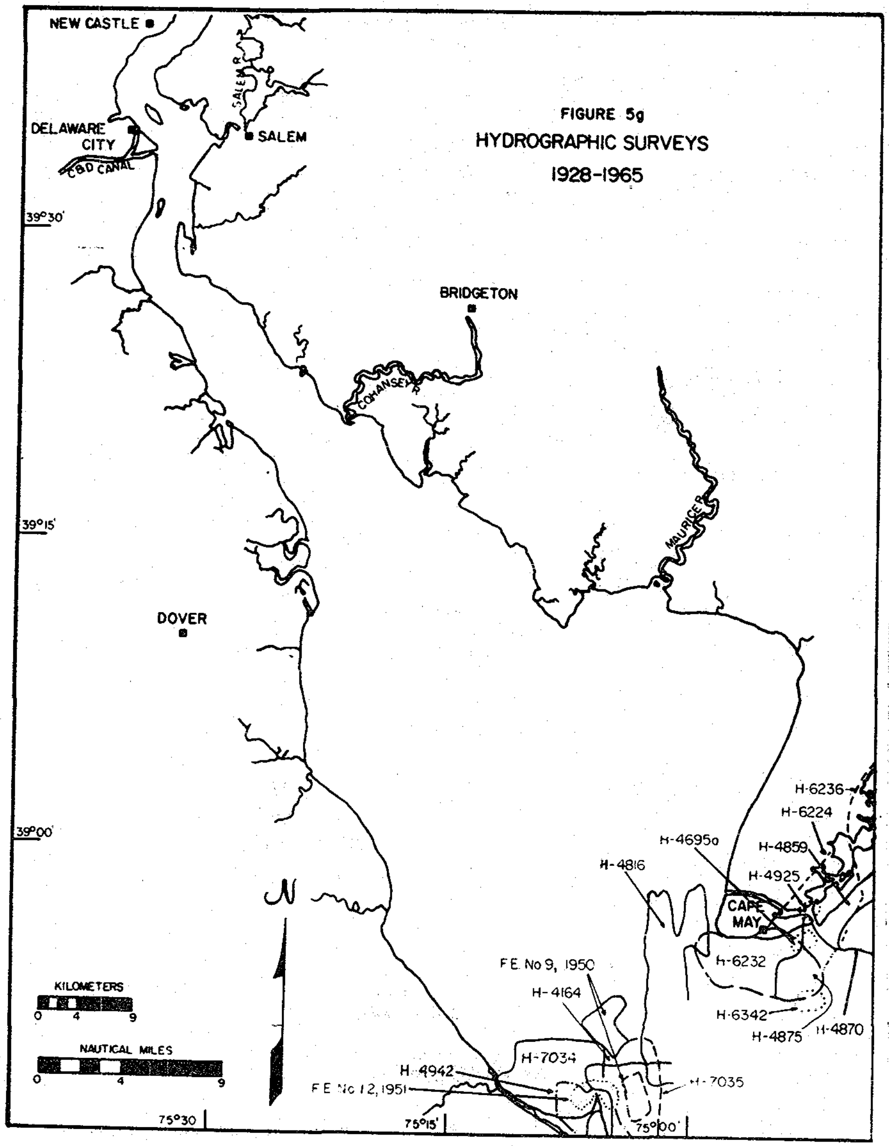


FIGURE 5g
HYDROGRAPHIC SURVEYS
1928-1965

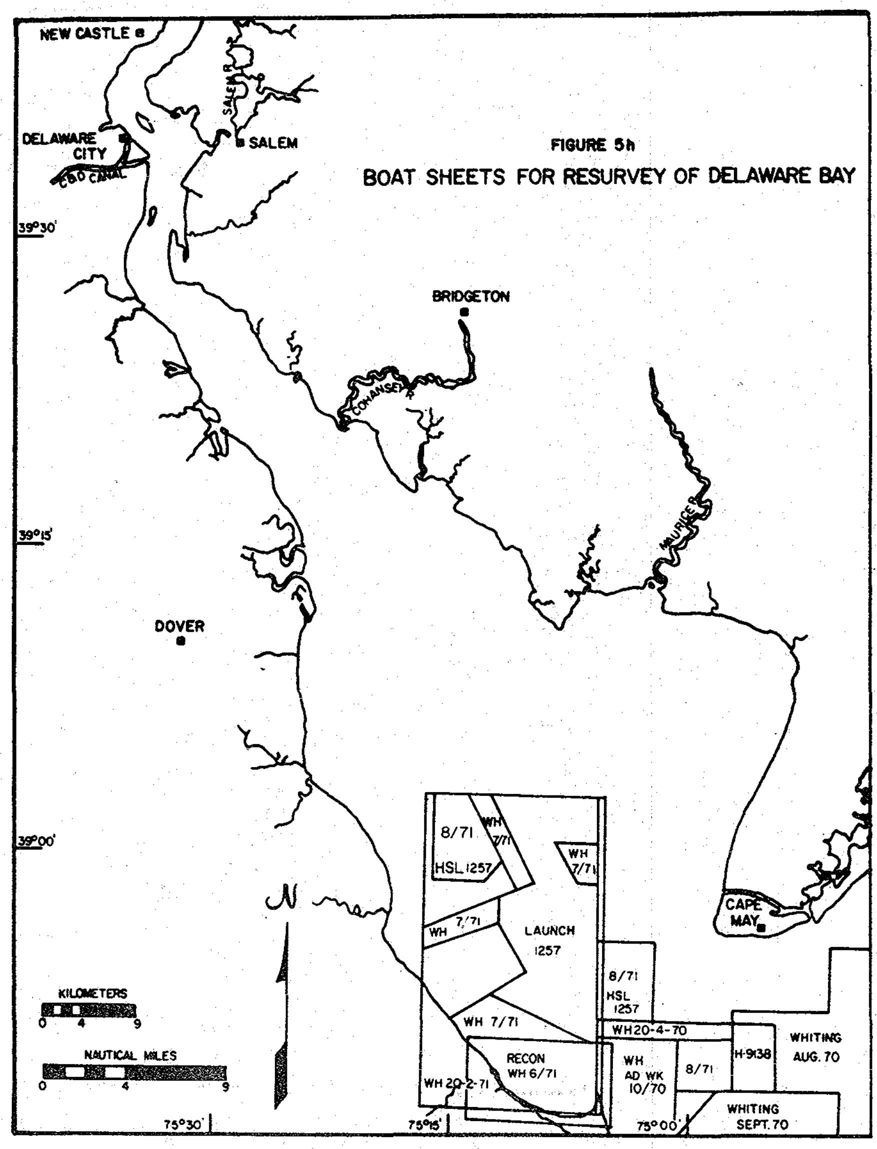


FIGURE 5h
BOAT SHEETS FOR RESURVEY OF DELAWARE BAY

Table III

Hydrographic Survey Summaries

Survey No.	Year	Scale	Hydrographic Index Sheet Nos.
H-101	1844	400,000	66C
H-116	1843	40,000	66C
H-117	1841	40,000	66B, 67A
H-118	1842-43	20,000	66C, 67A
H-119	1842	20,000	66C, 67A
H-120	1842	20,000	67A, 66C
H-121	1843	20,000	67B
H-122	1842	20,000	66C, 67A
H-123	1842	20,000	66C, 67A
H-124	1841	20,000	66B, 67A
H-125	1847	20,000	66C, 67B
H-132	1841	20,000	67A
H-133	1840-41	10,000	67A
H-134	1848	20,000	67B
H-148	1841-43	80,000	66B, 67A
H-149	1844	20,000	67B
H-151	1844	40,000	66C, 67B
H-156	1846-47	10,000	67B
H-157	1836-47	10,000	66A
H-299	1852	20,000	67B
H-352	1852	10,000	67B
H-670	1859	400,000	67B, 66C
H-801	1863	3,600	67B
H-808	1861	10,000	67B
H-11832	1873	1,250	67C
H-1183b	1873	1,250	67C
H-1249a	1875	20,000	67C
H-1249b	1875	20,000	67C
H-1475a	1880	20,000	67C
H-1475b	1880	20,000	67C
H-1476a	1880	20,000	67C, 66E
H-1476b	1880	10,000	67C, 66E
H-1503a	1881	5,000	67D
H-1503b	1881	10,000	67D
H-1504a	1881	10,000	67D
H-1504b	1881	10,000	67D
H-1519	1882	10,000	67D
H-1520	1882	10,000	67D
H-1533	1882-1900	40,000	66F, 67D
H-1544	1882	20,000	67D
H-1566	1883	20,000	66F, 67D

Prepared from National Ocean Survey Hydrographic Index Sheets.

Table III

Hydrographic Survey Summaries

Survey No.	Year	Scale	Hydrographic Index Sheet Nos.
H-1581	1882-85	20,000	66F, 67D
H-1582	1883	20,000	66F, 67D
H-1631	1884	20,000	67D, 66F
H-1632	1884	20,000	66F, 67D
H-1633	1884	40,000	66F
H-1655	1885	10,000	66G, 67D
H-1677	1885	10,000	66G, 67D
H-1678	1885	20,000	67D, 66G
H-1679	1885	20,000	66G, 67D
H-2164	1891	10,000	66G
H-2166	1891	10,000	66G
H-2192	1894	10,000	67D
H-2493	1900	9,600	67D
H-2494	1900	9,600	67D
H-2495	1900	9,600	67D
H-2496	1900	9,600	67D
H-2532b	1910	20,000	67E
H-2653	1903	10,000	67E
H-3076	1910	10,000 20,000	67E
H-3183	1910	20,000	67E
H-3552	1913	25,000	66H, 67E
H-3693	1914	30,000	66H, 67E
H-3731	1914	20,000	66H, 67E
H-4164	1920	40,000	67F
H-4695	1927	5,000	66H
H-4695a	1928	5,000	66I
H-4799	1927	20,000	66H
H-4816	1928	20,000	66I, 67F
H-4859	1928	10,000	66I
H-4870	1928	20,000	66I
H-4875	1928	20,000	66I
H-4925	1929	5,000	66I
H-4942	1929	20,000	67F
H-6224	1937	10,000	66J
H-6232	1937	10,000	66J
H-6236	1937	10,000	66J
H-6342	1938	40,000	66J
H-7034	1945	10,000	67F
H-7035	1945	10,000	67F
F. E. No. 9, 1950	1950	40,000	67F
F. E. No. 12, 1951	1951	10,000	67F

Table IV. Tidal Differences and other Constants**

No.	PLACE	POSITION		DIFFERENCES				RANGES		Mean Tide Level
		Lat	Long	Time		Height		Mean	Spring	
				High water	Low water	High water	Low water			
		° ′	° ′	h m	h m	feet	feet	feet	feet	feet
	NEW JERSEY and DELAWARE									
	Delaware Bay, Eastern Shore			RELATIVE TO BREAKWATER HBR.						
1757	Five Fathom Bank	38 51	74 38	-0 43	-0 38	0.0	0.0	4.1	4.9	2.0
1759	McCrie Shoal	38 51	74 51	-0 22	-0 21	+0.2	0.0	4.3	5.2	2.1
1761	Cape May Point	38 56	74 58	-0 10	-0 04	+0.6	0.0	4.7	5.6	2.3
1763	Bay Shore Channel	38 58	74 58	-0 09	-0 03	+0.8	0.0	4.9	5.8	2.4
1765	Miami Beach	39 02	74 56	+0 17	+0 26	+1.0	0.0	5.1	6.1	2.5
1767	Dennis Creek entrance	39 10	74 54	+0 48	+1 04	+1.5	0.0	5.6	6.6	2.8
1769	East Point, Maurice River Cove	39 12	75 02	+0 53	+1 12	+1.6	0.0	5.7	6.7	2.8
	Maurice River									
1771	Port Norris	39 14	75 02	+1 14	+1 38	+1.6	0.0	5.7	6.7	2.8
1773	Mauricetown	39 17	75 00	+1 48	+2 21	+1.7	0.0	5.8	6.8	2.9
1775	Millville	39 24	75 02	+2 37	+3 23	+1.9	0.0	6.0	7.0	3.0
1777	Egg Island Point	39 11	75 08	+0 33	+1 02	+1.6	0.0	5.7	6.7	2.8
				RELATIVE TO REEDY POINT						
1779	Fortescue	39 14	75 10	-2 05	-2 19	+0.4	0.0	5.9	7.0	2.9
1781	Ben Davis Point	39 17	75 17	-1 40	-1 49	+0.5	0.0	6.0	6.9	3.0
	Cohansey River									
1783	Entrance	39 21	75 22	-1 30	-1 29	+0.5	0.0	6.0	6.9	3.0
1785	Laning Wharf	39 23	75 20	-1 10	-1 14	+0.5	0.0	6.0	6.8	3.0
1787	Fairton	39 23	75 14	+0 05	-0 24	+0.7	0.0	6.2	7.0	3.1
1789	Bridgeton	39 25	75 14	+0 27	-0 13	+1.0	0.0	6.5	7.3	3.2
1791	Bay Side	39 23	75 24	-1 23	-1 22	+0.6	0.0	6.1	6.9	3.0
	Delaware Bay, Central Lighthouses			RELATIVE TO BREAKWATER HBR.						
1793	Brandywine Shoal Light	38 59	75 07	+0 09	+0 28	+0.8	0.0	4.9	5.9	2.4
1795	Fourteen Foot Bank Light	39 03	75 11	+0 18	+0 48	+1.1	0.0	5.2	6.2	2.6
1797	Miah Maull Shoal Light	39 08	75 13	+0 28	+1 08	+1.4	0.0	5.5	6.5	2.7
1799	Elbow of Cross Ledge Light	39 11	75 16	+0 40	+1 21	+1.5	0.0	5.6	6.5	2.8
				RELATIVE TO REEDY POINT						
1801	Ship John Shoal Light	39 18	75 23	-1 32	-1 36	+0.2	0.0	5.7	6.6	2.8
	Delaware Bay, Western Shore			RELATIVE TO BREAKWATER HBR.						
1803	Cape Henlopen	38 48	75 05	-0 05	-0 05	0.0	0.0	4.1	4.9	2.0
1805	BREAKWATER HARBOR	38 47	75 06	Daily predictions				4.1	4.9	2.1
1807	Roosevelt Inlet	38 49	75 12	+0 09	+0 13	+0.3	0.0	4.4	5.2	2.2
1809	Mispillion River entrance	38 57	75 19	+0 33	+1 00	+0.5	0.0	4.6	5.4	2.3
1811	Murderkill River entrance	39 04	75 24	+0 56	+1 32	+0.7	0.0	4.8	5.7	2.4
1813	St. Jones River entrance	39 04	75 24	+0 57	+1 33	+0.7	0.0	4.8	5.7	2.[illegible]
1815	Mahon River entrance	39 11	75 24	+1 13	+1 52	+1.3	0.0	5.4	6.3	2.7
1817	Leipsic River entrance	39 15	75 24	+1 18	+1 59	+1.4	0.0	5.5	6.4	2.7
1819	Leipsic, Leipsic River	39 15	75 31	+3 42	+3 50	-0.6	0.0	3.5	4.0	1.7
				RELATIVE TO REEDY POINT						
1821	Woodland Beach	39 20	75 28	-1 15	-1 14	+0.4	0.0	5.9	6.8	2.9
	Delaware River									
1823	Liston Point	39 25	75 32	-0 55	-0 59	+0.2	0.0	5.7	6.4	2.8
1825	Taylors Bridge, Blackbird Creek	39 24	75 36	+1 47	+0 54	-2.6	0.0	2.9	3.3	1.4
1827	Reedy Island	39 31	75 34	-0 16	-0 16	+0.1	0.0	5.6	6.2	2.8
1829	Salem Cove	39 34	75 31	0 00	0 00	+0.1	0.0	5.6	6.1	2.8
1831	Salem, Salem River	39 35	75 28	+0 19	+0 20	+0.1	0.0	5.6	6.1	2.8
1833	REEDY POINT	39 34	75 34	Daily predictions				5.5	6.0	2.7
	Chesapeake and Delaware Canal									
1835	Biddle Point, Delaware	39 33	75 37	-0 05	+0 01	-0.4	0.0	5.1	5.5	2.5
1837	Summit Bridge, Delaware	39 33	75 44	-0 34	-0 55	*0.64	*0.64	3.5	3.9	1.7
1839	Chesapeake City, Maryland	39 32	75 49	-1 15	-1 52	*0.47	*0.47	2.6	3.0	1.3
1841	Pea Patch Island, Delaware	39 35	75 34	+0 08	+0 12	0.0	0.0	5.5	6.0	2.7
1843	New Castle, Delaware	39 39	75 34	+0 30	+0 49	+0.1	0.0	5.6	6.0	2.8
1845	Deepwater Point, N. J	39 42	75 31	+0 46	+1 11	+0.1	0.0	5.6	6.0	2.8
1847	Christina River entrance, Del	39 43	75 31	+0 51	+1 16	+0.1	0.0	5.6	5.9	2.8
1849	Wilmington, Christina River, Del	39 44	75 33	+0 56	+1 27	+0.2	0.0	5.7	6.0	2.8
1851	Edgemoor, Del	39 45	75 30	+0 56	+1 27	+0.1	0.0	5.6	5.9	2.8
1853	Oldmans Point, N. J	39 46	75 28	+1 03	+1 34	+0.1	0.0	5.6	5.9	2.8

Table IV. Tidal Differences and other Constants**

No	PLACE	POSITION Lat	Long	DIFFERENCES Time High water	Time Low water	Height High water	Height Low water	RANGES Mean	Spring	Mean Tide Level
		° ′	° ′	h m	h m	feet	feet	feet	feet	feet
				RELATIVE TO PHILADELPHIA						
1855	Marcus Hook, Pa	39 49	75 25	-1 20	-1 21	-0.3	0.0	5.6	5.9	2.8
1857	Chester, Pa	39 51	75 21	-0 59	-1 00	-0.2	0.0	5.7	6.0	2.8
1859	Billingsport, N. J	39 51	75 14	-0 39	-0 40	-0.2	0.0	5.7	6.0	2.8
1861	Fort Mifflin, Pa	39 52	75 13	-0 29	-0 30	-0.2	0.0	5.7	6.0	2.8
	Schuylkill River									
1863	Girard Point, Pa	39 54	75 12	-0 25	-0 25	-0.2	0.0	5.7	6.0	2.8
1865	Point Breeze, Pa	39 55	75 12	-0 21	-0 20	-0.2	0.0	5.7	6.0	2.8
1867	Grays Ferry Bridge, Pa	39 57	75 12	-0 15	-0 14	-0.1	0.0	5.8	6.1	2.9
1869	Fairmount Bridge, Pa	39 58	75 11	-0 06	-0 04	-0.1	0.0	5.8	6.1	2.9
1871	Philadelphia, South Broad St., Pa	39 53	75 11	-0 25	-0 26	-0.1	0.0	5.8	6.1	2.9
1873	Gloucester City, N. J	39 54	75 08	-0 13	-0 13	-0.1	0.0	5.8	6.1	2.9
1875	Philadelphia, Washington Ave., Pa	39 56	75 08	-0 04	-0 04	0.0	0.0	5.9	6.2	3.0
1877	PHILADELPHIA, Pier 11 North, Pa	39 57	75 08	Daily predictions				5.9	6.2	3.0
1879	Camden, Cooper Point, N. J	39 57	75 08	+0 04	+0 04	0.0	0.0	5.9	6.2	3.0
1881	Philadelphia, Pier 80 North, Pa	39 58	75 07	+0 10	+0 11	0.0	0.0	5.9	6.2	3.0
1883	Philadelphia, Bridesburg, Pa	40 00	75 04	+0 26	+0 28	+0.1	0.0	6.0	6.3	3.0
1885	Torresdale, Pa	40 03	74 59	+0 58	+1 02	+0.3	0.0	6.2	6.5	3.1
1887	Burlington, N. J	40 05	74 52	+1 22	+1 28	+0.5	0.0	6.4	6.7	3.2
1889	Bristol, Pa	40 06	74 51	+1 29	+1 36	+0.6	0.0	6.5	6.8	3.3
1891	Florence, N. J	40 07	74 48	+1 39	+1 50	+0.7	0.0	6.6	6.9	3.3
1893	Bordentown, N. J	40 09	74 43	+1 41	+2 00	+0.8	0.0	6.7	7.0	3.3
1895	Trenton, N. J	40 11	74 45	+1 44	+2 21	+0.9	0.0	6.8	7.1	3.4

* Ratio

** From NOS <u>Tide Tables</u>

later than the time of high water at the Capes. The variation in tidal amplitude with distance along the estuary is due to the opposing effects of convergence of the sides of the estuary which tends to increase the amplitude, and friction which tends to decrease it. Harleman (1966) has constructed a one-dimensional mathematical model for the tidal dynamics of the Delaware Estuary, based on the equation for a shallow water wave undergoing damping by friction. He has determined that the tidal wavelength in the estuary is 205 miles.

When the tidal wave enters the estuary, the crest travels faster than the trough. This phenomenon may be seen in Figure 6 which shows the appropriate position of the crests and troughs at each 1/2 hour after entering the bay. This effect leads to a distortion in the shape of the wave as it progresses up the estuary -- as is shown in Figure 7.

A quantitative explanation can be made if we look at the time of arrival of high and low tide vs. distance up the estuary (Figure 8). The inverse slope of these lines is the speed of the tidal wave. A simple calculation based on the time it takes the tidal crest and tidal trough to travel from the Capes to a point up the estuary shows that the high tide travels at 25.9 fps while low tide travels at 20.9 fps. From the expression for the velocity of a shallow water wave, the apparent depth calculated for the crest of the tidal wave is 20 ft. while that for the trough is 13.5 ft. The difference is 6.5 ft. and compares favorably with the tidal range in Figure 9.

While considering Figure 9, note that the effect of improvements in the channel for navigation purposes has been to change the tidal

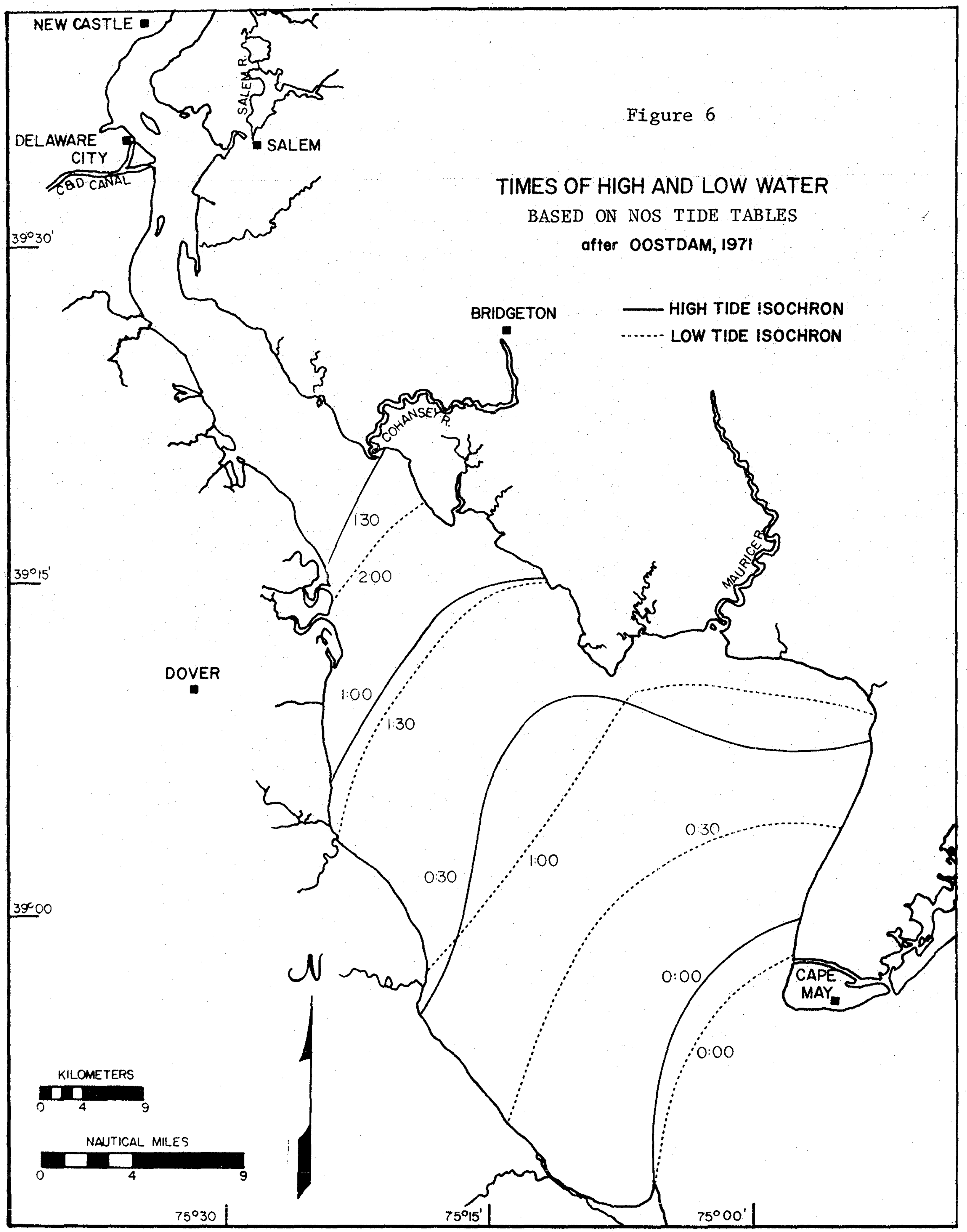
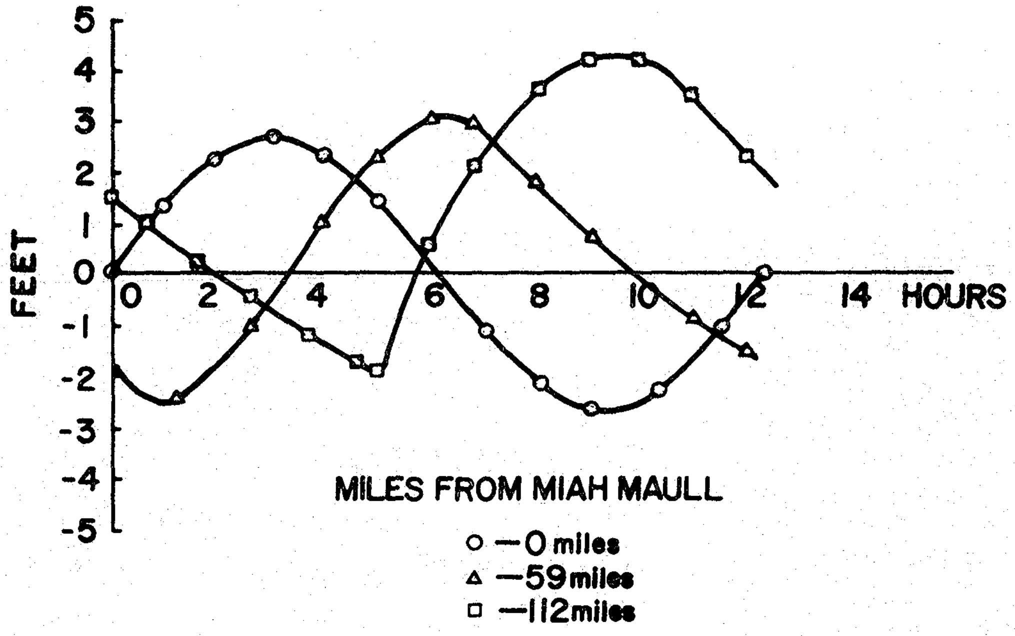
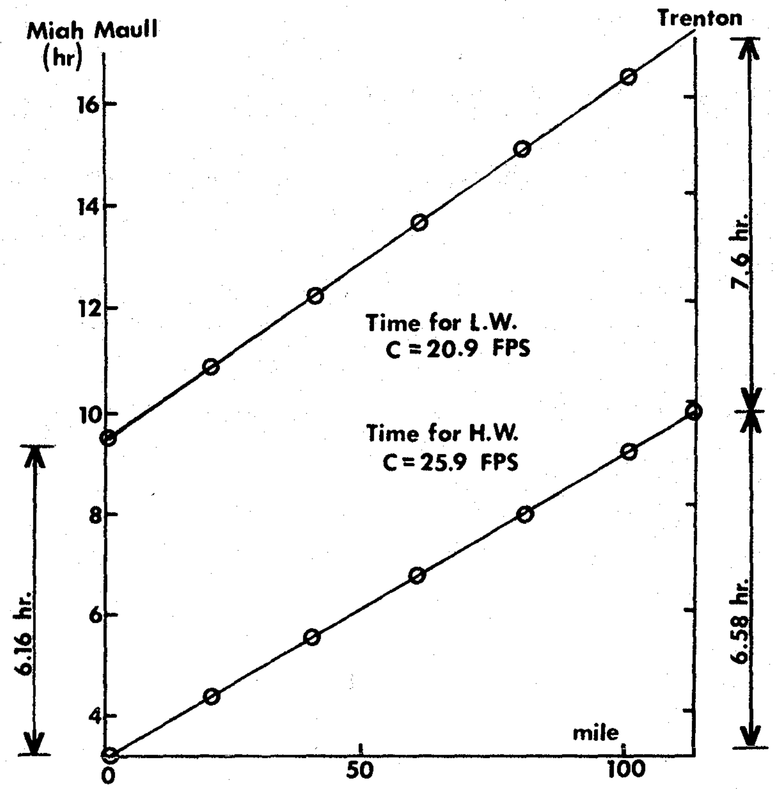


Figure 6
TIMES OF HIGH AND LOW WATER
BASED ON NOS TIDE TABLES
after OOSTDAM, 1971
HIGH TIDE ISOCHRON
LOW TIDE ISOCHRON
NEW CASTLE
SALEM R.
SALEM
DELAWARE CITY
C&D CANAL
BRIDGETON
COHANSEY R.
MAURICE R.
DOVER
CAPE MAY
1:30
2:00
1:00
1:30
0:30
1:00
0:30
0:00
0:00
39°30'
39°15'
39°00
75°30
75°15'
75°00'
KILOMETERS
0
4
9
NAUTICAL MILES
0
4
9



DELAWARE ESTUARY (1951 CHANNEL)--- TIDAL VARIATIONS IN ELEVATION at 0, 59 and 112 MILES from MIAH MAULL (drawn from data in WICKER, 1965)

Figure 7



DELAWARE ESTUARY (1951 Channel)
TIME FOR HIGH WATER & LOW WATER

Figure 8

range drastically, especially at Trenton.

Coreolis force provides a major modification to the flows in the estuary, both tidal and nontidal. Its effect on the tides is seen in a graph of tidal ranges on the New Jersey and Delaware sides of the bay (Figure 9). As the flood tide enters the bay, the Coreolis force deflects it to the right causing the high tide to build up more on the New Jersey side. As the tide ebbs, the water builds up on the Delaware side so that the low tide is lower on the New Jersey side. Thus the total range of tide is greater on the New Jersey side, as can be seen in the figure.

Tides are being, or have been, observed at all of the locations listed in Table IV. The known length of record for several of the more important stations is shown in Table V, which also indicates the availability of tidal harmonics. The stations listed are shown in Figure 10. The observations refer tidal height to mean sea level at a standard station. For the Delaware Estuary this station is Sandy Hook, New Jersey. In practice, the actual tidal observations are referred to a network of tidal bench marks, which provide a local elevation reference. These bench marks are tied, by means of a precise level net, to mean sea level at the standard station. The locations of the tidal bench marks are shown in Figure 11. The whole subject of tidal datum planes is dealt with in Marmer (1951).

Tide predictions for the Delaware Estuary are made by the National Ocean Survey (NOS) and published in the annual tide tables. The predictions are made on the basis of tidal harmonics for a few stations, and may be extended to the rest of the Bay by the constants given

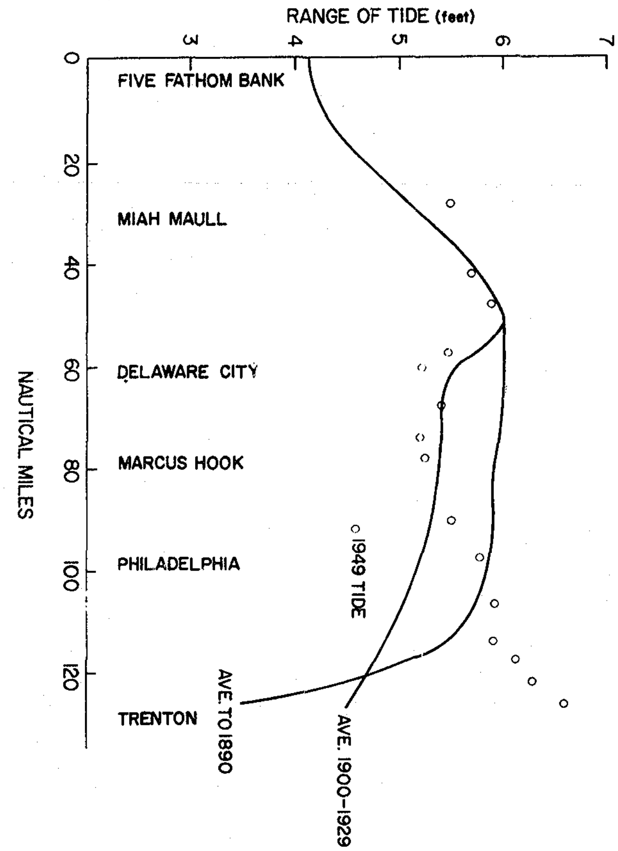


Figure 9. Tidal ranges in the Delaware Estuary, modified from Zeskind and LeLacheur (1926).

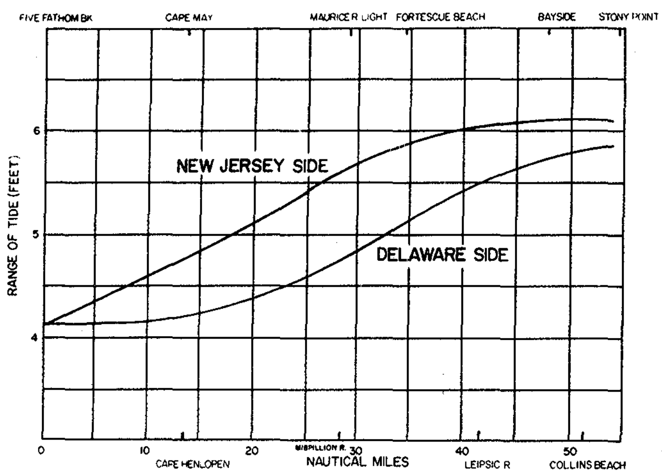


Figure 10. Tidal ranges in Delaware Bay after Zeskind and LeLacheur

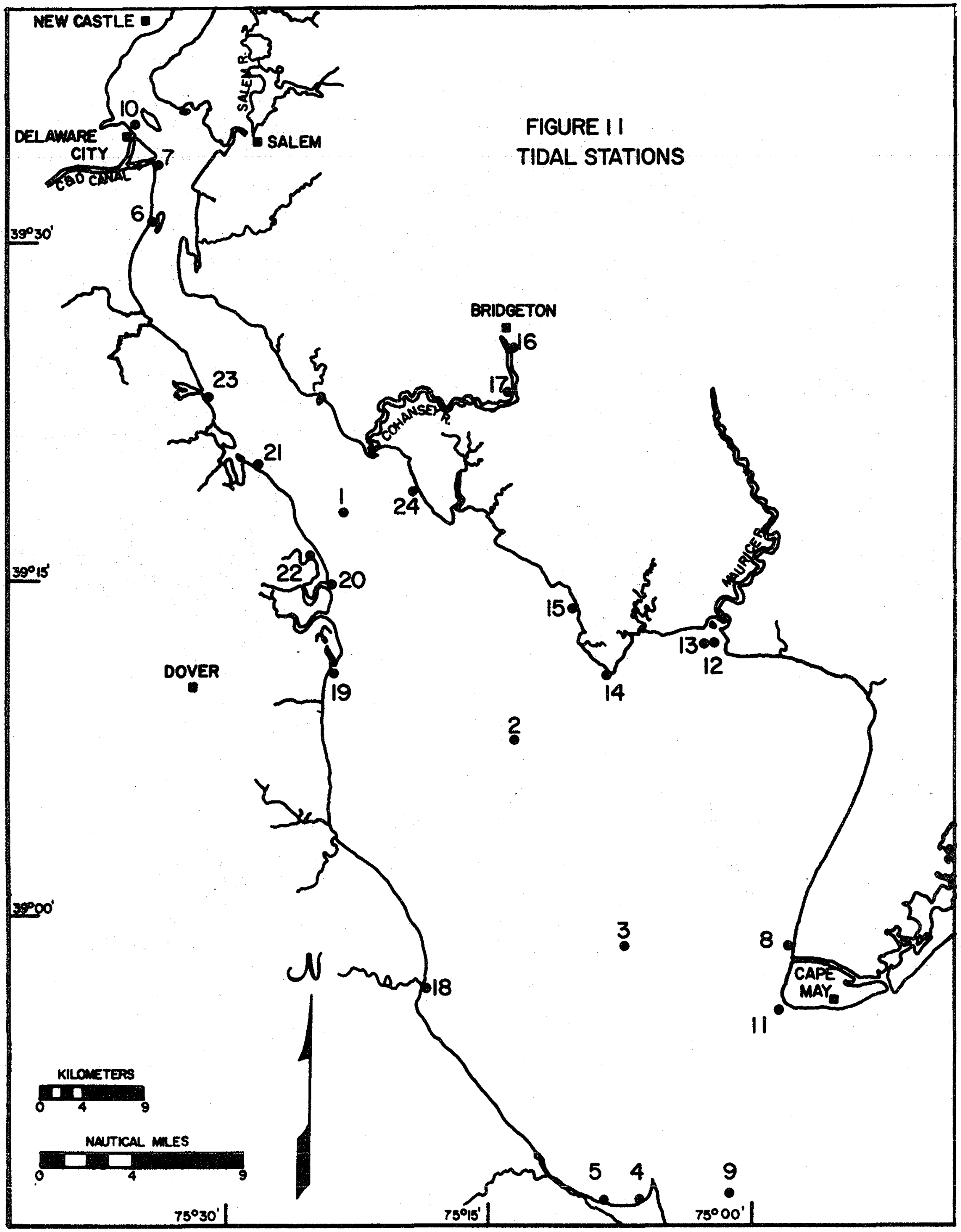


FIGURE 11
TIDAL STATIONS
NEW CASTLE
DELAWARE CITY
C&D CANAL
SALEM R.
SALEM
BRIDGETON
COHANSEY R.
MAURICE R.
DOVER
CAPE MAY
N
KILOMETERS
0 4 9
NAUTICAL MILES
0 4 9
39°30'
39°15'
39°00'
75°30'
75°15'
75°00'
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24

Table V

Summary of Significant Tidal Observations in Delaware Bay

NO.	NAME OF STATION	LAT. N° '	LONG. W° '	KNOWN PERIOD OF RECORD	AGENCY	NOTES
1.	Ship John Lt.	39 18	75 23	Jan. 1931 - Dec. 1939	Corps of Eng.	
2.	Miah Maull Lt.	39 08	75 13	28 Aug. 1931 - Feb. 1934	Corps of Eng.	
3.	Brandywine Lt.	38 59	75 07	28 April 1932 - 31 Mar. 1939	Corps of Eng.	
4.	Breakwater Harbor	38 47	75 06	58 days in 1883 5d 1914		
			1 mo (1963-8)	7 Jan. 1919 - 11 Jan. 1920	U.S.C. & G.S.	a
				1 Jan. 1922 - 5 Jan. 1923		
				30 Mar. 1932 - 31 Mar. 1939		
				Scattered to 1957		
				4 d (1882)		
				4 mos (1883-4)		
				3 mos (1910-4)		
5.	Lewes	38 47	75 08	28 July 1931 - 1 Nov. 1932	U.S.C. & G.S.	b
				May 1936 - Dec. 1939		
6.	Reedy Island	39 31	75 34	Oct. 1921 - Oct. 1930	U.S.C. & G.S.	
7.	Reedy Point	39 33.74	75 33.74	June 1928 - Dec. 1939	U.S.C. & G.S.	b
				Aug. 1956 - Dec. 1966		a
8.	Cape May	38 58.1	74 57.6	1 Jan. 1966 - 1968, 1970	U.S.C. & G.S.	b
9.	Delaware Bay Entrance	38 48	74 01.4	17 Apr. 1940 - 21 Apr. 1940	U.S.C. & G.S.	a
10.	Delaware City	39 35	75 35	25 Aug. 1923 - 29 Aug. 1924	U.S.C. & G.S.	b
11.	Cape May Point	38 56	74 58	1 mo (1836)		
				10 d (1867)		
				3 d (1883)		
				1 mo (1885)		
12.	East Point, Maurice River Cove	39 12	75 02	2 mos (1884-5)		
13.	East Point, Maurice River Cove	39 12	75 02	11 d (1885)		
14.	Egg Island Point	39 11	75 08	2 mos (1841-2)		
				18 d (1867-85)		
15.	Fortescue	39 14	75 10	1 mo (1880-2)		
16.	Cohasex River, Bridgeton	39 25	75 14			
17.	Bay Side	39 23	75 14	516 d (1182)		
18.	Mispillion River Entrance		75 19	17 d (1883)		
19.	Mahon River Entrance	39 11	75 24	5 mos (1841-3)		
				2 mos (1883)		
20.	Leipsic River Entrance	39 15	75 24	8 d (1882)		
21.	Woodland Beach	39 20	75 28	3 mos (1924)		
22.	Duck Creek Entrance	39 16	75 25	1 mo (1841)		
				1/2 mo (1882)		
				4 d (1910)		
23.	Collins Beach	39 23	75 31	1/2 mo (1881)		
24.	Sea Breeze	39 19	75 19	1-1/2 mo (1880-2)		

NOTES: a - National Ocean Survey has harmonic constants for prediction
b - NOS has harmonic constants - Not used for prediction
c - Sufficient data for harmonic analysis is available in the Judgement of Mr. D. C. Simpson, Acting Chief, Predictions Branch, Oceanographic Division, NOS.

in Table IV. The most recent tidal harmonic constants are given in Tables VIa through VId. These constants may be used in formula (1) to predict the tidal height.

$$h = Z_o + \sum_{i=1} B_i f_i(t) \cos(a_i t - \kappa'_i + (V_o + u)_i) \qquad (1)$$

The subscript i refers to each of the several constituents. Z_o is the mean tide level referred to the datum at Sandy Hook, New Jersey, found in Table VI; B_i is the corrected amplitude found in Table VI; $f_i(t)$ is the node factor for each year found in Table VIIa, a_i is the angular speed of the constituent found in Table VIII; κ'_i is the phase (corrected for longitudinal differences) found in Table VI and $(V_o + u)_i$ is the equilibrium argument of the constituent for the meridian of Greenwich found in Table VIIb and sets t, the time in seconds, to start at 0:00 on January 1 of the year for which the prediction is desired.

METEOROLOGICAL EFFECTS ON TIDES

The actual tides may vary from those predicted from the harmonic constants. This is primarily due to meteorological conditions. Figure 12 shows the discrepancy between observed and predicted tides at Philadelphia in an extreme case. On March 1st and 2nd, 1914, a blizzard with 25-40 mph northwest winds completely wiped out a predicted high tide. The figure shows the predicted and recorded tides at Philadelphia on this occasion. Wind and the barometer effect, due to variations in atmospheric pressure, combine to produce such occurrences.

Table VIa

FORM C&GS-444
(11-67)

U.S. DEPARTMENT OF COMMERCE
ESSA- COAST AND GEODETIC SURVEY

TIDES ~~CURRENTS~~ STANDARD HARMONIC CONSTANTS FOR PREDICTION

STATION *Breakwater Harbor, Del.*

Lat. *38° 47' N.*
Long. *75° 06' W.*
Long. *75° 10 W.*

Component	H Amplitude	κ Epoch	A κ' − κ	B 1.03 × H	C 360° − κ'	D − κ'
	ft. ~~kn.~~	°	°	ft. ~~kn.~~	°	°
M_2	1.939	239.6	+ 5.3	1.997	+	−244.9
S_2	0.366	262.9	+ 0.2	0.377	+	−263.1
N_2	0.426	217.7	+ 8.0	0.439	+	−225.7
K_1	0.338	126.0	− 0.1	0.348	+	−125.9
M_4	0.039	232.1	+ 10.6	0.040	+	−242.7
O_1	0.275	112.8	+ 5.4	0.283	+	−118.2
M_6					+	−
$(MK)_3$					+	−
S_4					+	−
$(MN)_4$					+	−
ν_2	0.084	225.7	+ 7.6	0.087	+	−233.3
S_6					+	−
μ_2	0.040	213.4	+ 10.4	0.041	+	−223.8
$(2N)_2$	(0.057	187.3)	+ 10.7	0.059	+	−198.0
$(OO)_1$	(0.012	139.2)	− 5.6	0.012	+	−133.6
λ_2	(0.014	250.4)	+ 2.9	0.014	+	−255.4
S_1	0.039	58.3	+ 0.1	0.040	+	− 58.4
M_1	(0.020	119.4)	+ 2.6	0.021	+	−143.0
J_1	(0.021	132.5)	− 2.8	0.022	+	−129.7
Mm					+	−
Ssa	0.098	50.7	− 0.4	0.098	+	− 50.3
Sa	0.226	151.4	− 0.2	0.226	+	−151.2
MSf					+	−
Mf					+	−
ρ_1	(0.011	107.1)	+ 7.7	0.011	+	−114.8
Q_1	0.041	109.1	+ 8.1	0.042	+	−117.2
T_2	(0.022	262.9)	+ 0.4	0.023	+	−263.3
R_2					+	−
$(2Q)_1$					+	−
P_1	0.110	127.0	+ 0.3	0.113	+	−127.3
$(2SM)_2$					+	−
M_3					+	−
L_2	0.083	272.7	+ 2.6	0.085	+	−275.3
$(2MK)_3$					+	−
K_2	0.110	269.8	− 0.2	0.113	+	−269.6
M_8					+	−
$(MS)_4$					+	−

REMARKS

Time meridian *75° W. = +5* h.
Extreme range .... ft. / kn.
Dial ....
Marigram gear ....
Marigram scale ....
Z_0 .... *2.08* ft.
Permanent current .... kn.
The DATUM is ~~a plane~~ .... ~~ft.~~ ~~below~~ mean ~~low water springs~~ / ~~lower~~ low water.

First used for 1940 Tables (modified 1966)

Amplitudes of short period constituents increased 5%

ν_2 analyzed 1919, 1922 and inferred 1936-1937

$(2N)_2$ analyzed 1919 and inferred 1922 + 1936

Source of constants *Means of analyses for 3 years 1919, 1922 and 1936-37. Sa + Ssa from monthly MSL for scattered years between 1919 + 1957*

Compiled by *[illegible]* *2-5-69* (Date) Verified by .... (Date)

USCOMM-DC 50160-P67

Table VIb

TIDES: RECAPITULATION OF RESULTS

Station: Ferry Terminal, Cape May, New Jersey   Lat.: 38° 58.1 N

Length of Series: 365 days, Series begin: 1966-1-1-0   Long.: 74° 57.6 W

HARMONIC CONSTANTS

Component	H (Feet)	κ (°)	Component	H (Feet)	κ (°)
M_2	2.323	238.2	Mm	.129	189.1
S_2	.428	263.8	Ssa	.051	60.5
N_2	.531	217.7	Sa	.225	162.6
K_1	.337	173.8	MSf	.039	19.5
M_4	.033	173.2	Mf	.076	358.2
O_1	.277	110.6	ρ_1	.014	165.0
M_6	.027	287.9	Q_1	.047	112.0
$(MK)_3$	.008	327.0	T_2	.032	211.9
S_4	.009	320.4	R_2	.005	91.0
$(MN)_4$	.006	162.4	$(2Q)_1$	.020	351.7
ν_2	.098	218.9	P_1	.103	121.2
S_6	.002	101.6	$(2SM)_2$	.005	131.1
μ_2	.029	260.8	M_3	.022	231.1
$(2N)_2$	.084	218.1	L_2	.164	263.8
$(OO)_1$	.015	120.6	$(2MK)_3$	.013	249.7
λ_2	.030	242.8	K_2	.115	265.7
S_1	.036	64.4	M_8	.007	330.5
M_1	.013	128.7	$(MS)_4$	.017	190.9
J_1	.014	109.6			

Remarks: NOT ACCEPTED FOR PREDICTIONS

RESULTS FROM HARMONIC CONSTANTS

Greenwich Intervals* (LI = +5.17 hr.)

	Hours
Mean *HWI*	0.93
Mean *LWI*	7.10
Tropic *HHWI* 6	0.92
Tropic *LHWI*	0.94
Tropic *HLWI*	6.83
Tropic *LLWI* 6	7.37
Tropic D_1HWI	

Age of Inequalities

	Hours
Phase	26
Parallax	37
Diurnal	12

Ranges and Inequalities

	Feet
Mean (*Mn*)	4.87
Spring (*Sg*)	5.71
Neap (*Np*)	3.95
Perigean (*Pn*)	5.99
Apogean (*An*)	4.04
Great diurnal (*Gt*)	5.34
Great tropic (*Gc*)	5.36
Tropic diurnal ($2D_1$)	
Inequality *DHQ*	0.39
Inequality *DLQ*	0.08
Tropic *HWQ*	1.25
Tropic *LWQ*	0.16
HTL–*MSL*	0.01

Ratios and Differences

Sg÷*Mn*	1.17
Np÷*Mn*	.81
Pn÷*Mn*	1.23
An÷*Mn*	.83
$(K_1+O_1)\div M_2$	0.27
$M_4-(F1+C_7)$	3
Sequence	

*Greenwich intervals ... [illegible]

Computed by SCB, 8/23/68 (Date) Verified by Dc, 8-23-68 (Date)

Table VIc

FORM C&GS-444
(11-67)

U.S. DEPARTMENT OF COMMERCE
ESSA- COAST AND GEODETIC SURVEY

TIDES ~~CURRENTS~~ STANDARD HARMONIC CONSTANTS FOR PREDICTION

STATION Reedy Point, Del.

Lat. 39° 33.'7 N.
Long. 75° 34.'0 W.
Long. 75°.57 W.

COMPONENT	H AMPLITUDE (ft.)	κ EPOCH (°)	A κ'−κ +0.17a (°)	B 1.04 ×H (ft.)	C 360°−κ' (°)	D −κ' (°)
M_2	2.505	317.4	+11.1	2.605	+	−328.5
S_2	0.366	352.8	+6.2	0.381	+	−359.0
N_2	0.469	305.3	+13.8	0.488	+	−319.1
K_1	0.300	165.0	+2.9	0.312	+	−167.9
M_4	0.177	189.6	+22.3	0.184	+	−211.9
O_1	0.235	154.5	+8.2	0.244	+	−162.7
M_6	0.113	313.6	+33.4	0.118	+	−347.0
$(MK)_3$					+	−
S_4					+	−
$(MN)_4$	0.081	182.0	+24.9	0.084	+	−206.9
ν_2	0.161	291.5	+13.4	0.167	+	−304.9
S_6					+	−
μ_2	0.117	60.2	+16.0	0.122	+	−76.2
$(2N)_2$	(0.062	293.2)	+16.4	0.064	+	−309.6
$(OO)_1$	(0.010	175.5)	−2.4	0.010	+	−173.1
λ_2	0.064	311.2	+8.9	0.067	+	−320.1
S_1	0.074	138.7	+3.1	0.077	+	−141.8
M_1	(0.017	159.8)	+5.6	0.018	+	−165.4
J_1	0.032	129.9	+0.3	0.033	+	−130.2
Mm					+	−
Ssa	0.095	13.4	−0.4	0.095	+	−13.0
Sa	0.296	118.8	−0.2	0.296	+	−118.6
MSf	0.108	182.0	−4.9	0.108	+	−177.1
Mf	0.051	13.5	−5.3	0.051	+	−8.2
ρ_1					+	−
Q_1	0.043	168.3	+10.9	0.045	+	−179.2
T_2	(0.022	352.8)	+6.4	0.023	+	−359.2
R_2					+	−
$(2Q)_1$					+	−
P_1	0.089	162.8	+3.3	0.093	+	−166.1
$(2SM)_2$					+	−
M_3					+	−
L_2	0.265	319.6	+8.5	0.276	+	−328.1
$(2MK)_3$	0.050	321.9	+19.4	0.052	+	−341.3
K_2	0.084	351.5	+5.8	0.087	+	−357.3
M_8					+	−
$(MS)_4$	0.058	231.0	+17.4	0.060	+	−248.4

REMARKS

Time meridian 75° W. = +5 h.
Extreme range ft./kn.
Dial
Marigram gear
Marigram scale
Z_0 2.78 ft.
Permanent current kn.
The DATUM is ~~a plane~~ ~~ft.~~ ~~below~~ mean ~~low water springs~~ ~~lower~~ low water.

First used for 1961 Tables (modified 1966)

Amplitudes of short period constituents increased 4%

Column A includes 0.17a

Source of constants C&GS analysis of 369 day series beginning 1958-1-1-0
Sa & Ssa from monthly MTL 1939

Compiled by Rau 2-5-69 (Date) Verified by (Date)

Table VId

FORM C&GS-444
(11-67)

U.S. DEPARTMENT OF COMMERCE
ESSA- COAST AND GEODETIC SURVEY

TIDES ~~CURRENTS~~ STANDARD HARMONIC CONSTANTS FOR PREDICTION

STATION *Philadelphia, Pa*

Lat. 39° 57'.1 N.
Long. 75° 08'.4 W.
Long. 75° 14 W.

Component	H Amplitude (ft. ~~kn.~~)	κ Epoch (°)	A κ'−κ +0.2a (°)	B 1.04 ×H (ft. ~~kn.~~)	C 360°−κ' (°)	D −κ' (°)
M_2	2.602	39.0	+ 11.2	2.706	+	− 50.2
S_2	0.298	78.8	+ 6.3	0.310	+	− 85.1
N_2	0.413	19.9	+ 13.8	0.430	+	− 33.7
K_1	0.333	211.6	+ 2.9	0.346	+	−214.5
M_4	0.348	333.9	+ 22.3	0.362	+	−356.2
O_1	0.244	195.3	+ 8.2	0.254	+	−203.5
M_6	0.153	181.6	+ 33.5	0.159	+	−215.1
$(MK)_3$	0.042	117.4	+ 14.1	0.044	+	−131.5
S_4					+	−
$(MN)_4$	0.135	319.0	+ 24.9	0.140	+	−343.9
ν_2	0.152	15.4	+ 13.4	0.158	+	− 28.8
S_6					+	−
μ_2	0.115	156.4	+ 16.0	0.120	+	−172.4
$(2N)_2$	0.082	351.8	+ 16.4	0.085	+	− 8.2
$(OO)_1$	(0.010	227.9)	− 2.3	0.010	+	−225.6
λ_2	0.074	41.9	+ 8.9	0.077	+	− 50.8
S_1	0.058	155.7	+ 3.1	0.060	+	−158.8
M_1	(0.017	203.4)	+ 5.6	0.018	+	−209.0
J_1	(0.019	219.8)	+ 0.3	0.020	+	−220.1
Mm	0.144	66.1	− 2.6	0.144	+	− 63.5
Ssa	0.156	62.3	− 0.4	0.156	+	− 61.9
Sa	0.281	110.2	− 0.2	0.281	+	−110.0
MSf	0.203	15.0	− 4.9	0.203	+	− 10.1
Mf	0.123	2.3	− 5.3	0.123	+	−357.0
ρ_1					+	−
Q_1	0.036	222.1	+ 10.9	0.037	+	−233.0
T_2	(0.018	78.8)	+ 6.5	0.019	+	− 85.3
R_2	0.049	13.7	+ 6.1	0.051	+	− 19.8
$(2Q)_1$					+	−
P_1	0.099	199.3	+ 3.3	0.103	+	−202.6
$(2SM)_2$					+	−
M_3					+	−
L_2	0.206	53.4	+ 8.5	0.214	+	− 61.9
$(2MK)_3$	0.071	78.8	+ 19.4	0.074	+	− 98.2
K_2	0.074	81.7	+ 5.9	0.077	+	− 87.6
M_8	0.056	118.6	+ 44.6	0.058	+	−163.2
$(MS)_4$	0.104	26.7	+ 17.4	0.108	+	− 44.1

REMARKS

Time meridian 75° W. = +5 h.
Extreme range .... {ft. kn.
Dial ....
Marigram gear ....
Marigram scale ....
Z_0 .... 3.20 ft.
Permanent current .... kn.
The DATUM is ~~a plane~~ .... ~~ft.~~
~~below~~ mean {~~low water springs~~ / ~~lower~~ low water.

First used 1963 tables
(modified 1966)
Amplitudes of short period
constituents increased 4%

Column A includes +0.20 a

Source of constants *Our analysis of 369 days of observations beginning 1955-1-1-0*
Sa & Ssa from 19 years of monthly mean river level

Compiled by *Rac* *2-10-69* (Date) Verified by .... (Date)

Table VIIa. Node factor f for middle of each year, 1940 to 1999.

Constituent	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949
J_1	0.836	0.827	0.846	0.888	0.944	1.003	1.057	1.103	1.136	1.157
K_1	0.888	0.882	0.894	0.920	0.956	0.996	1.034	1.067	1.091	1.107
K_2	0.757	0.748	0.766	0.812	0.882	0.970	1.068	1.162	1.242	1.295
L_2	0.860	1.021	1.180	1.144	0.876	0.748	1.091	1.255	0.894	0.482
M_1	1.623	1.313	0.879	1.076	1.714	1.944	1.480	1.138	1.927	2.339
M_2*, N_2, 2N, λ_2, μ_2, ν_2	1.036	1.038	1.035	1.028	1.018	1.006	0.994	0.982	0.972	0.966
M_3	1.055	1.057	1.053	1.042	1.027	1.009	0.990	0.973	0.959	0.949
M_4, MN	1.074	1.077	1.071	1.057	1.036	1.012	0.987	0.964	0.945	0.933
M_6	1.113	1.118	1.108	1.086	1.055	1.018	9.981	0.947	0.919	0.901
M_8	1.154	1.160	1.147	1.117	1.074	1.025	0.975	0.929	0.894	0.870
O_1, Q_1, 2Q, ρ_1	0.816	0.806	0.826	0.870	0.929	0.994	1.055	1.107	1.147	1.173
OO	0.505	0.486	0.526	0.623	0.774	0.969	1.189	1.408	1.598	1.729
MK	0.920	0.915	0.925	0.946	0.974	1.002	1.028	1.047	1.061	1.069
2MK	0.953	0.950	0.957	0.973	0.991	1.008	1.021	1.028	1.032	1.032
Mf	0.642	0.626	0.659	0.736	0.848	0.981	1.120	1.249	1.354	1.424
Mm	1.126	1.131	1.121	1.096	1.061	1.019	0.976	0.935	0.902	0.880

Constituent	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959
J_1	1.165	1.160	1.143	1.112	1.070	1.002	0.959	0.901	0.855	0.829
K_1	1.113	1.109	1.096	1.074	1.043	1.001	0.966	0.929	0.900	0.883
K_2	1.317	1.303	1.257	1.184	1.092	0.995	0.903	0.827	0.776	0.770
L_2	1.074	1.330	1.014	0.653	1.001	1.260	1.112	0.867	0.915	1.115
M_1	1.717	1.120	1.778	2.161	1.664	0.964	1.276	1.656	1.527	1.053
M_2*, N_2, 2N, λ_2, μ_2, ν_2	0.963	0.965	0.970	0.982	0.990	1.003	1.015	1.026	1.033	1.038
M_3	0.945	0.948	0.956	0.969	0.986	1.004	1.023	1.039	1.051	1.057
M_4, MN	0.928	0.931	0.941	0.959	0.981	1.006	1.031	1.052	1.068	1.076
M_6	0.894	0.898	0.914	0.939	0.972	1.009	1.046	1.079	1.104	1.116
M_8	0.861	0.867	0.887	0.920	0.962	1.012	1.062	1.107	1.141	1.158
O_1, Q_1, 2Q, ρ_1	1.183	1.177	1.155	1.119	1.069	1.010	0.945	0.884	0.835	0.808
OO	1.784	1.750	1.637	1.459	1.246	1.023	0.819	0.656	0.546	0.491
MK	1.072	1.070	1.063	1.051	1.033	1.009	0.981	0.953	0.930	0.916
2MK	1.032	1.032	1.032	1.029	1.023	1.012	0.996	0.977	0.960	0.951
Mf	1.452	1.435	1.375	1.278	1.154	1.016	0.880	0.761	0.675	0.630
Mm	0.872	0.877	0.896	0.926	0.965	1.008	1.051	1.088	1.116	1.130

Constituent	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
J_1	0.831	0.860	0.909	0.766	1.025	1.076	1.117	1.146	1.161	1.165
K_1	0.885	0.903	0.934	0.972	1.011	1.048	1.077	1.098	1.110	1.113
K_2	0.752	0.781	0.836	0.914	1.008	1.106	1.195	1.265	1.307	1.316
L_2	1.199	1.081	0.849	0.893	1.200	1.237	0.838	0.690	1.185	1.310
M_1	0.767	1.197	1.690	1.699	1.166	1.175	1.976	2.175	1.503	1.197
M_2*, N_2, 2N, λ_2, μ_2, ν_2	1.037	1.033	1.024	1.014	1.001	0.989	0.978	0.969	0.964	0.963
M_3	1.056	1.049	1.037	1.020	1.002	0.983	0.967	0.954	0.947	0.945
M_4, MN	1.076	1.066	1.050	1.027	1.003	0.978	0.956	0.940	0.930	0.928
M_6	1.116	1.111	1.075	1.041	1.004	0.967	0.935	0.911	0.897	0.894
M_8	1.157	1.137	1.102	1.055	1.005	0.956	0.914	0.883	0.865	0.861
O_1, Q_1, 2Q, ρ_1	0.810	0.840	0.891	0.954	1.018	1.076	1.124	1.159	1.178	1.182
OO	0.495	0.557	0.675	0.845	1.053	1.276	1.487	1.655	1.758	1.782
MK	0.917	0.932	0.956	0.985	1.013	1.036	1.053	1.064	1.071	1.072
2MK	0.952	0.962	0.980	0.998	1.014	1.024	1.030	1.032	1.032	1.032
Mf	0.633	0.684	0.776	0.898	1.035	1.172	1.293	1.385	1.439	1.451
Mm	1.128	1.113	1.084	1.046	1.003	0.959	0.922	0.893	0.876	0.872

*Factor f of MS, 2SM, and MSf are each equal to factor f of M_2.
Factor f of P_1, R_2, S_1, S_2, S_4, S_6, T_2, Sa, and Ssa are each unity.

Constituent	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
J_1	1.155	1.132	1.097	1.051	0.995	0.936	0.881	0.842	0.827	0.839
K_1	1.105	1.088	1.063	1.029	0.991	0.951	0.916	0.891	0.882	0.890
K_2	1.289	1.232	1.150	1.055	0.957	0.871	0.804	0.763	0.748	0.760
L_2	0.882	0.668	1.118	1.270	1.014	0.808	0.988	1.179	1.169	0.994
M_1	1.987	2.176	1.503	1.012	1.535	1.777	1.428	0.870	0.874	1.361
M_2*, N_2, 2N, λ_2, μ_2, ν_2	0.966	0.973	0.983	0.995	1.008	1.020	1.029	1.035	1.038	1.036
M_3	0.950	0.960	0.975	0.993	1.012	1.029	1.044	1.054	1.057	1.054
M_4, MN	0.934	0.948	0.967	0.991	1.016	1.039	1.059	1.072	1.077	1.073
M_6	0.903	0.922	0.951	0.986	1.024	1.060	1.090	1.110	1.118	1.112
M_8	0.873	0.898	0.935	0.981	1.032	1.081	1.122	1.149	1.160	1.151
O_1, Q_1, 2Q, ρ_1	1.170	1.143	1.101	1.047	0.984	0.920	0.863	0.822	0.806	0.819
OO	1.716	1.575	1.380	1.159	0.940	0.750	0.607	0.517	0.485	0.512
MK	1.068	1.059	1.045	1.024	0.998	0.970	0.943	0.923	0.915	0.922
2MK	1.032	1.031	1.028	1.020	1.006	0.989	0.970	0.956	0.950	0.955
Mf	1.417	1.341	1.233	1.102	0.962	0.831	0.723	0.652	0.625	0.647
Mm	0.882	0.906	0.940	0.982	1.025	1.067	1.100	1.123	1.131	1.124

Constituent	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
J_1	0.877	0.930	0.989	1.045	1.093	1.130	1.153	1.164	1.163	1.148
K_1	0.913	0.948	0.987	1.026	1.060	1.086	1.104	1.112	1.111	1.100
K_2	0.799	0.864	0.949	1.045	1.142	1.226	1.285	1.315	1.310	1.270
L_2	0.848	1.001	1.238	1.157	0.745	0.811	1.263	1.244	0.749	0.746
M_1	1.656	1.468	0.974	1.323	2.050	2.032	1.292	1.367	2.142	2.122
M_2*, N_2, 2N, λ_2, μ_2, ν_2	1.030	1.021	1.009	0.997	0.984	0.974	0.967	0.964	0.964	0.969
M_3	1.045	1.031	1.013	0.994	0.977	0.962	0.951	0.946	0.947	0.954
M_4, MN	1.061	1.042	1.018	0.993	0.969	0.949	0.935	0.928	0.930	0.939
M_6	1.092	1.063	1.027	0.989	0.954	0.924	0.904	0.894	0.896	0.910
M_8	1.125	1.085	1.036	0.936	0.939	0.901	0.874	0.862	0.864	0.881
O_1, Q_1, 2Q, ρ_1	0.858	0.915	0.979	1.041	1.096	1.140	1.168	1.182	1.180	1.161
OO	0.596	0.735	0.921	1.137	1.361	1.560	1.706	1.778	1.766	1.668
MK	0.941	0.967	0.996	1.022	1.043	1.058	1.068	1.072	1.071	1.065
2MK	0.969	0.987	1.005	1.019	1.027	1.031	1.032	1.032	1.032	1.032
Mf	0.715	0.820	0.949	1.088	1.221	1.333	1.412	1.450	1.443	1.392
Mm	1.103	1.070	1.029	0.986	0.944	0.909	0.884	0.872	0.874	0.891

Constituent	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
J_1	1.120	1.080	1.030	0.972	0.914	0.864	0.833	0.829	0.852	0.896
K_1	1.079	1.051	1.015	0.976	0.937	0.905	0.886	0.883	0.897	0.926
K_2	1.203	1.115	1.016	0.922	0.842	0.785	0.754	0.750	0.772	0.821
L_2	1.216	1.248	0.898	0.801	1.077	1.208	1.107	0.921	0.893	1.096
M_1	1.334	1.156	1.778	1.829	1.282	0.800	1.083	1.487	1.560	1.214
M_2*, N_2, 2N, λ_2, μ_2, ν_2	0.977	0.988	1.000	1.013	1.024	1.032	1.037	1.038	1.034	1.027
M_3	0.966	0.982	1.000	1.019	1.036	1.048	1.056	1.057	1.051	1.040
M_4, MN	0.955	0.976	1.000	1.025	1.048	1.065	1.075	1.076	1.069	1.054
M_6	0.932	0.964	1.000	1.038	1.072	1.099	1.115	1.117	1.105	1.082
M_8	0.911	0.952	1.000	1.051	1.098	1.134	1.156	1.159	1.143	1.111
O_1, Q_1, 2Q, ρ_1	1.128	1.081	1.024	0.960	0.897	0.844	0.812	0.808	0.832	0.879
OO	1.505	1.296	1.072	0.863	0.688	0.565	0.498	0.489	0.538	0.643
MK	1.054	1.038	1.015	0.988	0.959	0.934	0.918	0.916	0.928	0.950
2MK	1.030	1.025	1.015	1.000	0.982	0.964	0.952	0.951	0.959	0.976
Mf	1.303	1.184	1.048	0.910	0.786	0.691	0.636	0.629	0.669	0.752
Mm	0.918	0.956	0.998	1.042	1.081	1.110	1.128	1.130	1.117	1.091

* Factor f of MS, 2SM, and MSf are each equal to factor f of M_2.
Factor f of P_1, R_2, S_1, S_2, S_4, S_6, T_2, Sa, and Ssa are each unity.

Table VIIb

Equilibrium argument ($V_0 + u$) for meridian of Greenwich at beginning of each calendar year, 1930 to 2000.

Constituent	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949
	°	°	°	°	°	°	°	°	°	°	°	°	°	°	°	°	°	°	°	°
J_1	180.4	272.3	4.4	110.5	202.1	293.1	23.2	126.2	213.5	299.1	23.1	120.2	203.5	288.0	14.2	116.2	205.5	296.0	27.3	133.1
K_1	6.1	8.4	10.7	14.0	15.9	17.4	18.2	19.1	17.9	15.6	12.4	9.6	6.0	3.1	1.2	1.4	1.6	2.7	4.4	7.4
K_2	191.8	196.6	201.6	208.3	212.4	215.3	216.6	217.9	215.1	210.3	204.2	199.4	192.7	187.0	182.9	182.8	182.8	184.8	188.2	194.6
L_2	352.2	170.1	330.8	167.9	18.8	201.7	6.0	193.1	35.9	227.4	44.3	215.2	49.6	249.0	82.0	240.2	64.4	271.8	118.7	270.7
M_1	228.3	126.5	21.6	293.3	234.4	134.1	27.0	285.7	227.4	132.6	22.0	260.9	173.4	109.5	12.9	252.0	151.2	91.3	14.5	257.4
M_2	337.2	78.6	180.1	257.1	358.4	99.6	200.5	276.8	17.2	117.5	217.6	293.2	33.3	133.4	233.8	309.9	50.6	151.6	252.8	329.8
M_3	145.8	117.9	90.1	25.7	357.7	329.4	300.7	235.2	205.8	176.2	146.4	79.9	49.9	20.2	350.6	284.8	256.0	227.4	199.2	134.7
M_4	314.3	157.2	0.2	154.3	356.9	199.2	41.0	193.6	34.4	234.9	75.1	226.5	66.6	266.9	107.5	259.8	101.3	303.2	145.7	299.6
M_6	291.5	235.8	180.2	51.4	355.4	298.8	241.5	110.3	51.6	352.4	292.7	159.7	99.9	40.3	341.2	209.6	151.9	94.9	38.5	269.5
M_8	268.7	314.4	0.3	308.6	353.8	38.4	82.0	27.1	68.9	109.8	150.3	92.9	133.2	173.8	215.0	159.5	202.5	246.5	291.3	239.3
N_2	161.4	174.1	186.9	162.1	174.7	187.1	199.3	173.8	185.5	197.1	208.4	182.3	193.6	205.1	216.7	191.0	203.0	215.3	227.8	203.0
2N	345.6	269.6	193.6	67.1	351.0	274.7	198.2	70.9	353.8	276.6	199.3	71.4	354.0	276.7	199.6	72.1	355.4	279.0	202.8	76.2
O_1	332.6	70.8	168.9	241.7	340.1	78.9	178.4	253.6	355.4	98.8	203.6	284.0	29.5	133.8	236.6	312.6	52.7	151.9	250.6	323.5
OO	216.6	124.9	33.6	329.2	236.7	142.4	45.7	332.9	228.3	118.6	4.2	274.6	158.2	45.4	297.5	222.0	123.2	27.4	293.9	229.1
P_1	350.1	350.3	350.6	349.8	350.0	350.3	350.5	349.8	350.0	350.2	350.5	349.7	350.0	350.2	350.5	349.7	350.0	350.2	350.4	349.7
Q_1	156.8	166.3	175.6	146.7	156.4	166.5	177.2	150.6	163.7	178.4	194.5	173.1	189.8	205.5	219.6	193.7	205.1	215.6	225.6	196.7
2Q	341.0	261.8	182.4	51.7	332.6	254.0	176.1	47.6	332.0	258.0	185.4	62.1	350.2	277.1	202.5	74.9	357.5	279.3	200.5	69.9
R_2	178.2	177.9	177.7	178.4	178.2	177.9	177.6	178.4	178.1	177.9	177.6	178.3	178.1	177.8	177.6	178.3	178.0	177.8	177.5	178.3
S_1	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0
$S_{2, 4, 6}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
T_2	1.8	2.1	2.3	1.6	1.8	2.1	2.4	1.6	1.9	2.1	2.4	1.7	1.9	2.2	2.4	1.7	2.0	2.2	2.5	1.7
λ_2	3.2	275.1	187.1	86.0	357.9	269.5	181.0	79.1	350.0	260.8	171.4	69.0	339.5	250.2	161.0	59.0	330.3	241.8	153.6	52.4
μ_2	315.4	157.6	359.8	153.2	355.3	197.2	38.9	191.5	32.7	233.7	74.6	226.6	67.4	268.3	109.4	261.9	103.4	305.1	147.1	300.4
ν_2	131.2	62.1	353.0	248.2	179.0	109.6	40.0	294.5	224.4	154.1	83.7	337.5	267.0	196.7	126.4	20.7	311.0	241.4	172.1	67.3
ρ_1	126.6	54.3	341.8	232.8	160.7	89.0	18.0	271.3	202.6	135.4	69.8	328.3	263.2	197.1	129.4	23.4	313.0	241.8	169.9	61.0
MK	343.3	87.0	190.8	271.1	14.4	117.0	218.7	295.8	35.1	133.0	229.9	302.8	39.3	136.5	234.9	311.3	52.2	154.3	257.2	337.3
2MK	308.2	148.8	349.5	140.3	341.0	181.8	22.8	174.5	16.6	219.4	62.8	216.8	60.6	263.8	106.3	258.4	99.6	300.6	141.3	292.2
MN	138.6	252.7	7.0	59.3	173.2	286.7	39.8	90.6	202.8	314.5	66.0	115.6	226.9	338.5	90.4	140.9	253.7	6.9	120.6	172.8
MS	337.2	78.6	180.1	257.1	358.4	99.6	200.5	276.8	17.2	117.5	217.6	293.2	33.3	133.4	233.8	309.9	50.6	151.6	252.8	329.8
2SM	22.8	281.4	179.9	102.9	1.6	260.4	159.5	83.2	342.8	242.5	142.4	66.8	326.7	226.6	126.2	50.1	309.4	208.4	107.2	30.2
Mf	212.0	117.1	22.3	313.8	218.3	121.8	23.6	309.7	206.4	99.9	350.3	265.3	154.4	45.8	300.4	224.7	125.2	27.7	291.6	222.8
MSf	22.8	281.4	179.9	102.9	1.6	260.4	159.5	83.2	342.8	242.5	142.4	66.8	326.7	226.6	126.2	50.1	309.4	208.4	107.2	30.2
Mm	175.8	264.5	353.2	95.0	183.7	272.4	1.2	103.0	191.7	280.4	9.1	110.9	199.6	288.4	17.1	118.9	207.6	296.3	25.0	126.8
Sa	279.9	279.7	279.4	280.2	280.0	279.7	279.5	280.2	280.0	279.8	279.5	280.3	280.0	279.8	279.5	280.3	280.0	279.8	279.6	280.3
Ssa	199.9	199.4	198.9	200.4	199.9	199.4	199.0	200.5	200.0	199.5	199.0	200.5	200.0	199.6	199.1	200.6	200.1	199.6	199.2	200.6

Constituent	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
	°	°	°	°	°	°	°	°	°	°	°	°	°	°	°	°	°	°	°	°
J_1	225.2	317.2	49.1	154.6	245.3	335.0	63.3	164.0	249.0	332.5	55.5	153.2	238.3	325.2	53.7	157.6	248.4	340.0	71.9	178.0
K_1	9.8	12.1	14.2	17.0	18.3	18.7	18.2	17.6	14.9	11.4	7.7	5.3	2.7	1.2	0.9	2.4	3.8	5.6	7.8	11.2
K_2	199.5	204.4	209.0	214.7	217.0	217.6	216.0	214.4	209.0	202.6	195.8	191.4	186.2	182.8	181.6	184.4	186.9	190.8	195.4	202.4
L_2	86.6	298.5	147.4	306.1	118.5	322.8	165.4	338.9	153.8	342.4	179.5	5.4	191.0	2.4	194.4	30.4	230.4	21.6	215.8	57.9
M_1	155.3	91.6	22.2	265.5	159.0	85.3	21.9	266.9	155.7	52.4	341.3	252.2	146.5	36.5	302.6	236.6	147.6	40.3	302.7	237.8
M_2	71.3	172.8	274.2	351.0	92.1	192.9	293.5	9.4	109.6	209.7	309.8	25.5	125.7	226.0	326.7	43.1	144.2	245.5	346.9	64.0
M_3	106.9	79.2	51.3	346.6	318.1	289.4	260.2	194.2	164.5	134.6	104.6	38.2	8.5	339.1	310.0	244.7	216.3	188.2	160.3	96.0
M_4	142.6	345.5	188.3	342.1	184.2	25.8	227.0	18.9	219.3	59.4	259.5	50.9	251.3	92.1	293.3	86.2	288.4	130.9	333.8	128.0
M_6	213.8	158.3	102.5	333.1	276.3	218.7	160.4	28.4	328.9	269.2	209.3	76.4	17.0	318.1	260.0	129.4	72.6	16.4	320.7	191.9
M_8	285.1	331.1	16.7	324.2	8.4	51.6	93.9	37.8	78.6	118.9	159.0	101.8	142.6	184.2	226.6	172.5	216.8	261.9	307.6	255.9
N_2	215.7	228.5	241.2	216.3	228.6	240.7	252.5	226.7	238.2	249.5	260.9	234.8	246.2	257.9	269.8	244.5	256.8	269.4	282.1	257.4
2N	0.2	284.2	208.2	81.5	5.1	288.5	211.6	84.0	6.7	289.4	212.0	84.1	6.8	289.8	213.0	85.8	9.5	293.2	217.3	90.7
O_1	61.6	159.8	258.0	331.2	70.3	170.1	271.1	348.2	92.2	197.4	303.2	23.0	126.8	229.0	329.8	44.1	143.1	241.6	339.8	52.6
OO	137.6	46.2	314.2	248.5	153.4	155.4	313.6	234.4	122.8	7.1	250.0	162.0	51.1	305.2	204.0	133.8	39.0	306.1	214.3	150.3
P_1	349.9	350.2	350.4	349.6	349.9	350.1	350.4	349.6	349.9	350.1	350.3	349.6	349.8	350.1	350.3	349.6	349.8	350.0	350.3	349.5
Q_1	206.1	215.5	225.0	196.4	206.8	217.9	230.2	205.4	220.7	237.2	254.3	232.3	247.4	260.8	272.9	245.5	255.8	265.5	275.0	246.0
2Q	350.6	271.3	192.0	61.6	343.3	265.7	189.2	62.7	349.2	277.1	205.4	81.6	7.9	292.7	216.1	86.8	8.4	289.4	210.2	79.4
R_2	178.0	177.7	177.5	178.2	178.0	177.7	177.4	178.2	177.9	177.7	177.4	178.1	177.9	177.6	177.4	178.1	177.8	177.6	177.3	178.1
S_1	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0
$S_{2, 4, 6}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0
T_2	2.0	2.3	2.5	1.8	2.0	2.3	2.6	1.8	2.1	2.3	2.6	1.9	2.1	2.4	2.6	1.9	2.2	2.4	2.7	1.9
λ_2	324.4	236.4	148.3	47.0	318.6	229.9	141.0	38.8	309.5	320.1	130.7	28.2	299.0	209.9	121.0	19.3	290.9	202.7	114.7	13.6
μ_2	142.6	344.9	187.1	340.3	182.1	23.7	225.0	17.4	218.3	59.1	259.9	52.0	253.0	94.1	295.4	88.3	290.1	132.1	334.3	127.8
ν_2	358.2	289.2	220.1	115.1	45.6	335.9	266.0	160.1	89.8	19.3	308.8	202.7	132.4	62.2	352.3	246.9	177.5	108.2	39.1	294.4
ρ_1	348.6	276.2	203.9	95.3	23.8	313.1	243.6	138.8	72.3	7.0	302.2	200.2	133.4	65.1	355.4	247.9	176.4	104.4	32.0	282.9
MK	81.0	184.9	288.4	8.1	110.4	211.6	311.7	27.0	124.6	221.2	317.4	30.7	128.4	227.3	327.5	45.6	148.0	251.1	354.7	75.1
2MK	132.8	333.5	174.1	325.0	165.9	7.1	208.7	1.3	204.4	48.0	251.8	45.7	248.6	90.8	292.4	83.8	284.6	125.3	326.0	116.8
MN	287.0	41.3	155.4	207.3	320.7	73.6	186.0	236.2	347.8	99.2	210.6	260.2	11.9	24.0	236.4	287.6	41.0	154.8	269.0	321.4
MS	71.3	172.8	274.2	351.0	92.1	192.9	293.5	9.4	109.6	209.7	309.8	25.5	125.7	226.0	326.7	43.1	144.2	245.5	346.9	64.0
2SM	288.7	187.2	85.8	9.0	267.9	167.1	66.5	350.6	250.4	150.3	50.2	334.5	234.3	134.0	33.3	316.9	215.8	114.5	13.1	296.0
Mf	128.0	33.2	208.1	228.6	131.6	32.7	291.3	213.1	105.3	354.8	243.4	159.5	52.1	308.1	207.1	134.8	38.0	302.3	207.2	138.9
MSf	288.7	187.2	85.8	9.0	267.9	167.1	66.5	350.6	250.4	150.3	50.2	334.5	234.3	134.0	33.3	316.9	215.8	114.5	13.1	296.0
Mm	215.6	304.3	33.0	134.8	223.5	312.2	41.0	142.7	231.5	320.2	48.9	150.7	239.4	328.1	56.9	158.6	247.4	336.1	64.8	166.6
Sa	280.1	279.8	279.6	280.4	280.1	279.9	279.6	280.4	280.1	280.0	279.7	280.4	280.2	279.9	279.7	280.4	280.2	280.0	279.7	280.5
Ssa	200.2	199.7	199.2	200.7	200.2	199.8	199.3	200.8	200.3	199.8	199.3	200.8	200.4	199.9	199.4	200.9	200.4	199.9	199.4	201.0

Table VIIb, Continued

Constituent	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
	°	°	°	°	°	°	°	°	°	°
J_1	270.0	1.8	93.1	197.4	286.6	14.3	100.2	198.6	281.8	4.9
K_1	13.4	15.5	17.1	19.0	19.2	18.2	16.2	14.1	10.5	6.8
K_2	207.2	211.5	214.8	218.4	218.2	215.8	211.5	207.6	200.9	194.2
L_2	262.8	60.3	245.2	81.8	282.4	99.0	276.4	99.7	297.9	130.9
M_1	155.2	48.6	307.8	234.9	158.7	51.8	302.5	198.6	135.7	41.8
M_2	165.4	266.8	8.0	84.5	185.3	285.8	26.0	101.8	201.8	301.9
M_3	68.1	40.2	11.9	306.8	277.9	248.6	219.0	152.7	122.7	92.8
M_4	330.9	173.6	15.9	169.1	10.5	211.5	52.1	203.6	43.7	243.8
M_6	136.3	80.4	23.9	253.6	195.8	137.2	78.1	305.3	245.5	185.7
M_8	301.7	347.1	31.8	338.2	21.0	63.0	104.1	47.1	87.3	127.5
N_2	270.1	282.7	295.2	270.0	282.0	293.8	305.3	279.3	290.6	301.9
2N	14.8	298.7	222.4	95.4	18.7	301.8	224.6	96.8	19.4	302.0
O_1	150.7	249.0	347.8	61.7	162.0	263.5	6.5	85.7	191.3	296.9
OO	58.7	326.4	232.6	163.9	64.6	321.1	212.6	126.5	9.8	253.0
P_1	349.8	350.0	350.2	349.5	349.7	350.0	350.2	349.5	349.7	349.9
Q_1	255.4	265.0	275.0	247.2	258.7	271.5	285.8	263.2	280.1	297.0
2Q	0.1	281.0	202.2	72.6	355.4	279.5	205.1	80.7	8.8	297.0
R_2	177.8	177.6	177.3	178.0	177.8	177.5	177.3	178.0	177.7	177.5
S_1	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0
$S_{2,4,6}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
T_2	2.2	2.4	2.7	2.0	2.2	2.5	2.7	2.0	2.3	2.5
λ_2	285.6	197.4	109.1	7.6	278.8	159.8	100.6	358.2	268.8	179.4
μ_2	330.0	172.1	14.0	167.0	8.4	209.7	50.7	202.8	48.6	244.4
ν_2	225.3	156.1	86.8	341.5	271.7	201.7	131.4	25.3	314.9	244.4
ρ_1	210.6	138.4	66.6	318.7	248.4	179.4	111.9	9.2	304.3	239.4
MK	178.9	282.3	25.1	103.6	204.4	304.0	42.2	115.9	212.3	308.7
2MK	317.4	158.1	358.8	150.0	351.4	193.3	35.9	189.4	33.2	237.0
MN	75.6	189.5	303.2	354.5	107.2	219.5	331.3	21.1	132.4	243.8
MS	165.4	266.8	8.0	84.5	185.3	285.8	26.0	101.8	201.8	301.9
2SM	194.6	93.2	352.0	275.5	174.7	74.2	334.0	258.2	158.2	58.1
Mf	44.0	308.7	212.4	141.1	41.3	298.8	193.0	110.4	359.3	248.0
MSf	194.6	93.2	352.0	275.5	174.7	74.2	334.0	258.2	158.2	58.1
Mm	255.3	344.0	72.8	174.6	263.3	352.0	80.7	182.5	271.2	0.0
Sa	280.2	280.0	279.8	280.5	280.3	280.0	279.8	280.5	280.3	280.1
Ssa	200.5	200.0	199.5	201.0	200.5	200.0	199.6	201.1	200.6	200.1

Constituent	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
	°	°	°	°	°	°	°	°	°	°
J_1	89.1	188.9	276.5	5.6	95.8	201.0	292.7	24.7	116.8	222.8
K_1	3.7	2.5	1.5	1.5	2.4	4.9	6.9	9.2	11.6	14.8
K_2	188.2	185.6	183.1	182.6	184.2	189.3	193.5	198.3	203.3	210.0
L_2	310.2	116.6	313.4	159.2	350.3	135.8	334.5	188.0	25.5	166.0
M_1	291.5	170.8	87.9	30.0	291.6	171.7	82.0	31.2	299.1	179.8
M_2	42.0	117.9	218.4	319.1	60.0	136.8	238.1	339.6	8.0	158.1
M_3	63.0	356.8	327.6	298.6	270.0	205.2	177.2	149.3	121.6	57.1
M_4	84.0	235.8	76.7	278.1	120.0	273.6	116.2	319.1	162.1	316.2
M_6	126.0	353.7	295.1	237.2	180.0	50.3	354.3	298.7	243.1	114.2
M_8	168.0	111.6	153.4	196.2	240.0	187.1	232.4	278.2	324.1	372.3
N_2	313.3	287.4	299.2	311.2	323.4	298.4	311.0	323.7	336.4	311.7
2N	224.7	97.0	20.0	303.2	226.7	100.0	23.8	307.8	231.9	105.3
O_1	41.6	119.4	221.1	321.4	60.8	134.2	232.6	330.7	68.8	141.6
OO	139.2	57.5	313.6	213.9	117.6	51.0	318.5	227.0	135.6	71.2
P_1	350.2	349.4	349.7	349.9	350.2	349.4	349.6	349.9	350.1	349.4
Q_1	312.9	289.0	301.9	313.5	324.2	295.8	305.4	314.8	324.2	295.3
2Q	224.3	98.5	22.7	305.6	227.5	97.4	18.3	299.0	219.6	88.9
R_2	177.2	178.0	177.7	177.4	177.2	177.9	177.7	177.4	177.2	177.9
S_1	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0
$S_{2,4,6}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
T_2	2.8	2.0	2.3	2.6	2.8	2.1	2.3	2.6	2.8	2.1
λ_2	90.0	347.8	258.8	170.0	81.4	340.0	251.9	163.9	75.9	334.8
μ_2	85.3	237.6	78.8	280.2	121.9	275.1	117.2	319.4	161.6	315.0
ν_2	174.0	68.0	358.0	288.2	218.6	113.5	44.3	335.2	266.2	161.4
ρ_1	173.6	69.6	0.7	290.5	219.4	110.9	38.8	326.4	254.0	145.0
MK	45.7	120.4	219.8	320.5	62.4	141.7	245.0	348.8	92.6	172.8
2MK	80.4	233.3	75.3	276.6	117.6	268.6	109.3	309.9	150.5	301.4
MN	355.3	45.3	157.5	242.2	23.4	75.1	189.1	303.2	57.5	109.8
MS	42.0	117.9	218.4	319.1	60.0	136.8	238.1	339.6	81.0	158.1
2SM	318.0	242.1	141.6	40.9	300.0	223.2	121.9	20.4	279.0	201.9
Mf	138.8	59.0	316.2	216.2	118.4	48.4	313.0	218.1	123.4	54.8
MSf	318.0	242.1	141.6	40.9	300.0	223.2	121.9	20.4	279.0	201.9
Mm	88.7	190.5	279.2	7.9	96.6	198.4	287.1	15.9	104.6	206.4
Sa	279.8	280.6	280.3	280.1	279.8	280.6	280.4	280.1	279.9	280.6
Ssa	199.6	201.1	200.6	200.2	199.7	201.2	200.7	200.2	199.8	201.3

Constituent	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
	°	°	°	°	°	°	°	°	°	°	°
J_1	314.4	45.2	135.2	237.9	325.0	50.2	134.0	231.1	322.5	39.3	125.8
K_1	16.7	18.0	18.7	19.4	18.0	15.6	12.2	9.5	6.0	3.2	1.5
K_2	213.9	216.6	217.6	218.5	215.4	210.3	204.0	199.2	192.7	187.2	183.4
L_2	2.2	212.4	49.0	205.8	30.4	229.4	66.7	242.7	59.3	244.2	83.7
M_1	85.9	33.5	305.0	184.1	79.3	4.9	293.5	176.9	64.8	319.9	251.4
M_2	259.4	0.5	101.3	177.6	278.0	18.2	118.3	194.0	294.0	34.2	134.5
M_3	29.1	0.7	332.0	266.4	237.0	207.3	177.4	110.9	81.0	51.3	21.8
M_4	158.7	0.9	202.7	355.2	196.0	36.4	236.6	27.9	228.0	68.4	269.1
M_6	58.1	1.4	304.0	172.8	114.0	54.6	354.9	221.9	162.1	102.6	43.6
M_8	317.5	1.9	45.3	350.3	31.9	72.8	113.2	55.8	96.1	136.8	178.1
N_2	324.3	336.7	348.8	323.3	334.9	346.4	357.8	331.7	83.0	354.5	6.1
2N	29.2	312.8	236.3	108.9	31.9	314.6	237.3	109.4	32.0	314.7	237.6
O_1	240.1	339.0	78.7	154.0	256.1	359.7	104.8	185.2	290.5	34.6	137.2
OO	338.4	243.8	146.6	73.2	327.7	217.2	102.3	12.5	256.5	144.4	37.4
P_1	349.6	349.8	350.1	349.3	349.6	349.8	350.1	349.3	349.6	349.8	350.0
Q_1	305.0	315.2	326.1	299.7	313.0	327.9	344.3	322.9	339.5	354.9	8.8
2Q	9.9	291.4	213.6	85.4	10.0	296.2	223.8	100.6	28.5	315.2	240.3
R_2	177.6	177.4	177.1	177.8	177.6	177.3	177.1	177.8	177.5	177.3	177.0
S_1	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0
$S_{2,4,6}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
T_2	2.4	2.6	2.9	2.2	2.4	2.7	2.9	2.2	2.5	2.7	3.0
λ_2	246.6	158.2	69.6	327.7	238.6	149.4	60.0	317.5	228.1	138.8	49.6
μ_2	157.1	358.9	200.5	353.2	194.8	35.8	236.1	28.2	229.0	69.9	271.0
ν_2	92.2	22.7	313.1	207.5	137.4	67.0	356.6	250.4	180.0	109.6	39.4
ρ_1	72.9	1.3	290.4	183.9	115.4	48.6	343.1	241.6	176.5	110.1	42.1
MK	276.0	18.5	120.0	197.0	296.0	33.8	130.5	203.4	300.0	37.4	136.0
2MK	142.1	342.9	184.0	335.8	177.9	20.8	224.4	18.4	222.1	65.2	267.6
MN	223.6	337.1	90.1	140.8	252.9	4.6	116.1	165.6	277.0	28.7	140.6
MS	259.4	0.5	101.3	177.6	278.0	18.2	118.3	194.0	294.0	34.2	134.5
2SM	100.6	359.5	258.7	182.4	82.0	341.8	241.7	166.0	66.0	325.8	225.5
Mf	319.2	222.4	124.0	49.6	305.9	198.8	88.8	3.7	253.0	144.9	40.1
MSf	100.6	359.5	258.7	182.4	82.0	341.8	241.7	166.0	66.0	325.8	225.5
Mm	295.1	23.8	112.5	214.3	303.0	31.8	120.5	222.3	311.0	39.7	128.4
Sa	280.4	280.2	279.9	280.7	280.4	280.2	279.9	280.7	280.4	280.2	280.0
Ssa	200.8	200.3	199.8	201.3	200.8	200.4	199.9	201.4	200.9	200.4	200.0

Table VIII

Angular Speeds of Tides

Component	Angular Speed a_i (°/hr)
Sa	0.0410667
Ssa	0.0821373
Mm	0.5443747
MSf	1.0158958
Mf	1.0980331
Q_1	13.3986609
ρ_1	13.4715145
O_1	13.9430356
M_1	14.4920521
P_1	14.9589314
K_1	15.0410686
J_1	15.5854433
S_1	15,0000000
$(OO)_1$	16.1391017
$(2N)_2$	27.8953548
μ_2	27.9682084
N_2	28.4397295
ν_2	28.5125831
M_2	28.9841042
λ_2	29.4556
L_2	29.5284789
T_2	29.9589333
S_2	30.0000000
K_2	30.0821373
M_2	43.4761563
M_4	57.9682084
$(MS)_4$	58.9841042
M_6	86.9523127
M_8	115.9364168
S_4	60.0000000
S_8	90.0000000

At present, we have not sorted out the separate effects of wind and atmospheric pressure; however, the following generalizations have been made (Zeskind and Le Lacheur, 1926):

1) Strong meteorological effects are largely confined to the winter months.

2) Meteorological low tides occur when the wind is blowing from the northwest and the barometer has been low and is rising.

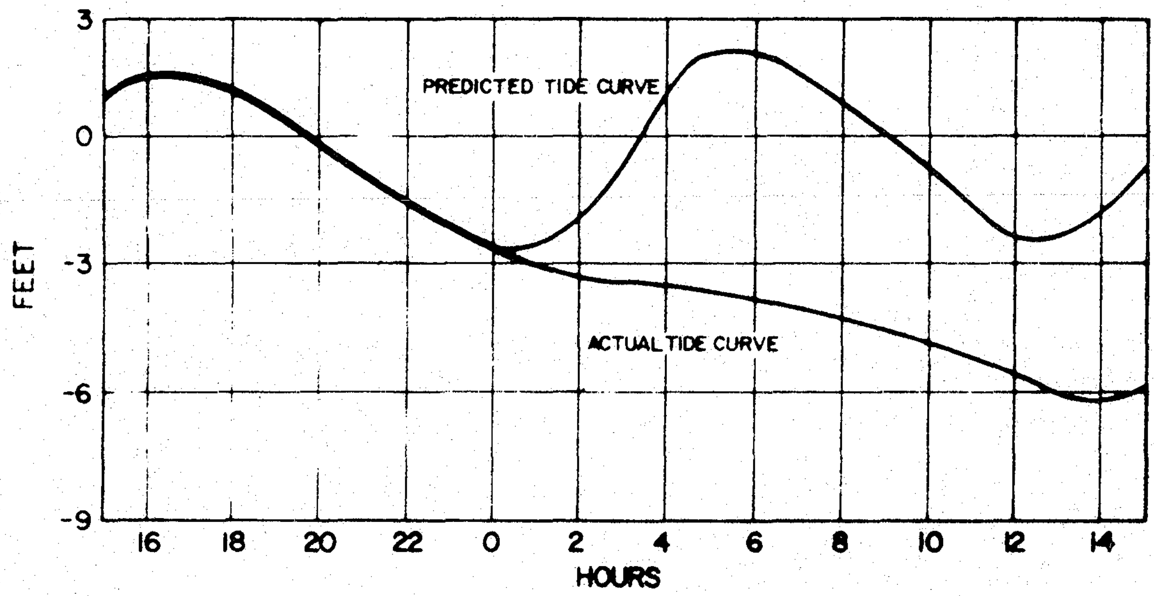
3) Meteorological high tides occur when there is an easterly wind and a falling barometer.

Meteorological high tides quite often accompany hurricanes. The arrival of the storm is heralded by a falling barometer and east winds. Water piles up somewhat to the right of the wind. This is at precisely the correct angle to flood the bay. The effects on tides at Philadelphia of such a storm is shown in Figure 13. As can be seen the result was a high tide 5.2 feet above the normal high tide. A similar, but more drastic meteorological high tide was the cause of extensive damage during the famous storm of March 1962.

It is difficult to predict the precise extent of the storm tide more than a few hours in advance -- largely because of the variability of storm tracks. The paths of a number of tropical storms have been plotted by the Corps of Engineers (1956a), and are reproduced in Figure 14.

METEOROLOGY AND WAVES

Surface weather observations for the Light Vessel, Delaware (August 1961 - November 1970), Harbor of Refuge (April 1966 - April



PREDICTED AND OBSERVED TIDE CURVES, PHILADELPHIA
MARCH 1-2, 1914
after ZESKIND AND LeLACHEUR
1926

Figure 12

EFFECT OF HURRICANE ON TIDE AT PHILADELPHIA
MODIFIED from CORPS of ENGINEERS

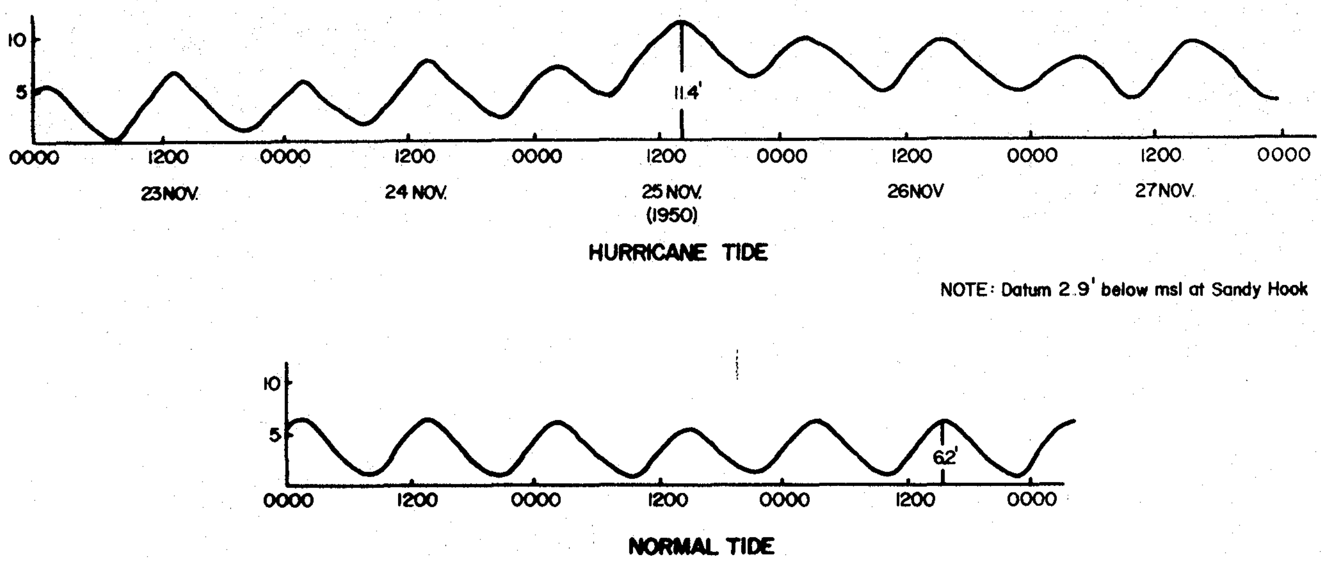


Figure 13

CORPS OF ENGINEERS

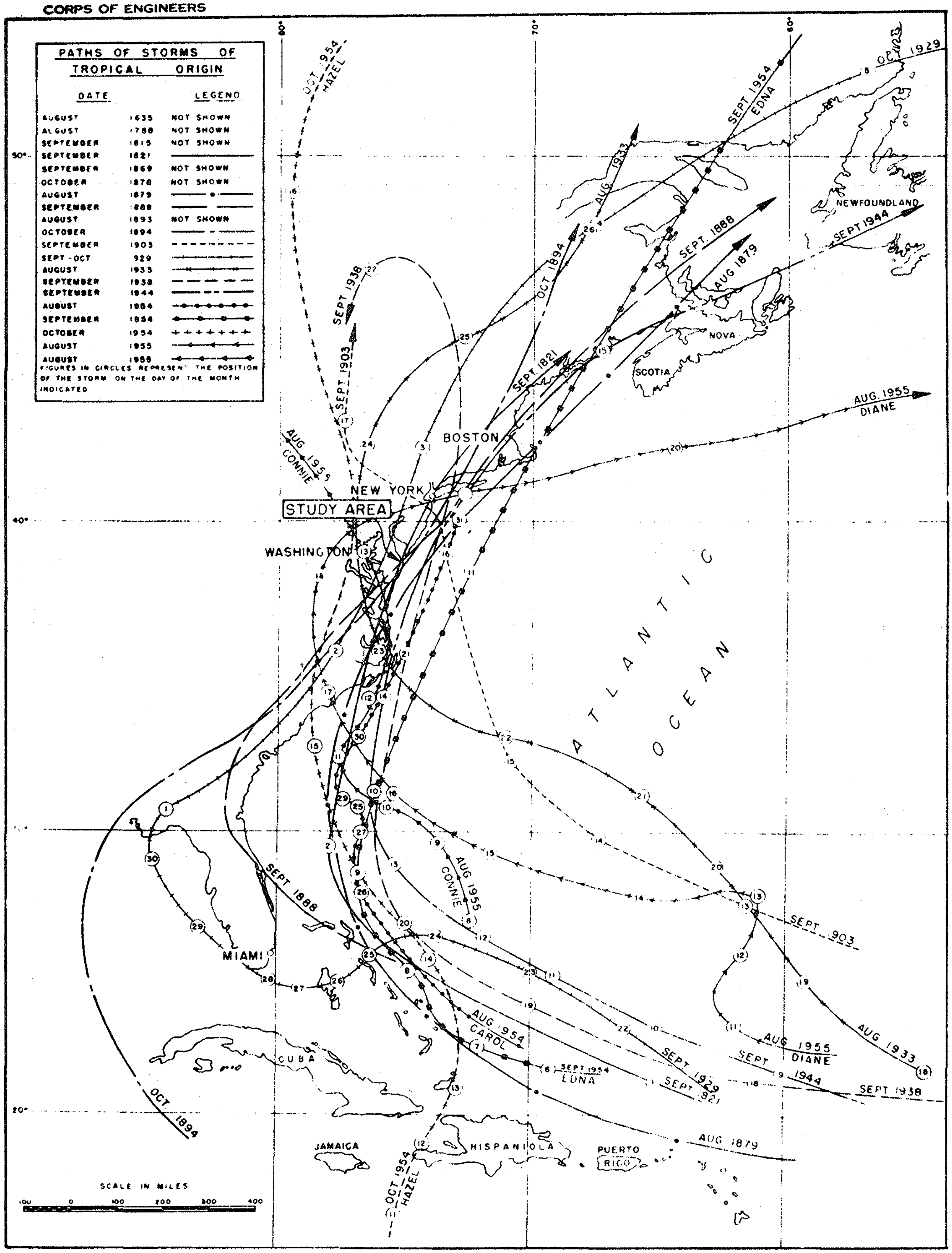


Figure 14

1971), Miah Maull Shoal (April 1966 - May 1972) and Dover Air Force Base (December 1942 - March 1965) are available at the College of Marine Studies, University of Delaware. Dover is the nearest station to Delaware Bay for which a climatological summary has been prepared by the Environmental Sciences Service Administration. The monthly air temperature and precipitation data from this summary are reproduced in Table IX.

Prevailing wind directions over the bay area for each month of the year are shown in Figure 15. Wind roses for stations in this region are shown in Figures 16a and 16b.

Monthly wave height and period distributions, and swell height and period distributions for Five Fathom bank (outside the bay), are shown in Figures 17 and 18 respectively. Table X shows average percentage frequency of occurrence of wave height direction groups for each month at a point inside the bay.

Table XI shows statistical estimates of extreme wind velocity and wave height for the bay area. A summary of environmental data for the bay area has been prepared by Brower (1972) and is shown in Table XII.

CURRENTS

Surface tidal currents tend to be directed along the axes of the bay except in the area behind Cape May, where the currents tend to follow the shore line. At local maximum flood and local maximum ebb,

Table IX

Average Temperature (°F)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Ann'l
1926	34.4	35.4	39.8	51.1	62.4	69.3	76.2	76.5	69.0	56.9	45.2	32.6	54.1
1927	33.7	41.0	46.0	50.8	61.7	68.0	75.8	69.9	68.6	59.3	52.0	40.0	55.6
1928	35.2	36.1	42.6	51.4	61.1	70.8	77.2	77.2	64.8	58.3	48.3	37.6	55.0
1929	34.6	35.3	49.7	56.0	63.4	72.2	75.6	72.8	69.8	54.8	47.9	38.0	55.8
1930	36.4	40.6	44.0	50.6	66.0	74.6	78.4	74.6	73.6	55.2	46.8	35.4	56.4
1931	36.2	37.4	40.6	52.1	62.4	72.0	79.4	75.8	73.6	61.4	52.8	44.6	57.4
1932	46.3	40.9	40.4	51.8	63.2	72.1	76.8	76.2	69.4	58.6	45.4	40.1	56.8
1933	42.8	38.2	42.1	53.1	66.6	74.2	75.0	75.8	71.6	56.2	44.0	36.8	56.4
1934	38.2	22.6	40.2	51.8	65.0	76.4	78.7	73.0	69.8	55.2	49.0	37.0	54.7
1935	33.0	33.9	48.6	51.4	60.6	71.5	77.2	74.3	66.1	57.2	50.4	31.5	54.6
1936	30.4	27.1	48.4	51.3	65.8	71.8	76.6	76.8	69.4	59.0	44.6	40.2	55.1
1937	43.6	36.4	39.2	52.4	64.3	72.4	76.1	77.0	65.6	55.4	46.4	36.2	55.4
1938	35.0	40.3	47.8	56.0	62.4	71.4	77.6	77.8	67.4	58.2	49.8	37.8	56.8
1939	35.3	41.6	45.4	52.9	66.0	74.8	76.0	77.1	69.9	58.8	44.0	38.4	56.7
1940	23.2	35.0	38.6	48.4	62.7	73.4	76.6	73.4	66.8	54.6	47.5	41.8	53.5
1941	34.2	33.2	38.3	57.2	66.4	71.4	76.8	74.8	72.6	64.3	50.4	41.7	56.8
1942	34.3	33.2	46.0	56.6	67.9	73.6	78.4	74.3	71.0	59.4	49.3	34.6	56.6
1943	35.5	38.4	45.2	50.8	65.7	78.2	76.7	76.8	68.5	56.4	46.3	36.5	56.2
1944	36.5	37.4	42.0	52.8	68.4	73.9	78.0	75.9	70.4	56.8	46.8	34.2	56.1
1945	30.4	36.8	54.4	57.0	61.8	73.2	75.7	73.6	72.7	57.3	50.7	31.7	56.3
1946	37.1	38.7	51.6	53.6	63.5	70.6	74.2	71.6	69.6	60.6	51.5	41.4	57.0
1947	42.4	31.8	38.4	55.2	63.8	70.6	75.0	76.4	69.0	62.4	44.6	35.2	55.4
1948	28.1	34.7	47.4	53.0	64.0	72.2	76.4	74.6	68.2	55.7	52.4	40.1	55.6
1949	43.3	42.3	45.8	53.5	64.0	74.1	80.4	76.4	67.1	62.0	48.6	41.1	58.2
1950	47.5	37.1	41.6	50.8	61.7	70.7	75.2	74.1	65.4	59.3	47.5	34.2	55.4
1951	37.5	37.6	44.5	54.3	63.9	72.2	77.3	75.3	69.5	60.8	45.0	41.7	56.6
1952	39.8	39.6	42.8	56.1	63.3	75.7	79.5	75.7	69.4	55.3	48.3	39.5	57.1
1953	41.3	42.0	46.4	54.3	67.5	73.1	78.1	75.0	70.4	59.6	47.4	41.2	58.0
1954	35.5	43.6	44.8	57.9	62.1	73.5	77.4	75.6	70.6	61.9	45.6	37.7	57.2
1955	33.8	37.2	46.8	57.0	66.6	69.5	81.8	78.5	67.8	60.4	46.1	32.5	56.5
1956	33.2	40.5	42.3	51.8	63.4	73.4	75.4	74.3	67.9	59.6	45.9	44.9	56.1
1957	32.2	39.9	43.9	58.1	65.8	75.0	77.1	74.5	71.4	56.0	50.1	41.2	57.1
1958	33.2	30.2	40.8	55.2	63.2	70.3	78.3	74.5	68.0	58.4	49.4	31.4	54.4
1959	34.3	36.8	44.7	56.9	68.4	74.1	77.3	77.5	71.8	62.8	47.8	41.3	57.8
1960	36.8	38.1	33.0	59.7	62.7	72.7	75.2	76.3	70.1	57.9	49.3	31.1	55.2
1961	28.4	38.4	46.0	51.0	61.0	72.1	77.0	75.2	74.1	59.1	49.7	36.5	55.7
1962	35.0	34.1	42.1	55.6	66.5	73.0	74.7	74.8	66.0	59.3	44.1	32.0	54.8
1963	31.8	37.0	47.1	54.9	62.6	72.4	76.7	73.3	65.3	61.1	50.7	31.3	55.3
1964	36.1	35.1	46.6	51.7	66.0	73.8	77.2	73.6	69.3	55.9	51.0	41.2	56.5
1965	33.0	37.2	42.2	52.0	68.8	72.5	76.3	75.3	71.6	56.8	48.7	40.4	56.2

Total Precipitation (Inches)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Ann'l
1926	2.80	3.38	2.47	2.62	2.44	2.22	8.97	5.84	3.17	1.87	4.24	3.42	45.44
1927	1.43	3.26	1.32	3.18	3.16	3.41	4.76	6.25	2.93	4.43	2.37	3.86	40.36
1928	3.15	3.12	3.30	6.52	2.48	4.61	4.05	13.62	8.73	0.62	2.53	2.24	54.97
1929	3.00	5.22	3.55	6.54	1.90	3.39	0.85	2.16	3.72	4.48	2.27	2.41	39.49
1930	3.81	1.79	1.63	2.32	2.61	1.97	3.75	3.06	4.34	1.17	2.04	2.11	30.60
1931	1.98	1.46	5.74	3.07	4.26	3.92	2.73	11.51	1.83	3.40	1.12	2.44	43.46
1932	5.33	2.86	7.15	3.17	6.32	2.96	1.70	1.86	1.97	5.90	5.45	4.29	48.96
1933	3.30	3.37	3.20	4.30	4.53	4.08	5.96	12.53	2.95	0.95	1.94	3.76	50.87
1934	2.38	4.35	5.06	2.92	6.62	2.60	10.78	3.14	7.84	2.23	3.73	2.11	53.74
1935	5.01	3.75	4.00	3.68	3.07	5.43	4.73	5.03	11.37	2.17	4.81	3.04	56.09
1936	7.95	5.02	5.88	3.24	1.45	4.59	5.59	4.76	4.30	2.78	0.79	4.32	50.67
1937	8.09	3.44	3.05	5.05	3.71	5.79	3.99	5.16	1.18	6.07	3.80	0.91	50.24
1938	2.90	3.03	2.38	1.98	3.91	4.26	13.43	1.36	8.02	1.78	3.24	2.77	49.06
1939	3.80	6.27	6.46	7.02	0.62	4.22	2.68	16.08	2.90	4.37	1.60	1.88	57.90
1940	2.50	2.88	3.82	6.12	6.05	1.18	1.68	6.55	4.47	1.68	4.76	2.41	44.10
1941	3.54	2.15	2.55	3.30	1.87	5.60	3.48	1.96	T	2.22	1.99	3.55	32.21
1942	3.80	2.00	6.37	0.83	1.60	2.17	5.31	10.49	2.19	4.94	3.00	4.21	46.91
1943	3.32	2.13	3.88	3.49	3.45	6.99	2.07	0.85	2.42	5.64	2.37	1.93	38.54
1944	4.00	1.84	6.33	6.21	2.61	1.78	2.55	4.93	5.70	3.35	4.80	2.70	46.80
1945	3.57	3.07	1.74	4.60	3.16	4.49	11.46	1.43	4.18	2.74	2.88	7.50	50.82
1946	2.28	2.25	3.53	2.33	5.06	2.95	5.17	2.95	2.33	1.83	1.54	1.78	34.00
1947	5.26	1.08	1.84	2.85	6.49	3.71	3.15	5.86	2.43	1.33	4.38	1.79	40.17
1948	6.91	3.37	3.18	2.48	12.96	3.94	4.44	5.54	1.03	3.27	6.57	6.36	60.05
1949	5.91	4.24	3.50	2.12	4.37	1.41	2.00	3.93	4.52	4.46	2.58	1.87	40.91
1950	2.07	3.15	4.00	1.65	4.38	3.06	3.46	1.61	7.33	1.92	3.98	1.89	38.50
1951	2.26	3.25	3.13	2.43	4.76	3.68	4.76	3.00	2.89	3.89	7.88	6.21	48.16
1952	5.23	2.03	5.09	6.19	5.27	2.87	4.53	10.93	3.37	0.98	5.06	3.46	55.01
1953	4.26	3.49	5.28	3.87	7.33	1.64	3.88	4.11	1.36	5.23	2.71	3.16	46.32
1954	3.19	1.49	3.75	3.31	3.75	1.11	1.51	5.04	4.01	2.36	4.60	3.30	37.42
1955	0.44	2.49	3.59	2.71	2.17	5.81	1.55	13.23	1.82	3.27	1.78	0.39	39.25
1956	2.18	3.46	3.85	2.58	2.31	3.56	5.05	4.64	4.20	5.90	6.51	3.87	48.11
1957	1.86	2.78	3.02	1.59	1.83	2.85	1.30	2.85	4.34	3.20	4.85	4.82	35.29
1958	3.61	4.80	7.06	4.05	4.51	3.40	5.31	12.11	2.25	3.30	3.49	2.34	56.23
1959	1.95	1.85	3.27	3.39	1.16	1.42	9.73	5.20	0.97	3.81	5.65	2.22	40.62
1960	2.24	3.41	2.00	2.13	4.79	2.20	6.25	3.35	10.19	2.98	1.92	2.02	43.48
1961	3.55	4.55	4.57	4.72	3.80	6.80	3.51	3.19	2.00	4.17	2.30	3.58	46.74
1962	2.56	3.35	3.40	5.02	1.49	3.20	2.48	1.41	3.44	1.40	5.01	3.10	35.86
1963	2.24	1.66	5.23	0.48	2.46	3.61	1.98	4.85	3.30	T	6.29	1.86	33.96
1964	3.95	5.35	2.86	5.61	0.58	0.68	3.28	1.33	4.63	3.26	1.58	2.93	36.04
1965	3.03	1.13	3.61	1.72	1.11	1.51	1.38	3.32	2.18	0.92	0.64	0.83	21.38

STATION HISTORY

Official observations at Dover date as far back as July 1870. There are some breaks in the record but since May 1906 the only one is that from June 1916 through June 1919. The following are Dover's observers and the beginning and ending dates of their record:

J. H. Bateman	Jul 1870 to Jul 1881
J. S. Jester	Oct 1890 to Dec 1896
A. A. Bateman	Jan 1898 to Dec 1898
Thomas F. Dunn	May 1906 to Aug 1911
W. C. Josting	Sep 1911 to Jun 1914
W. E. Kichline	Jul 1914 to May 1916
A. G. Livingston	Jul 1919 to Apr 1948
State Highway Department (Materials and Research Engineering)	May 1948 to present

Mr. A. G. Livingston, Engineer for the State Highway Department, provided an excellent record of observations for nearly 30 years. After his retirement in April 1948, other employees of the State Highway Department have continued doing a fine job of weather observing and reporting.

Since July 1919, the weather station has been located near the State Highway Department Building on Legislative Avenue; its elevation is 30 feet.

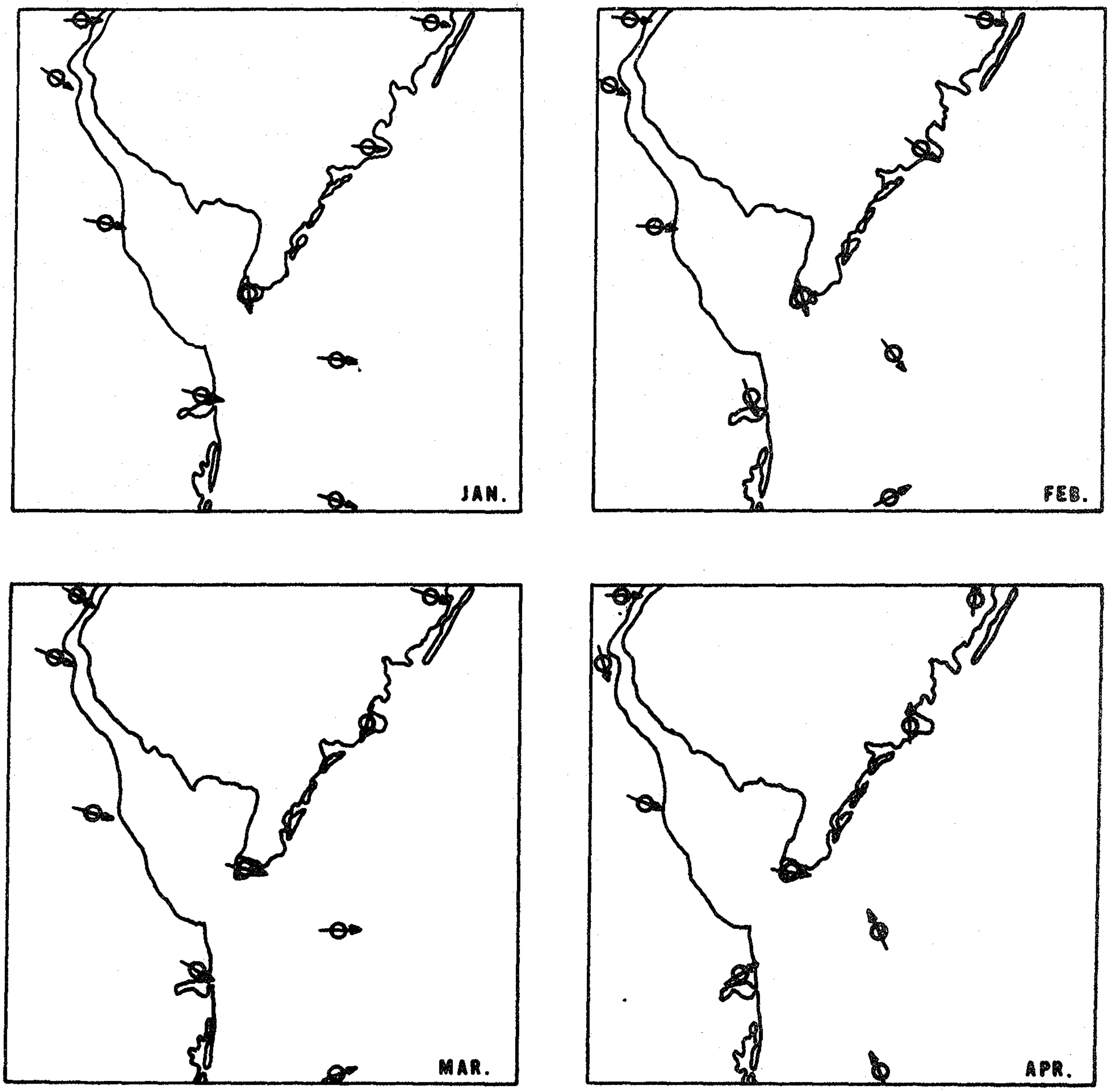


Figure 15a. **MONTHLY VARIATION IN PREVAILING WIND DIRECTION**

(Mather, 1968)

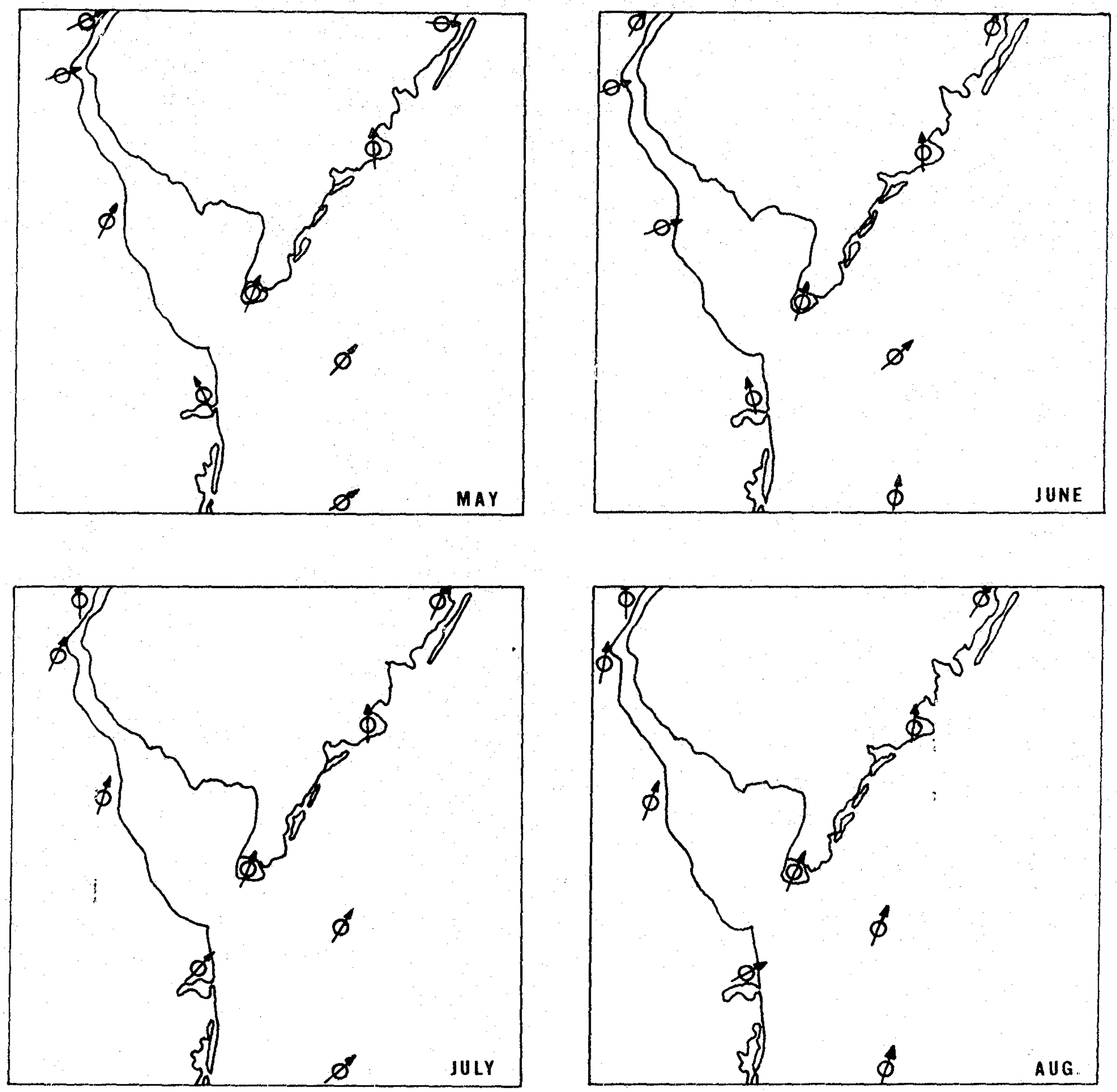


Figure 15b. **MONTHLY VARIATION IN PREVAILING WIND DIRECTION**

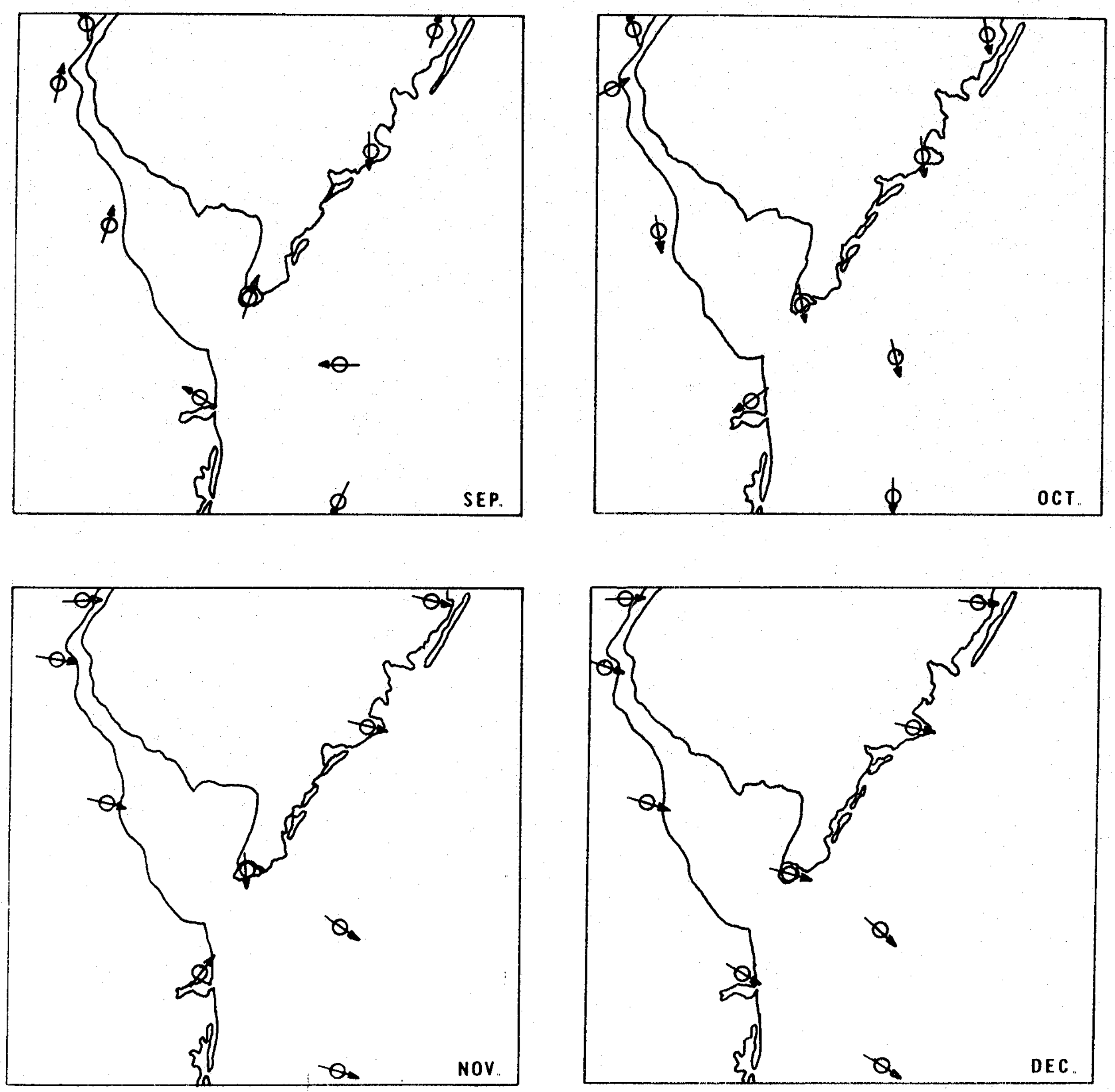


Figure 15c. MONTHLY VARIATION IN PREVAILING WIND DIRECTION

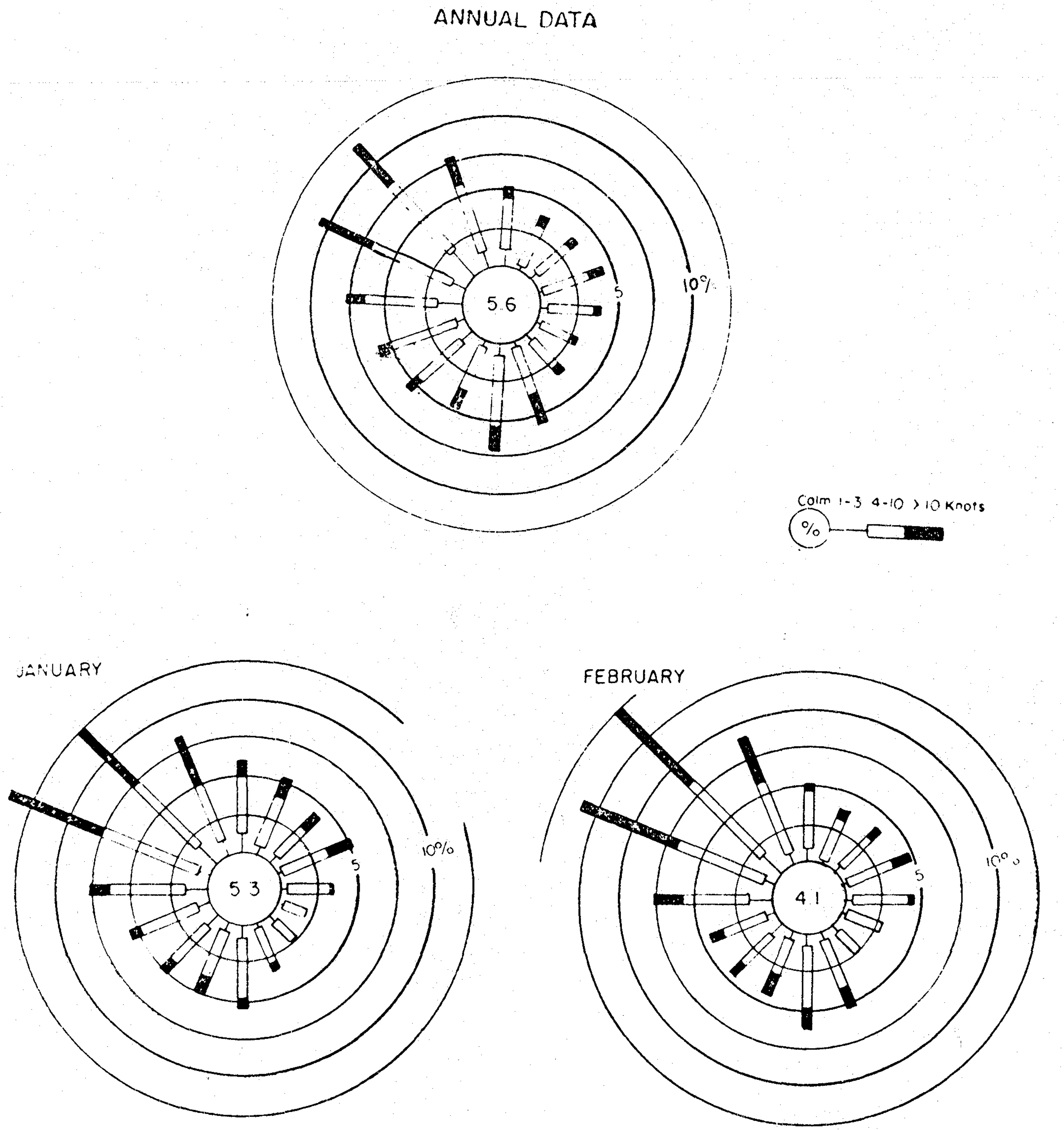


Figure 16a Monthly and Annual Wind Roses at Wilmington, Delaware (Mather 1968)

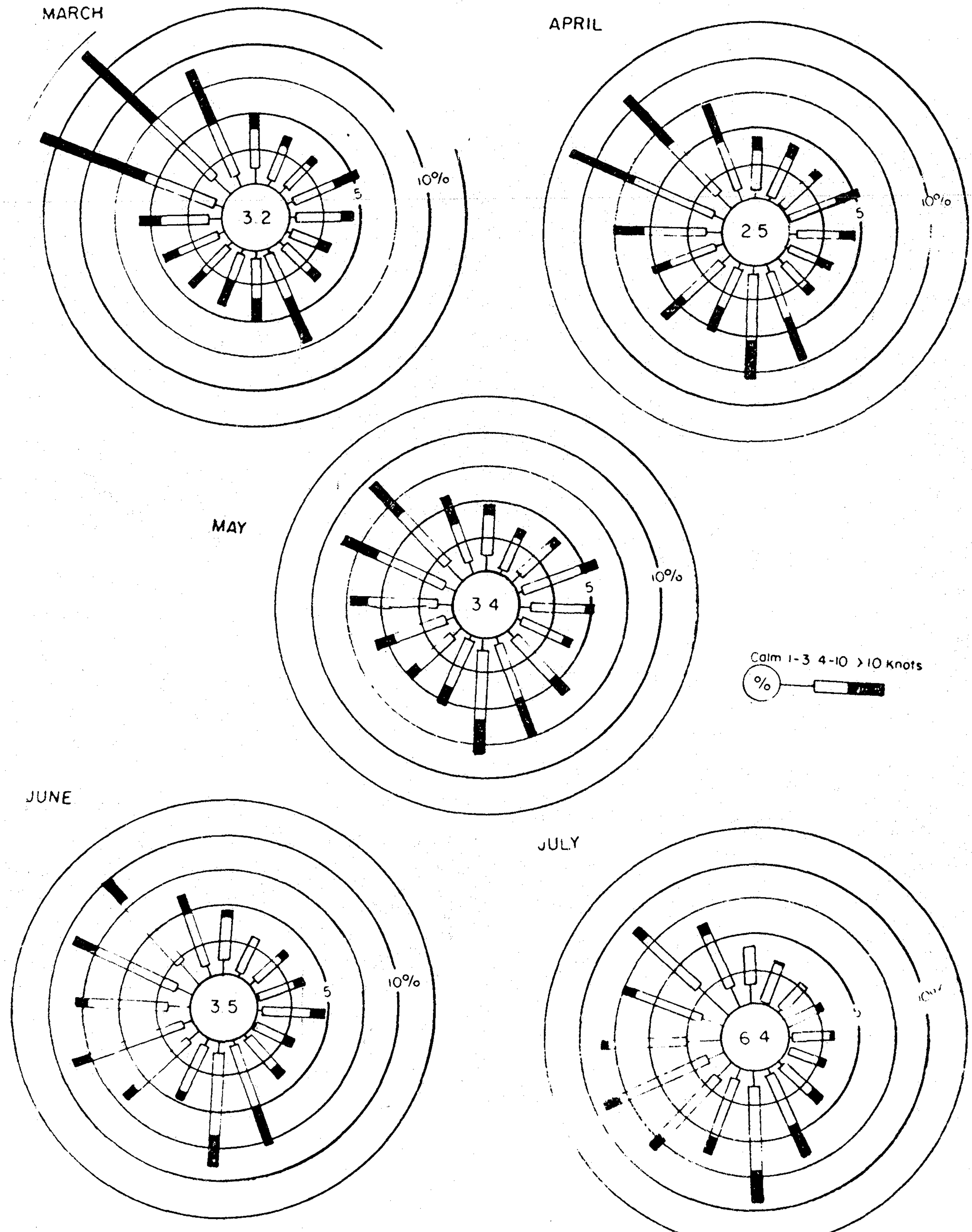


Figure 16a   Monthly and Annual Wind Roses at Wilmington, Delaware

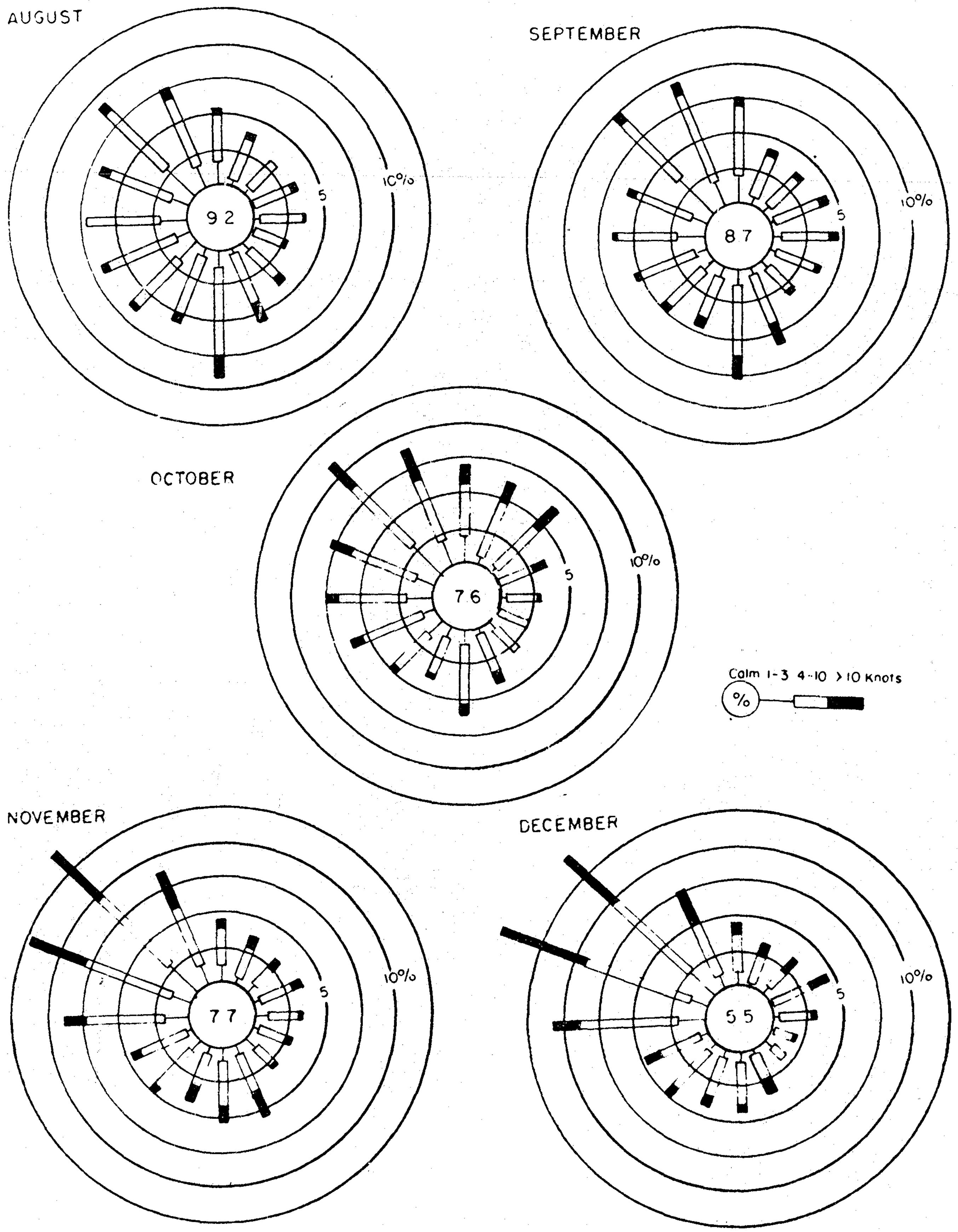


Figure 16a Monthly and Annual Wind Roses at Wilmington, Delaware

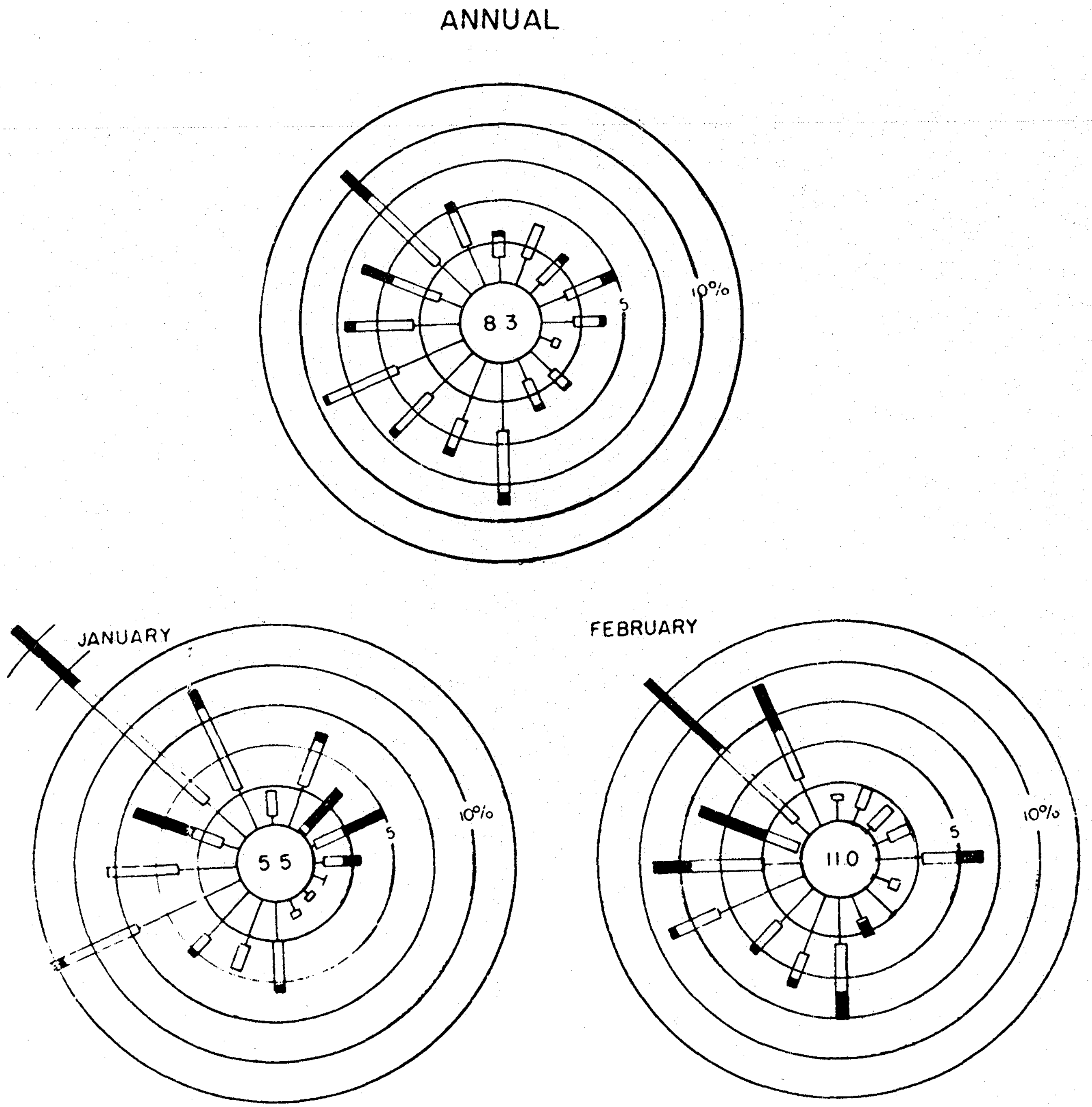


Figure 16a Monthly and Annual Wind Roses at Delaware City, Delaware (Mather, 1968)

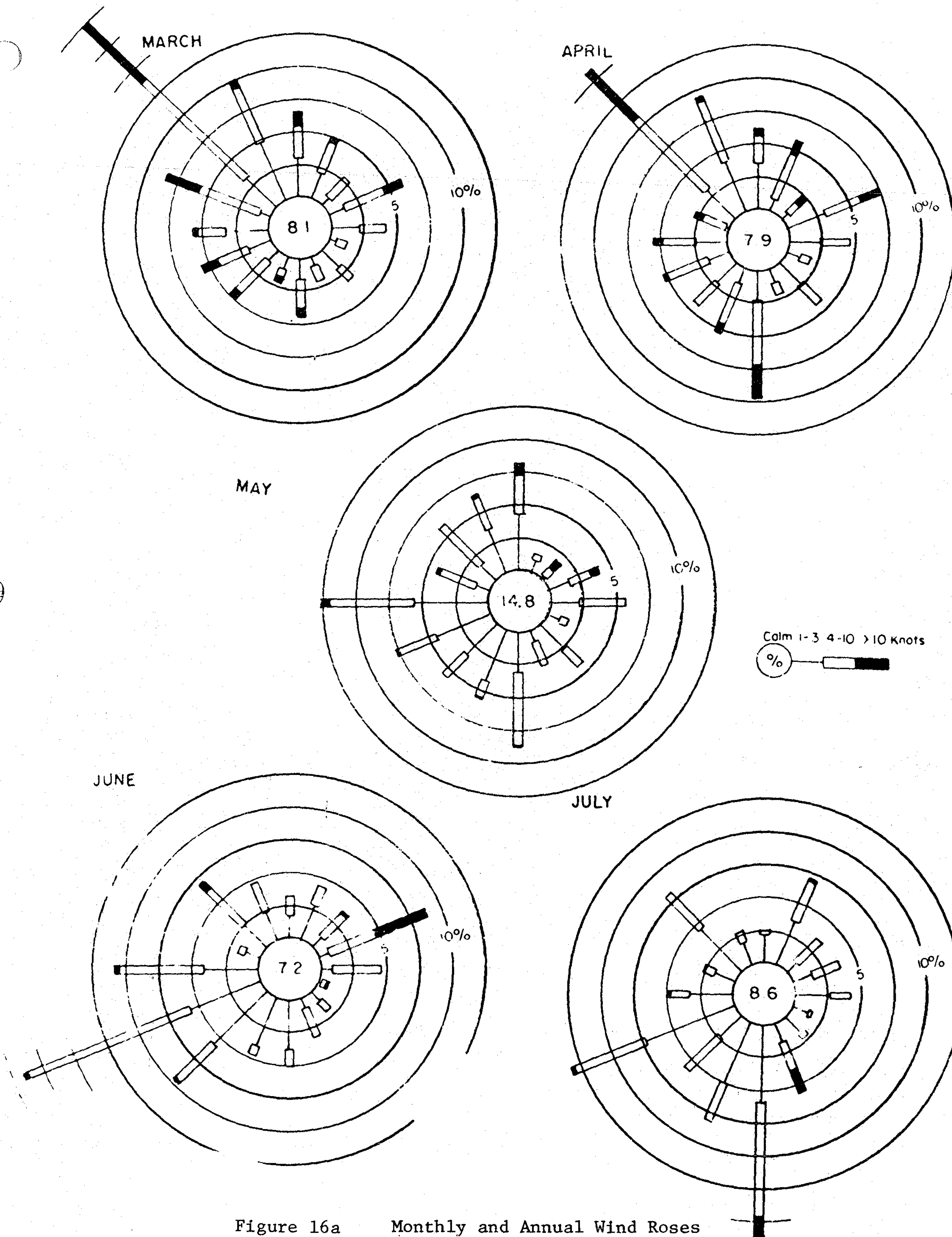


Figure 16a Monthly and Annual Wind Roses at Delaware City, Delaware

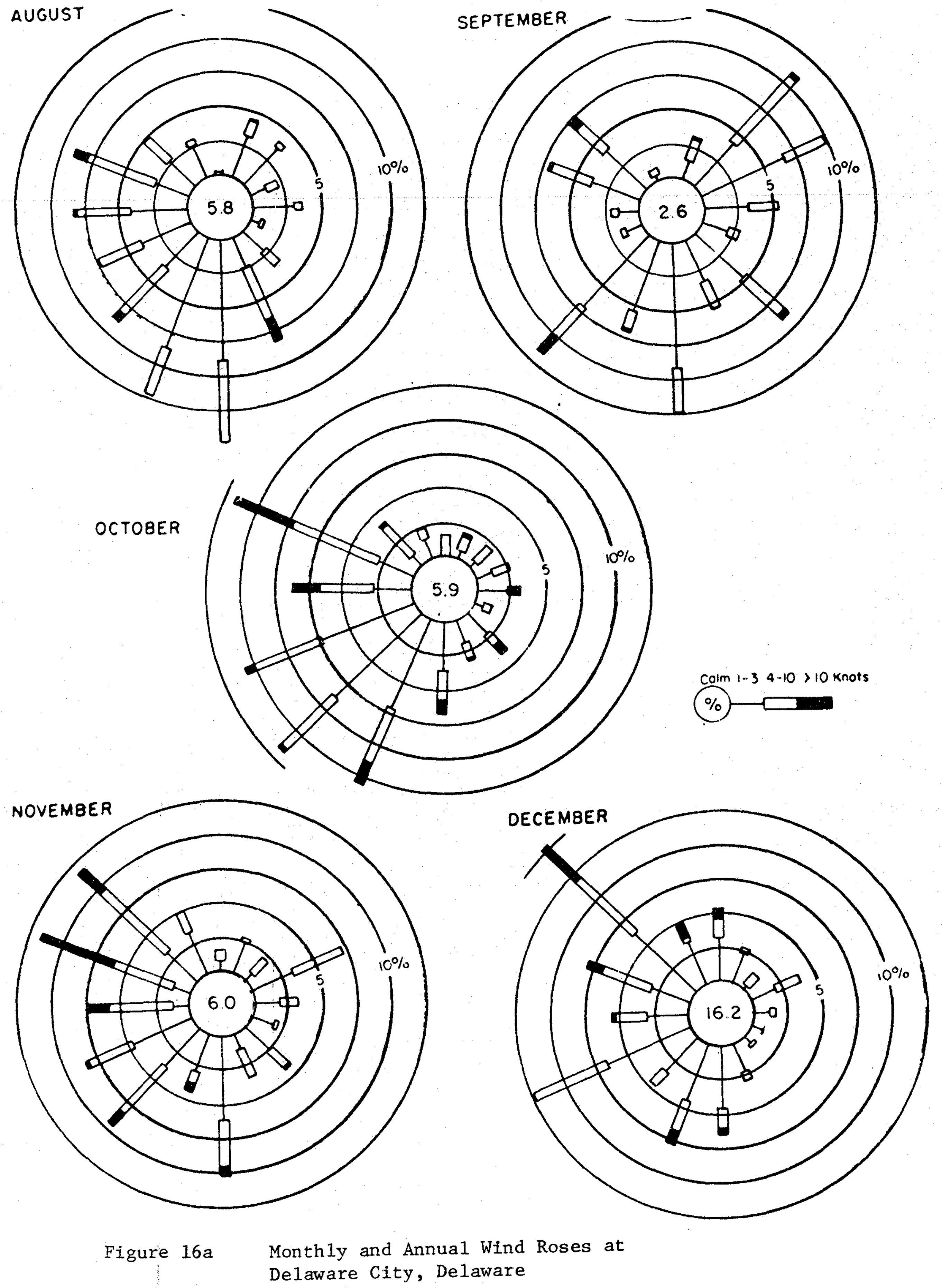


Figure 16a Monthly and Annual Wind Roses at Delaware City, Delaware

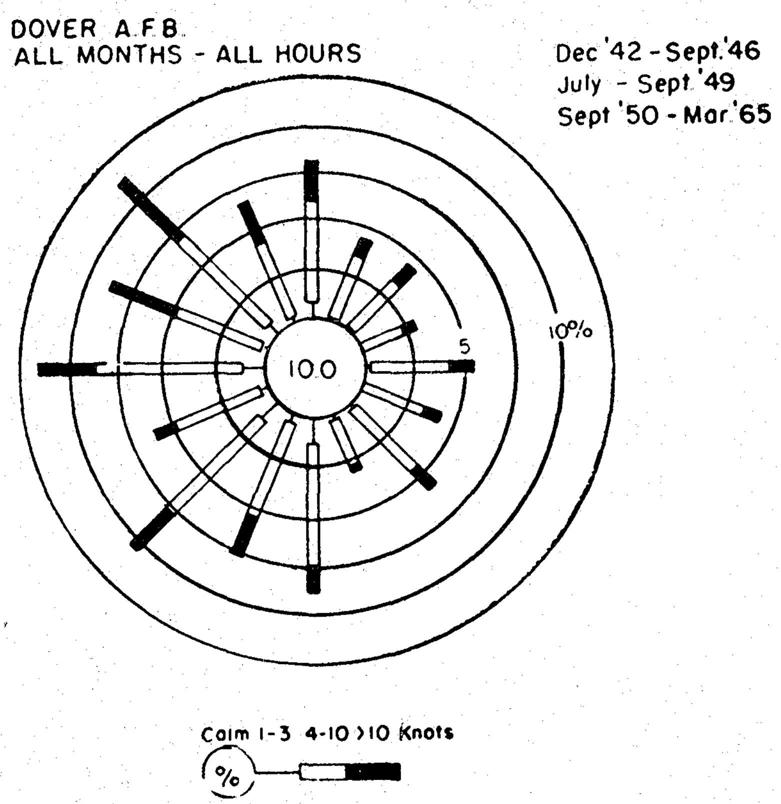


Figure 16a Monthly and Annual Wind Roses at Dover Air Force Base, Delaware for selected two-hour periods

(Mather 1968)

JANUARY

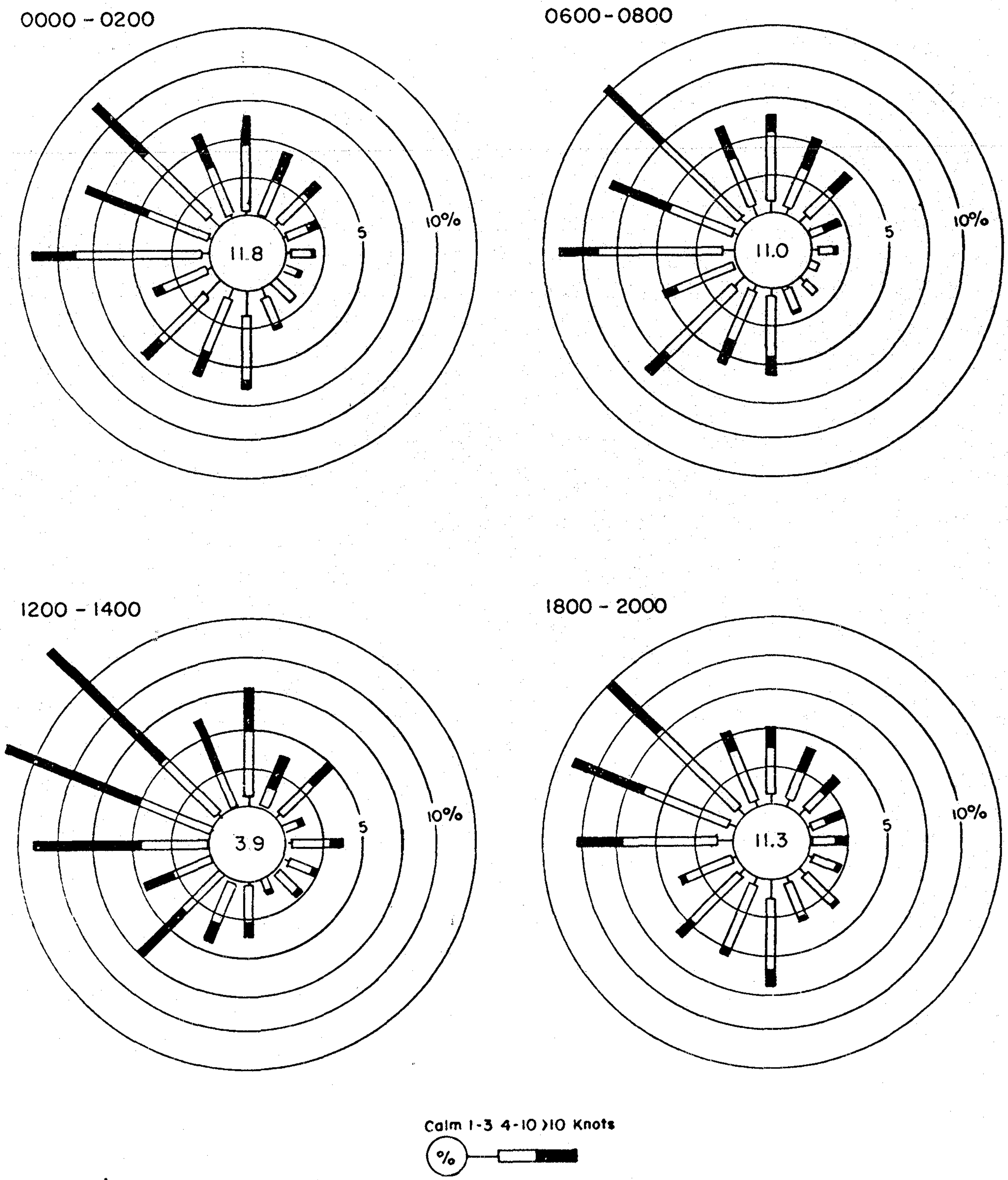


Figure 16a Monthly and Annual Wind Roses at
Dover Air Force Base, Delaware for selected two-hour periods

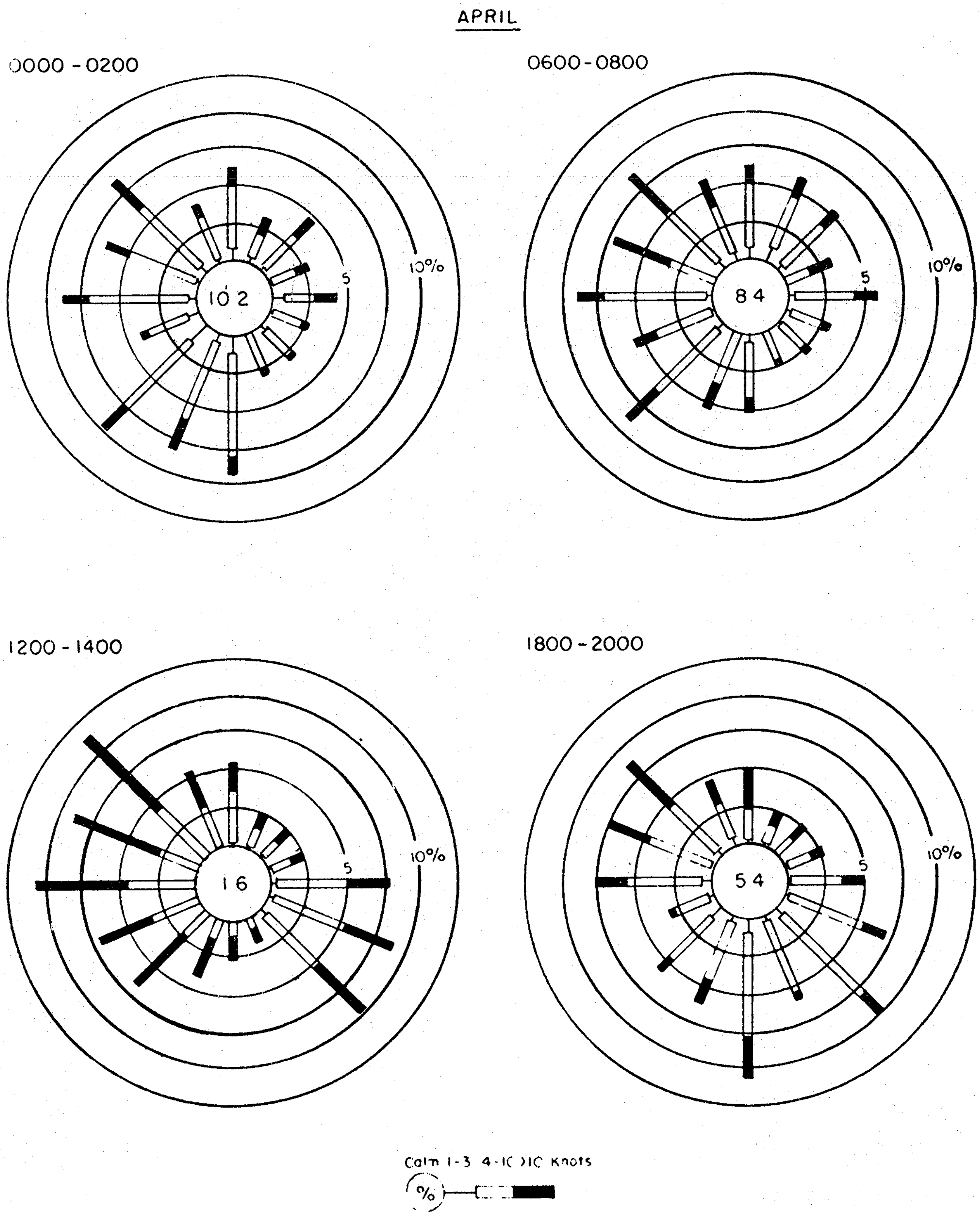


Figure 16a Monthly and Annual Wind Roses at Dover Air Force Base, Delaware for selected two-hour periods

JULY

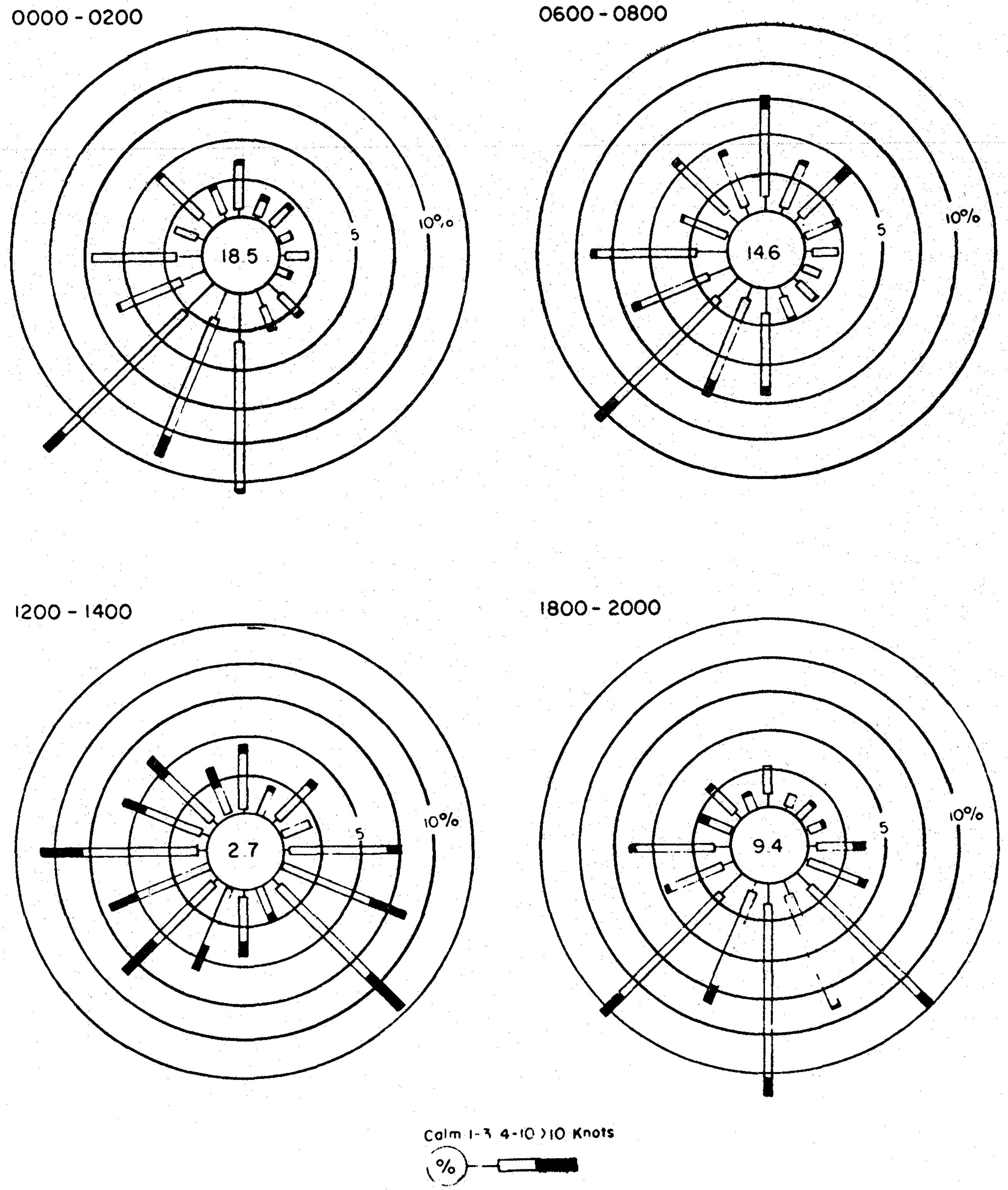


Figure 16a Monthly and Annual Wind Roses at Dover Air Force Base, Delaware for selected two-hour periods

OCTOBER

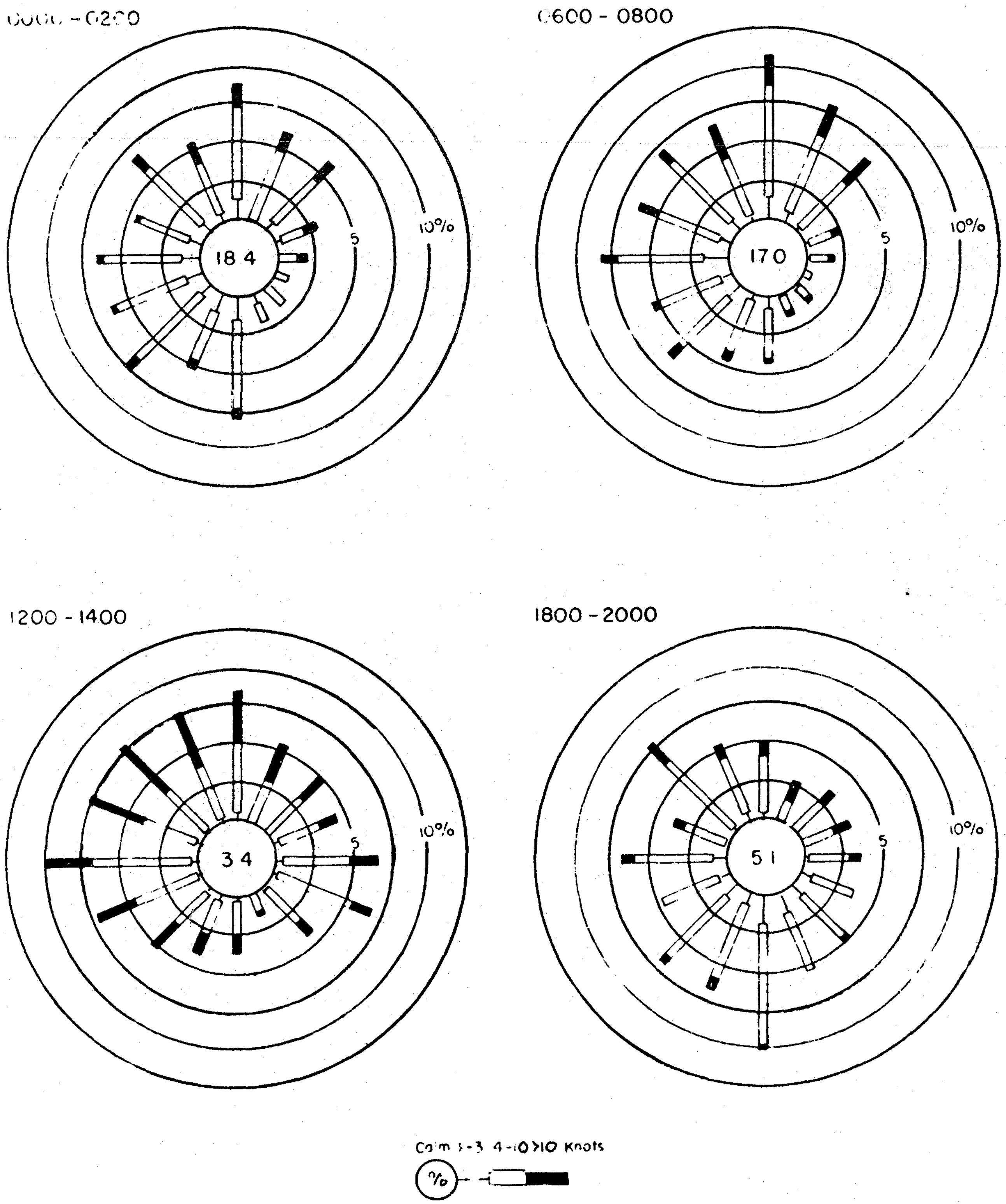


Figure 16a Monthly and Annual Wind Roses at Dover Air Force Base, Delaware for selected two-hour periods

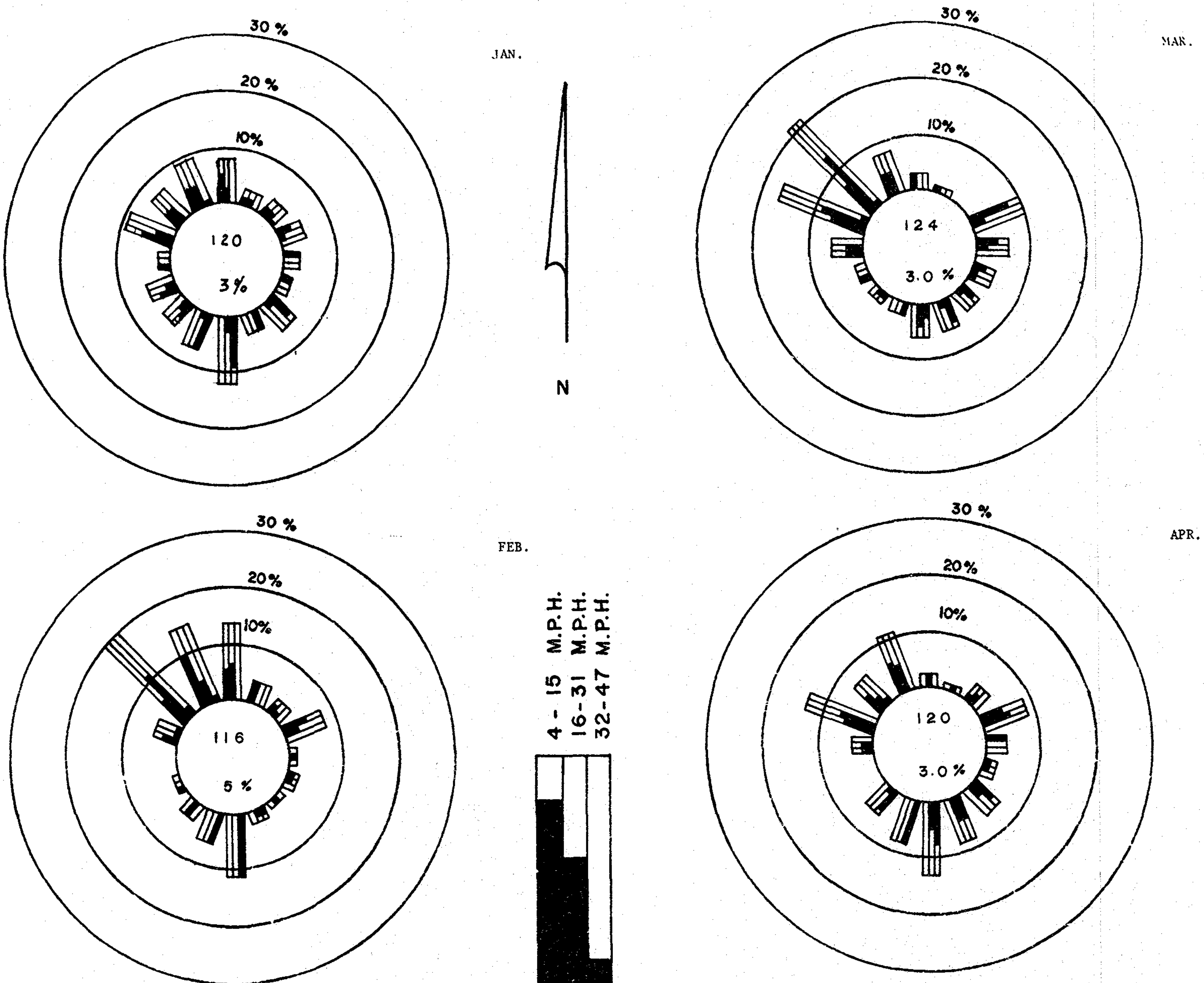


Figure 16a Monthly Wind Speed and Direction Distributions at Cape May, New Jersey

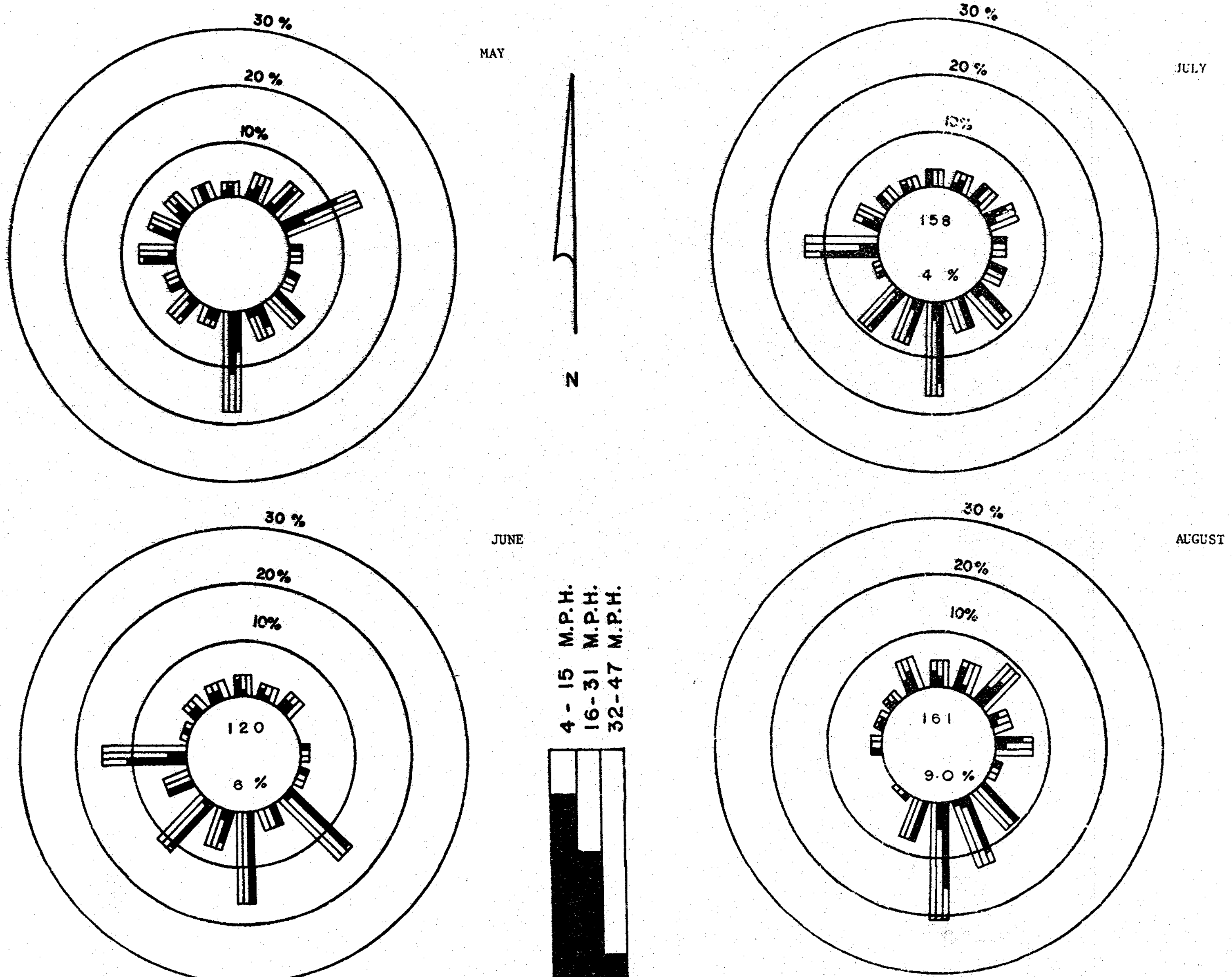
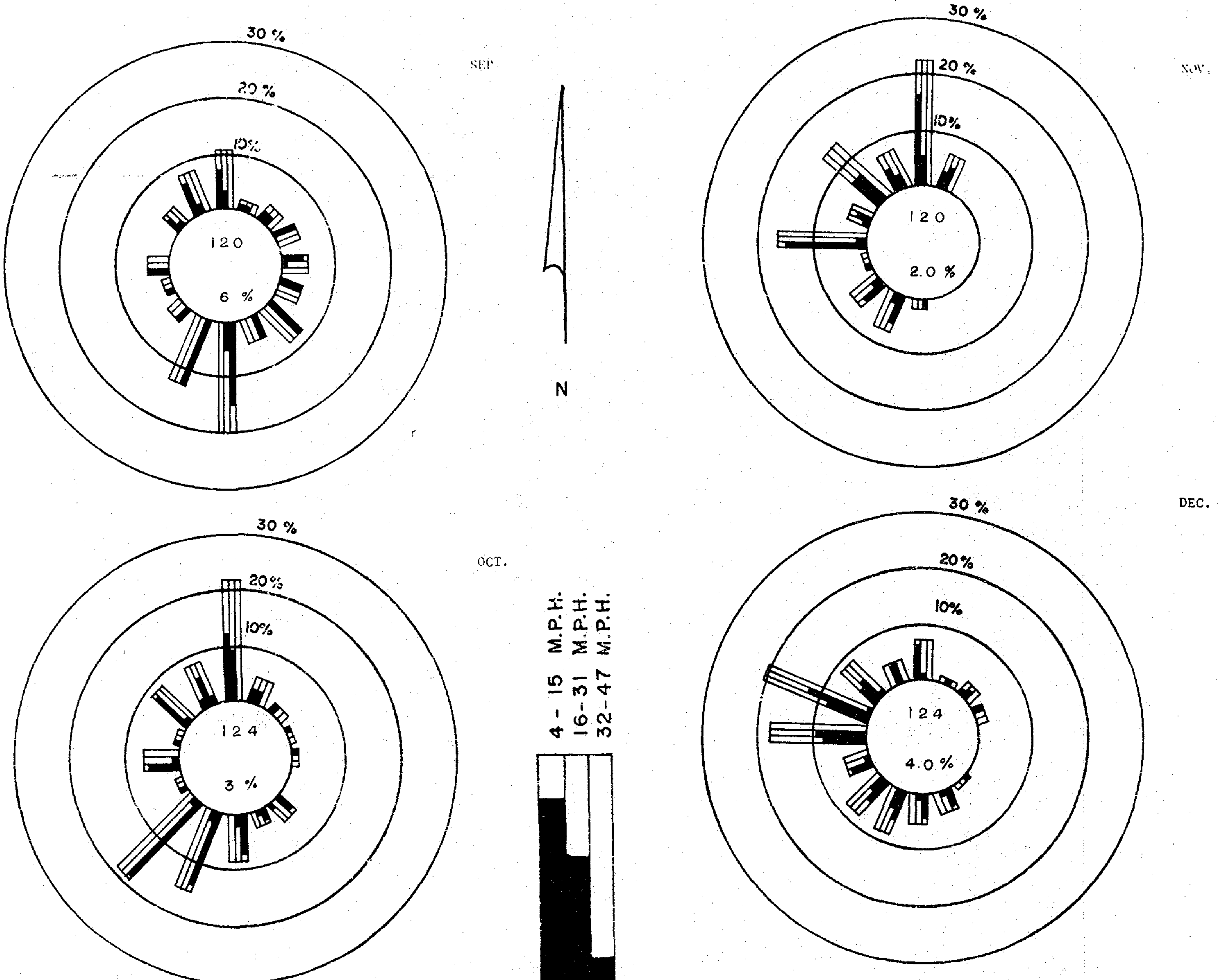


Figure 16a Monthly Wind Speed and Direction Distributions at Cape May, New Jersey



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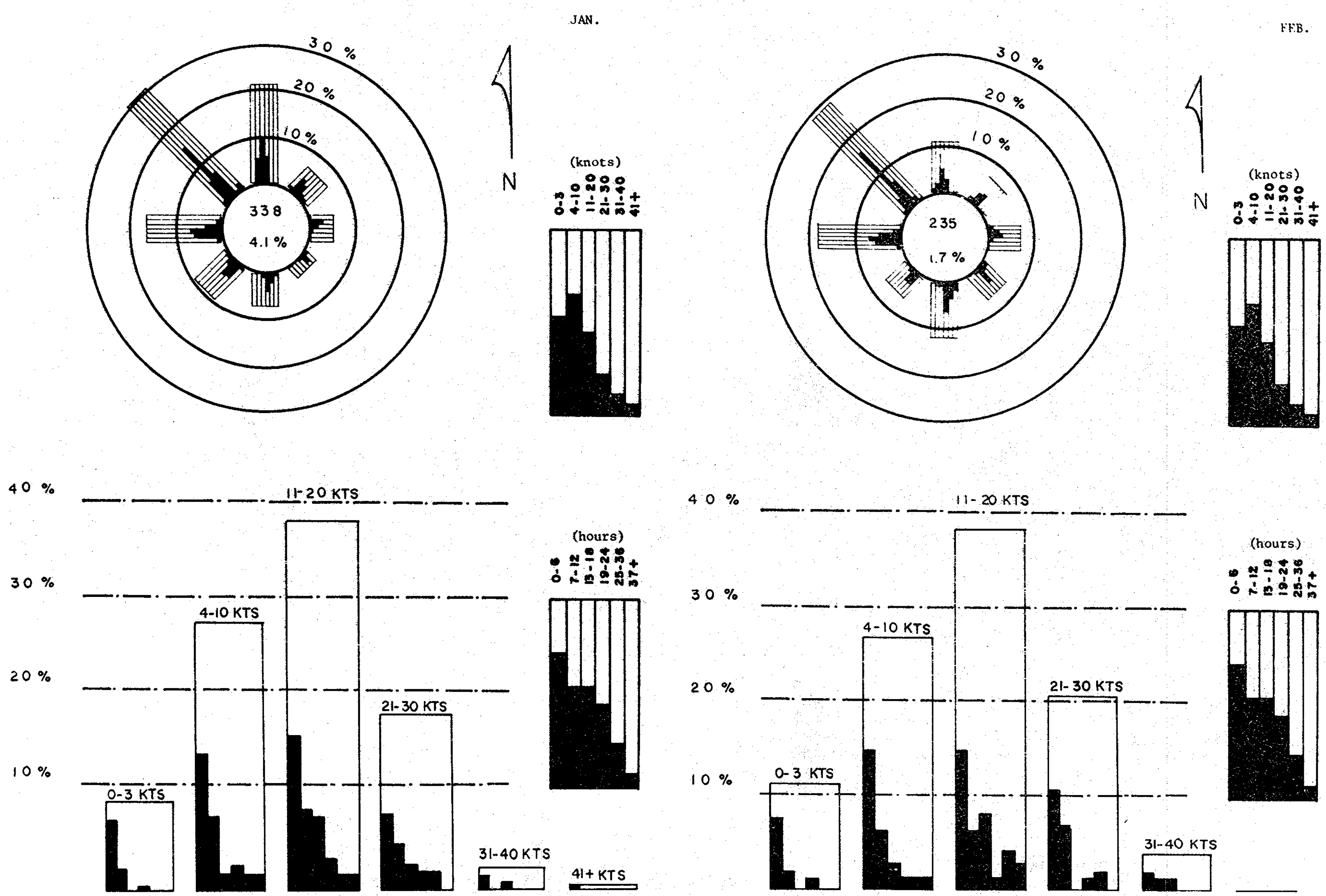


Figure 16b Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware

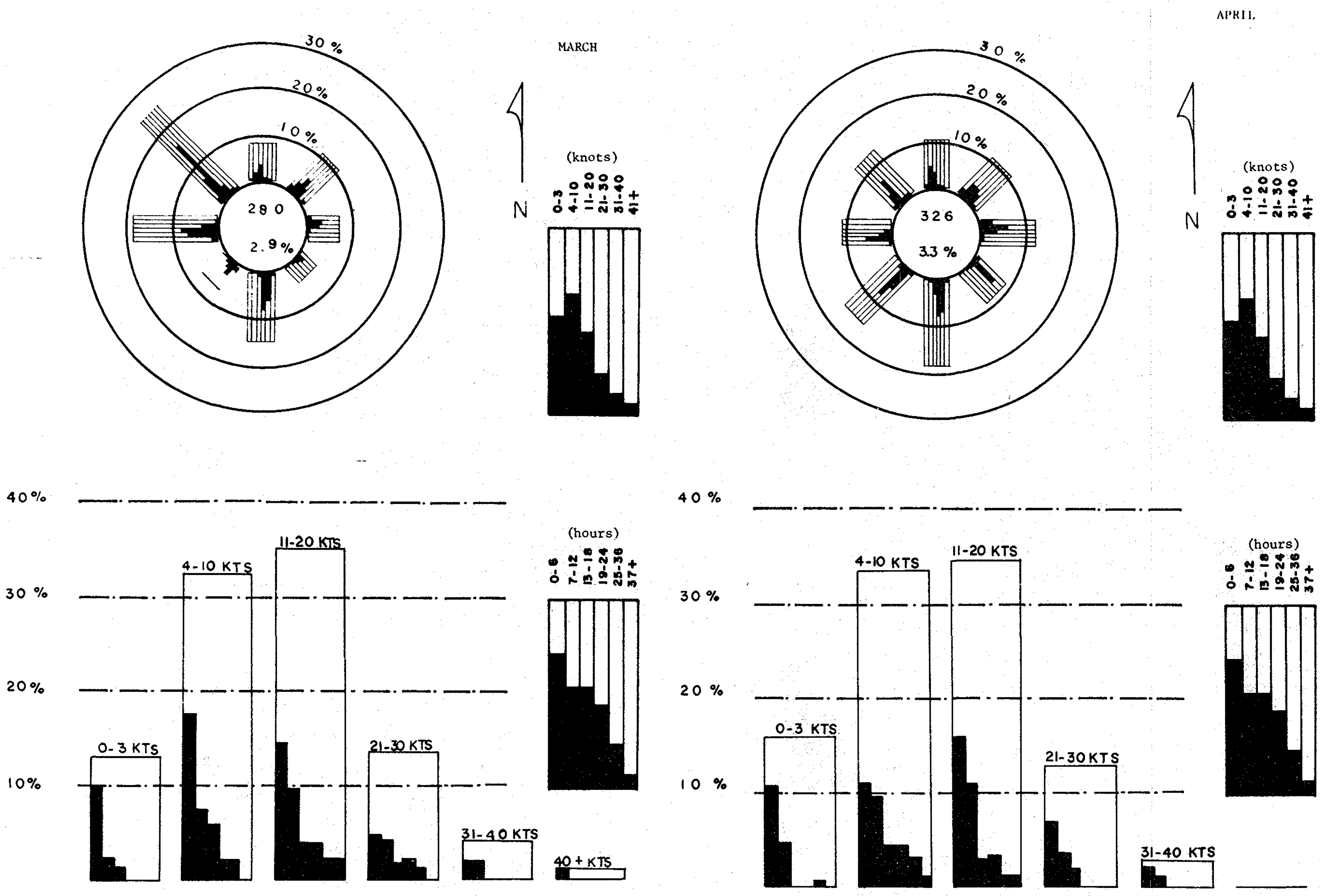


Figure 16b Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware

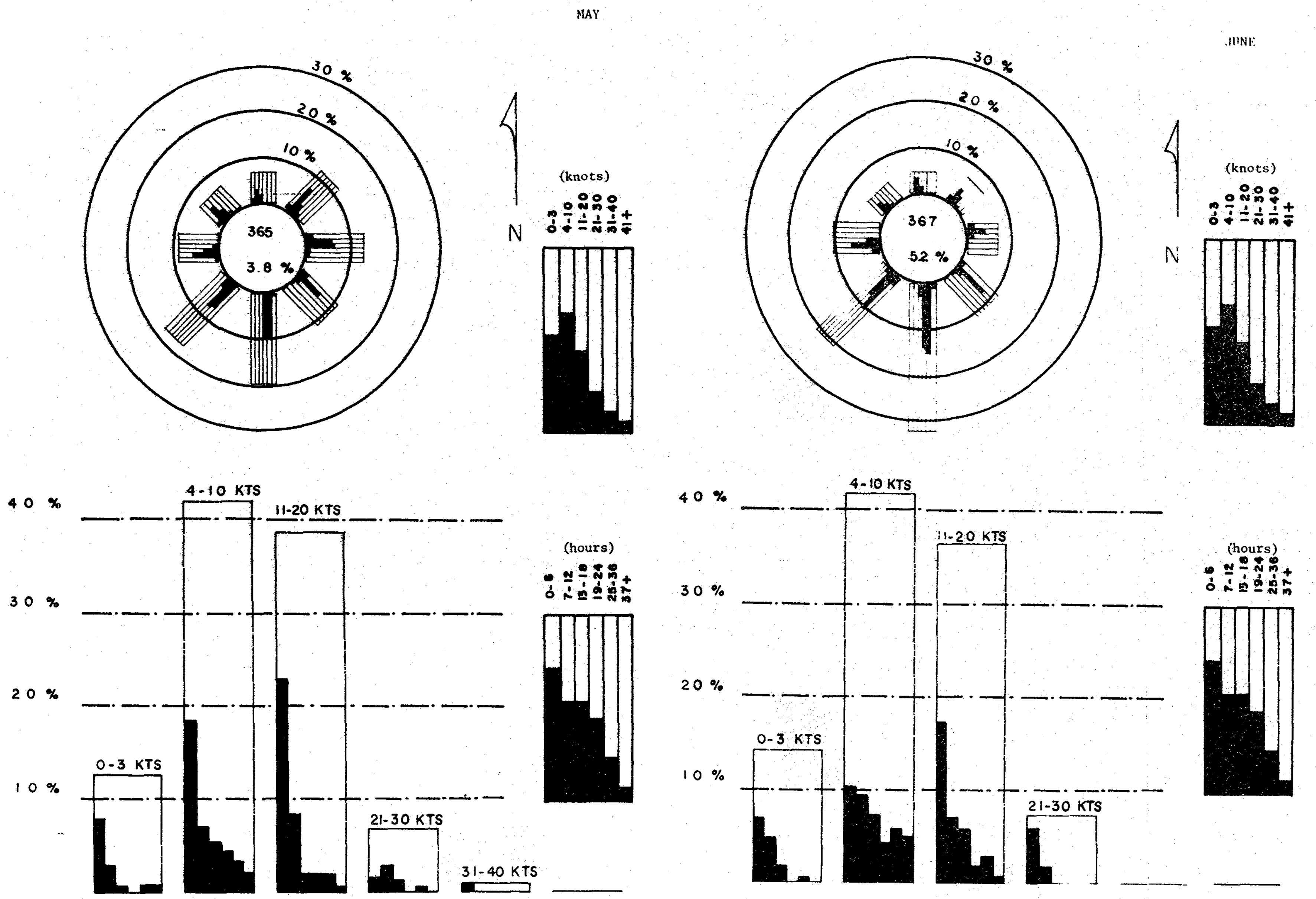


Figure 16b Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware

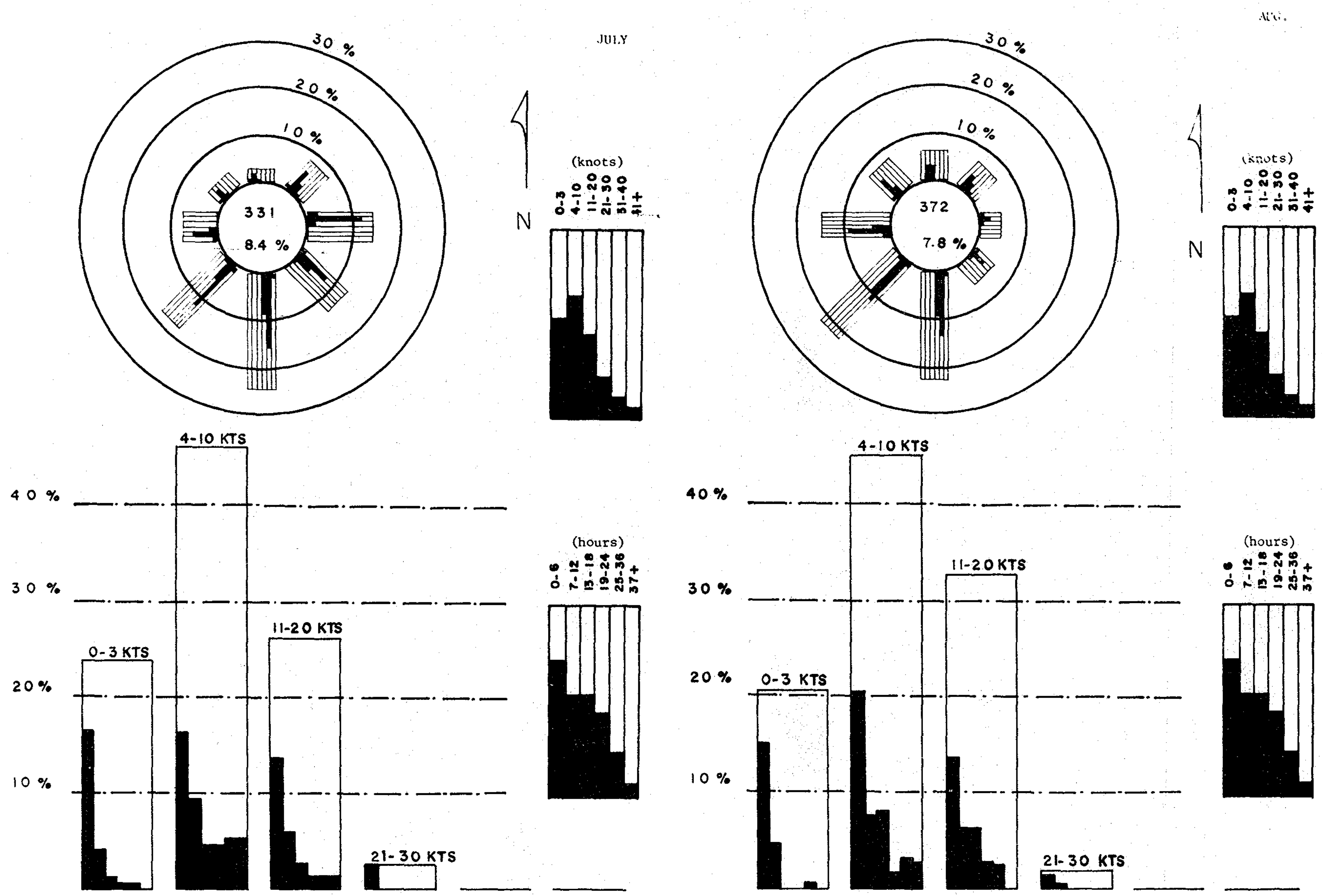
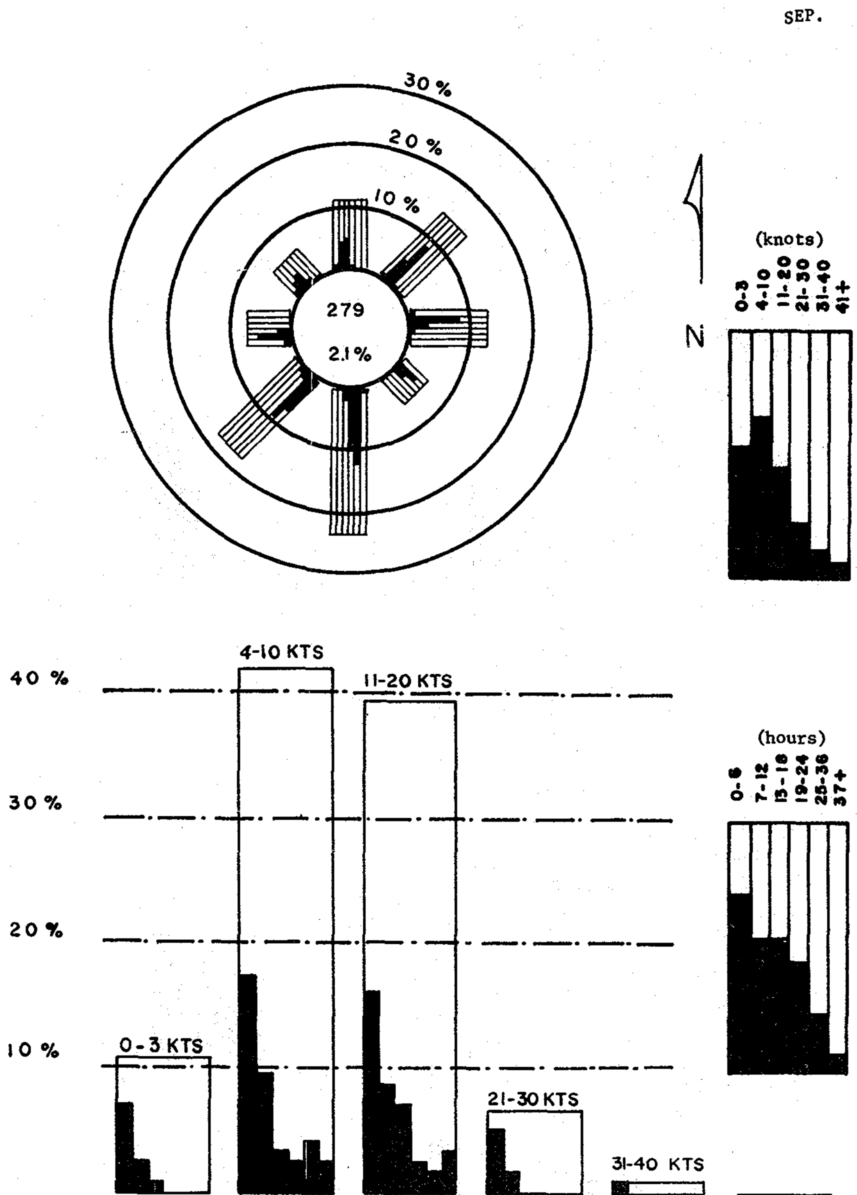


Figure 16b Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware



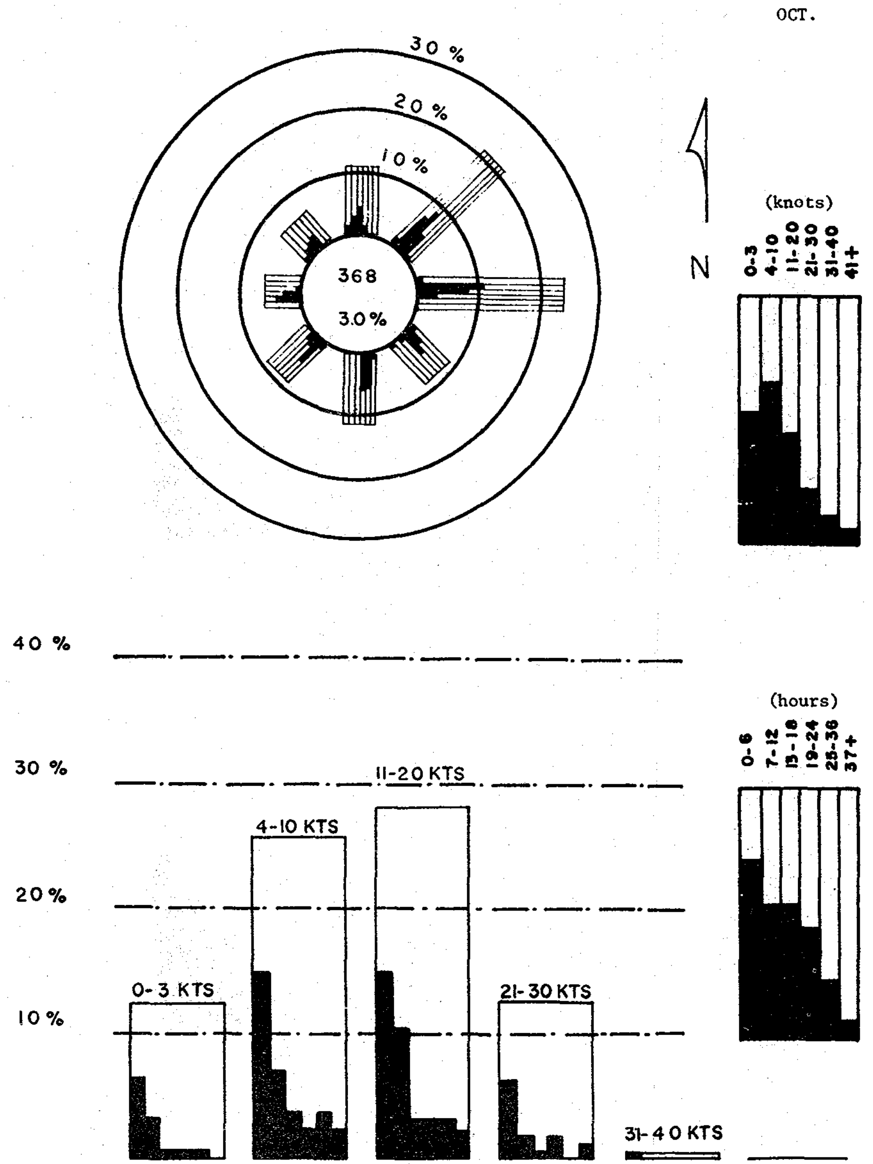
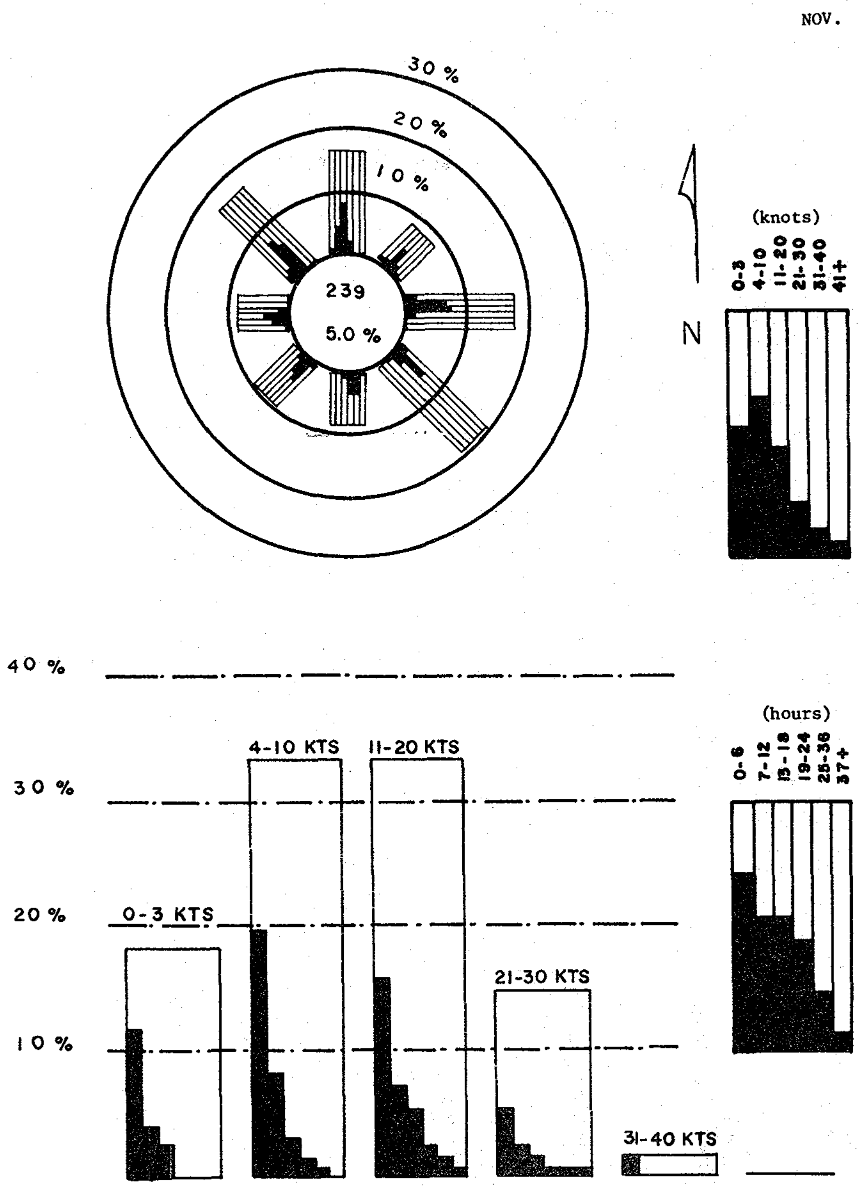
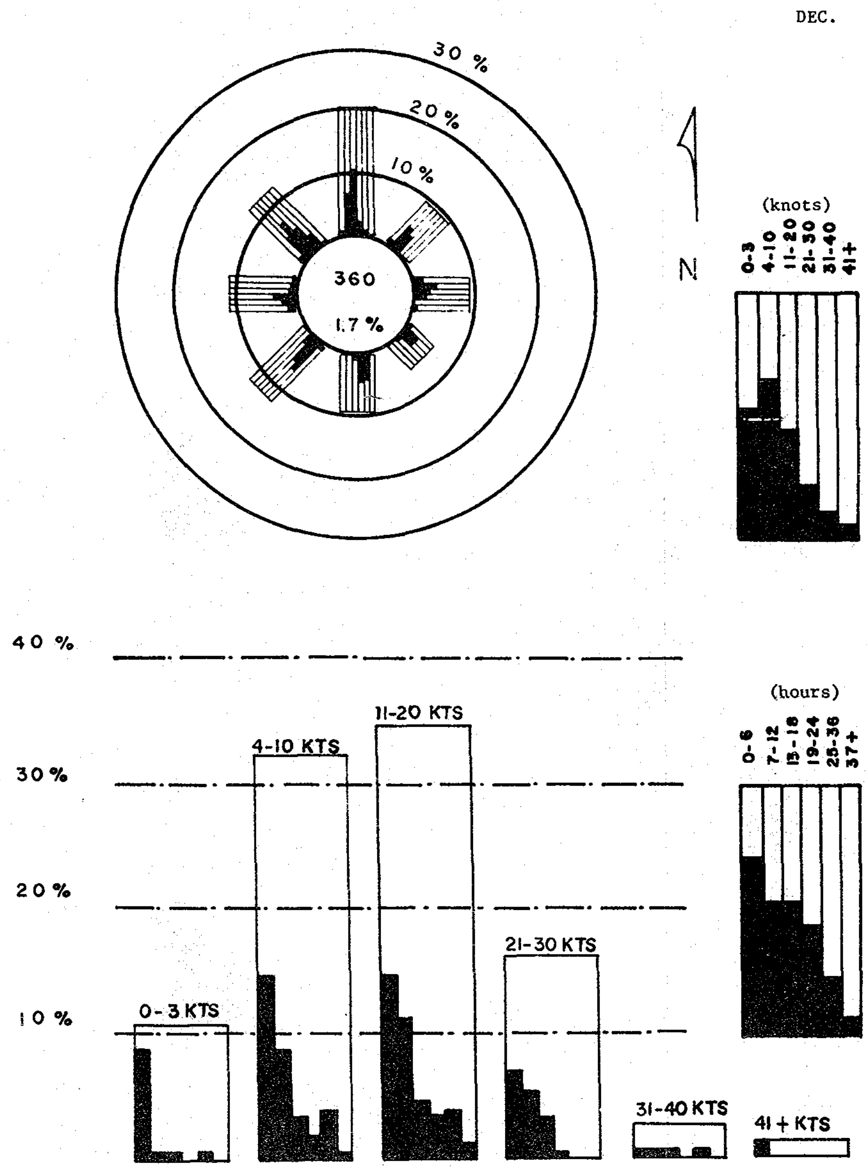


Figure 16b Monthly Wind Rose and Speed Duration Diagram at Five Fathom Bank, Delaware





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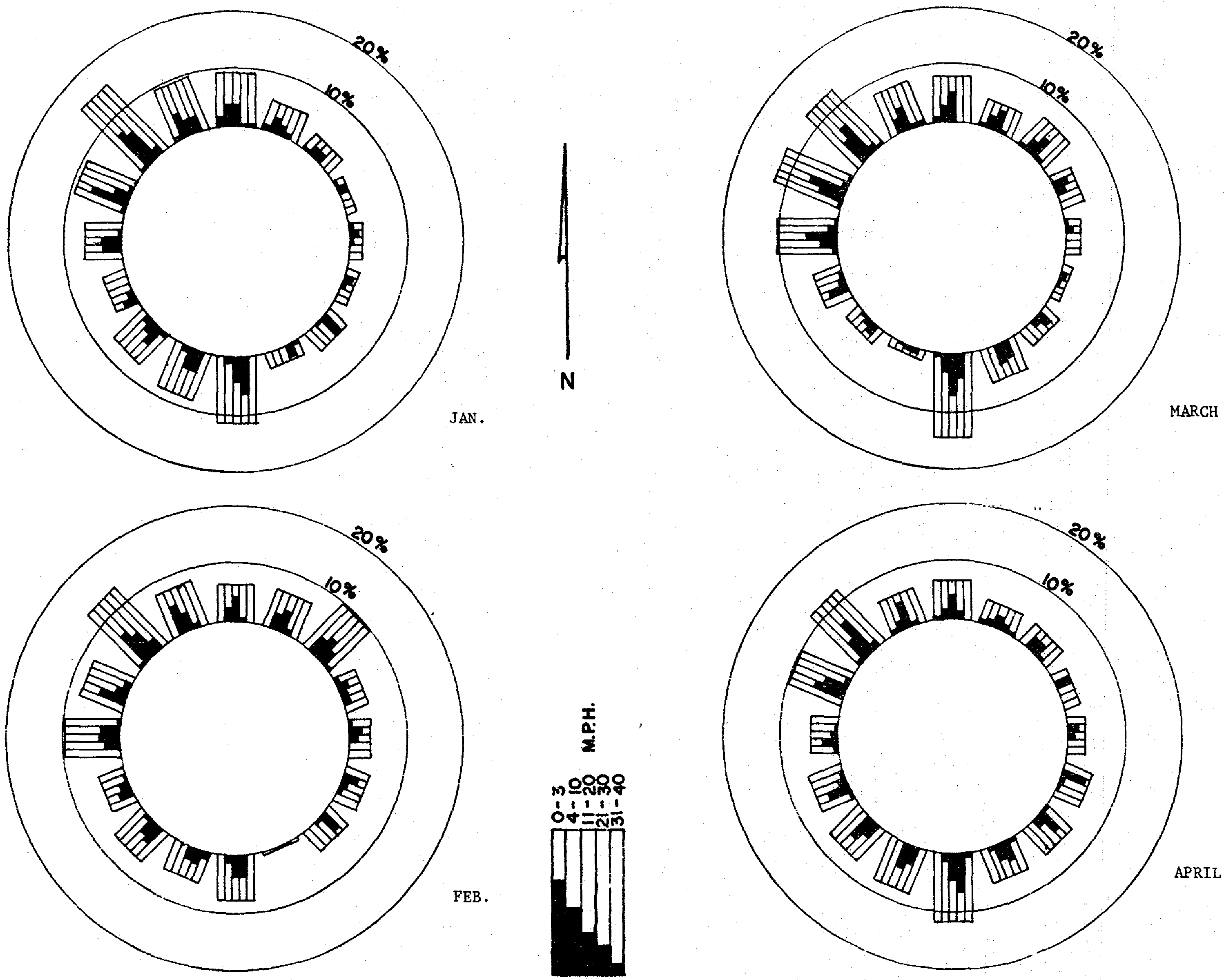
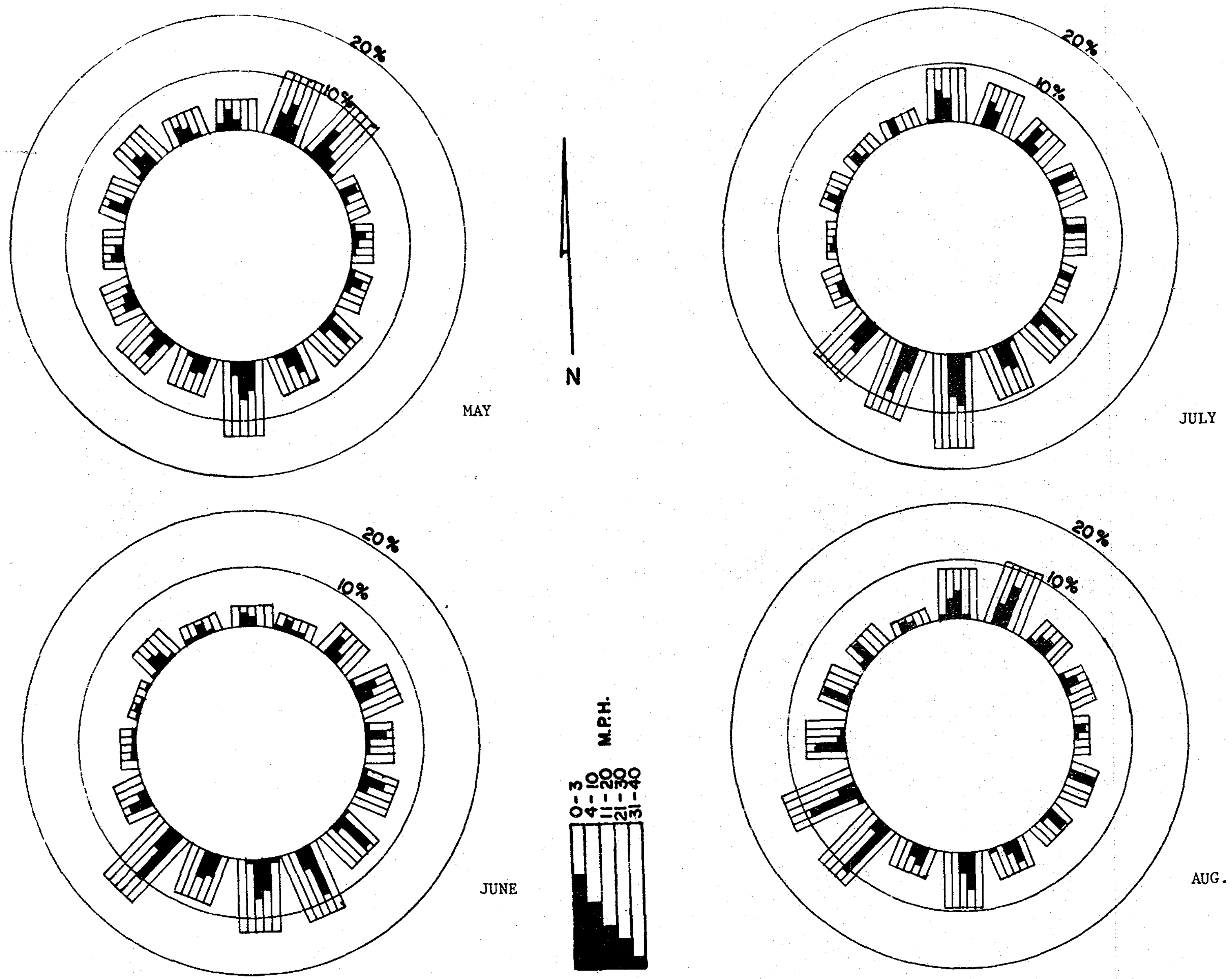


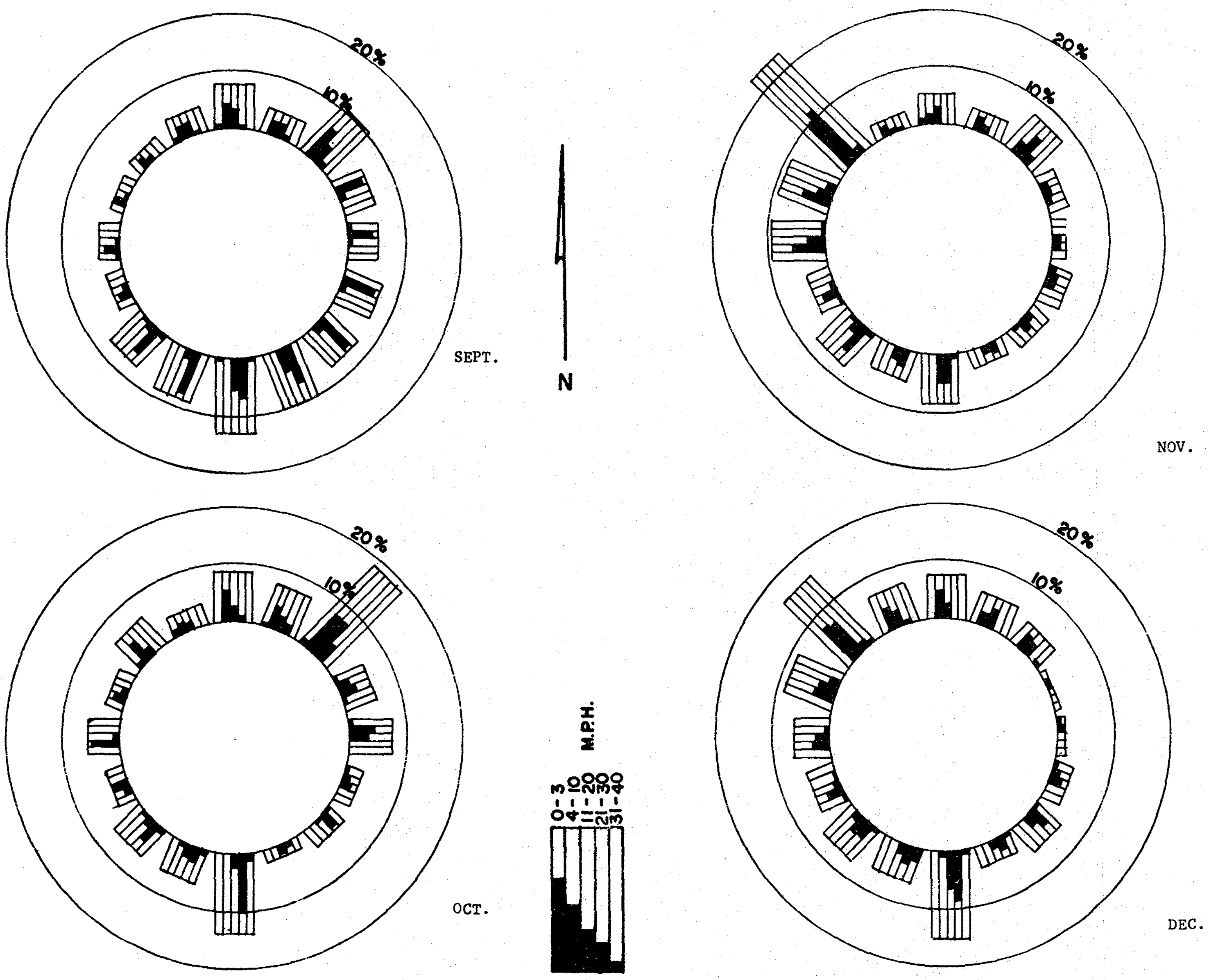
PERCENTAGE FREQUENCY OF WIND DIRECTION BY SPEED INDIAN RIVER INLET, DELAWARE

Figure 16b



PERCENTAGE FREQUENCY OF WIND DIRECTION BY SPEED INDIAN RIVER INLET, DELAWARE

Figure 16b



PERCENTAGE FREQUENCY OF WIND DIRECTION BY SPEED INDIAN RIVER INLET, DELAWARE

Figure 16b

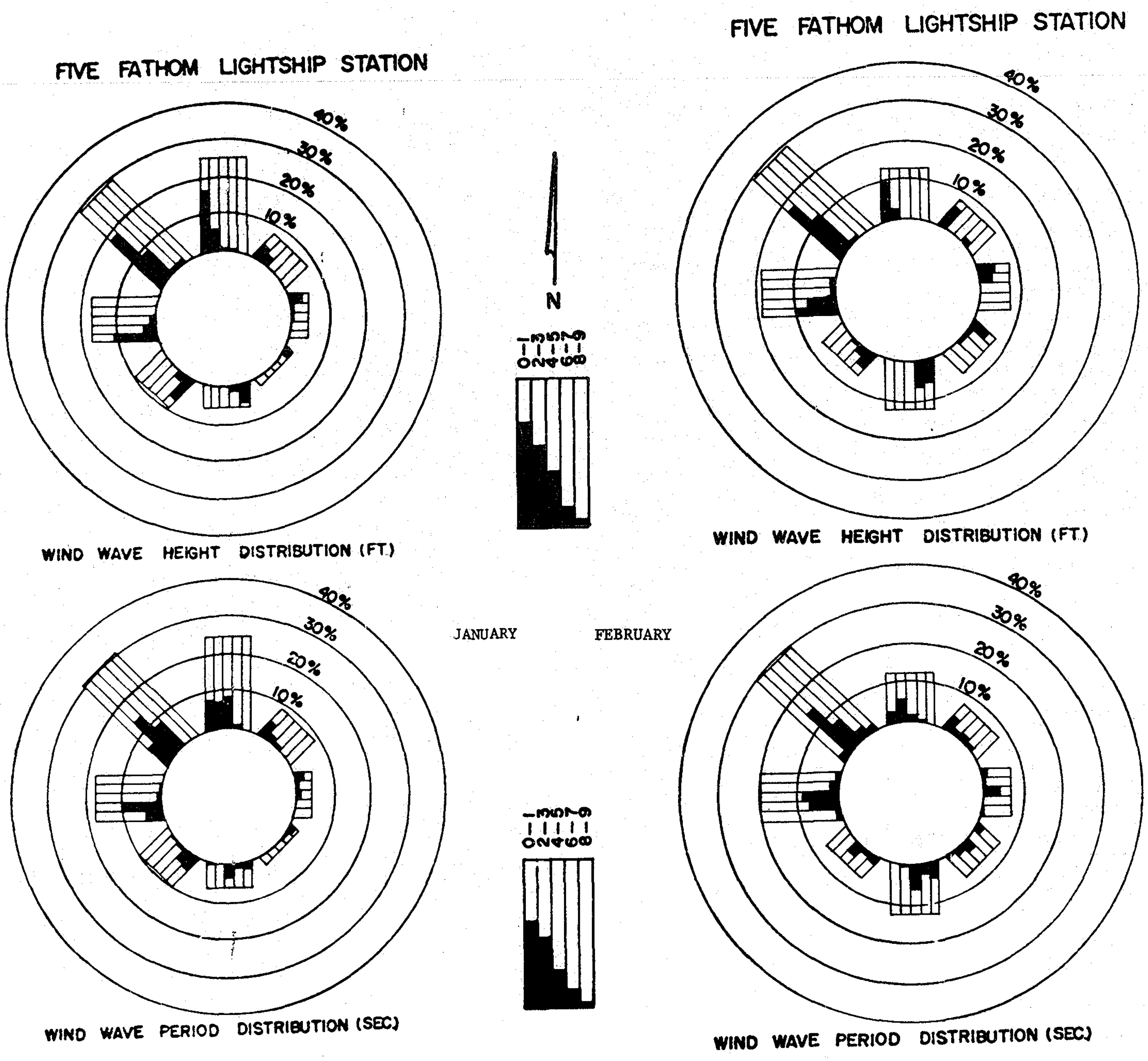


Figure 17 Monthly Wave Height and Wave Period Distributions at Five Fathom Light Station, Delaware

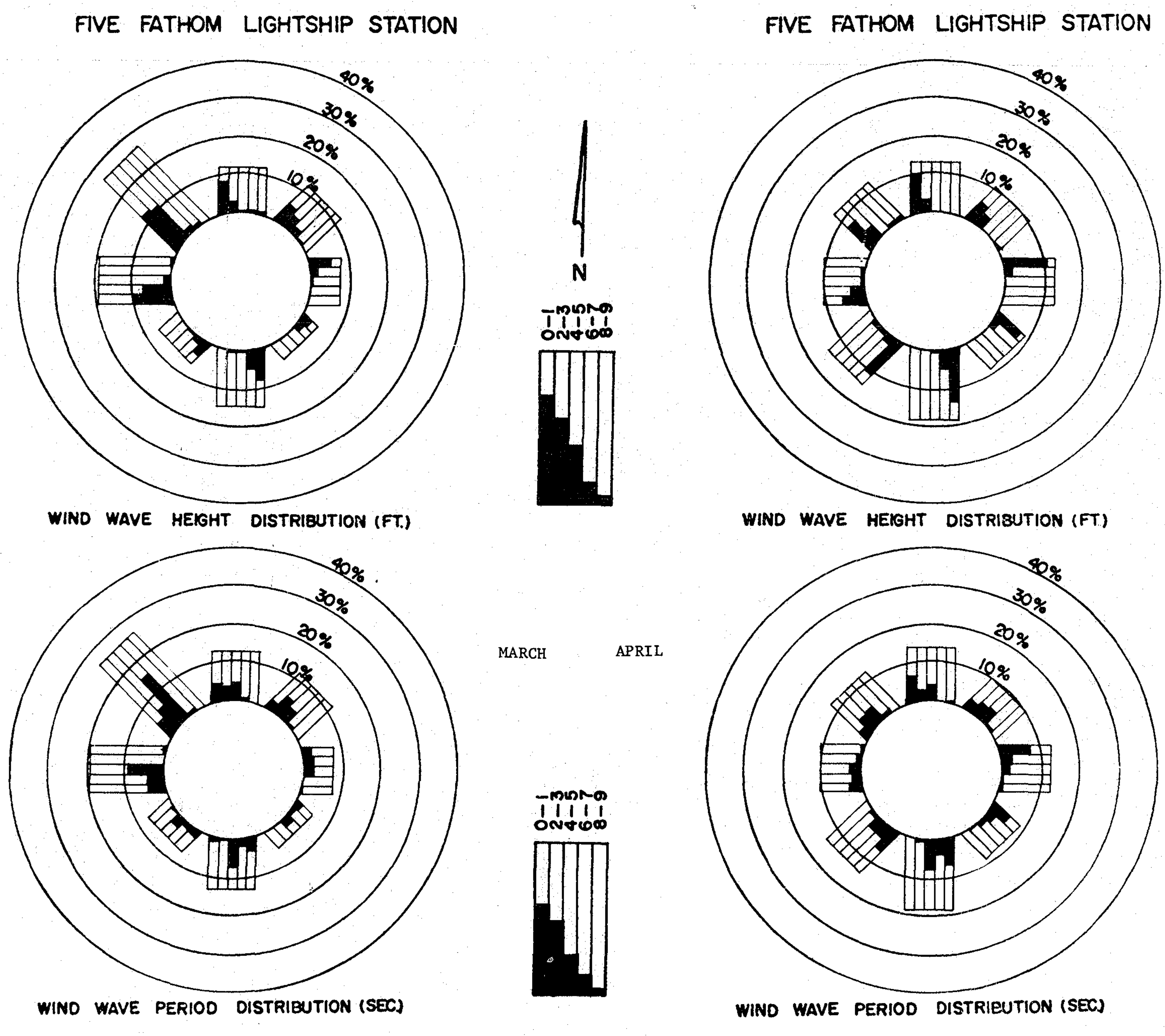


Figure 17 Monthly Wave Height and Wave Period Distributions at Five Fathom Light Station, Delaware

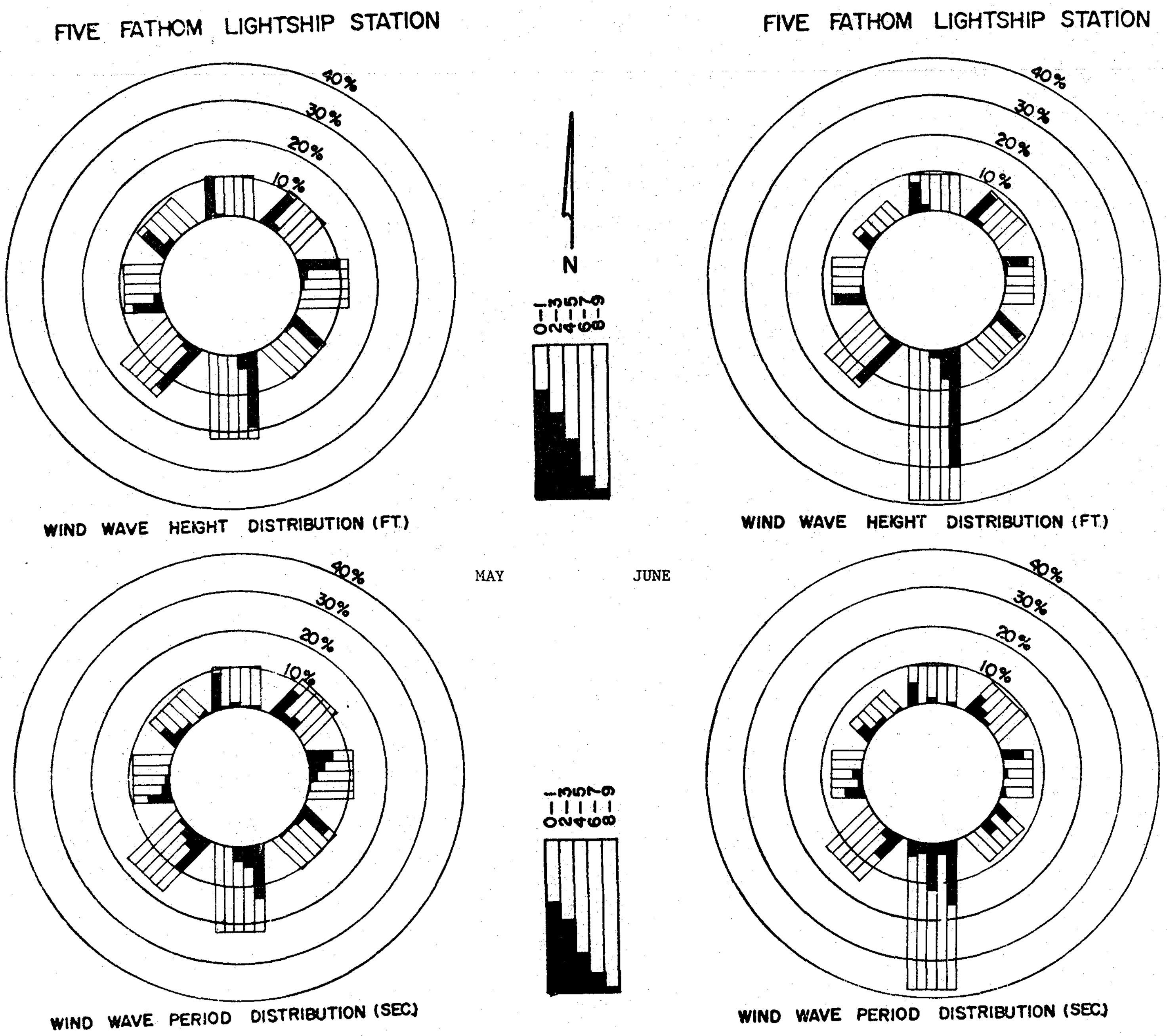
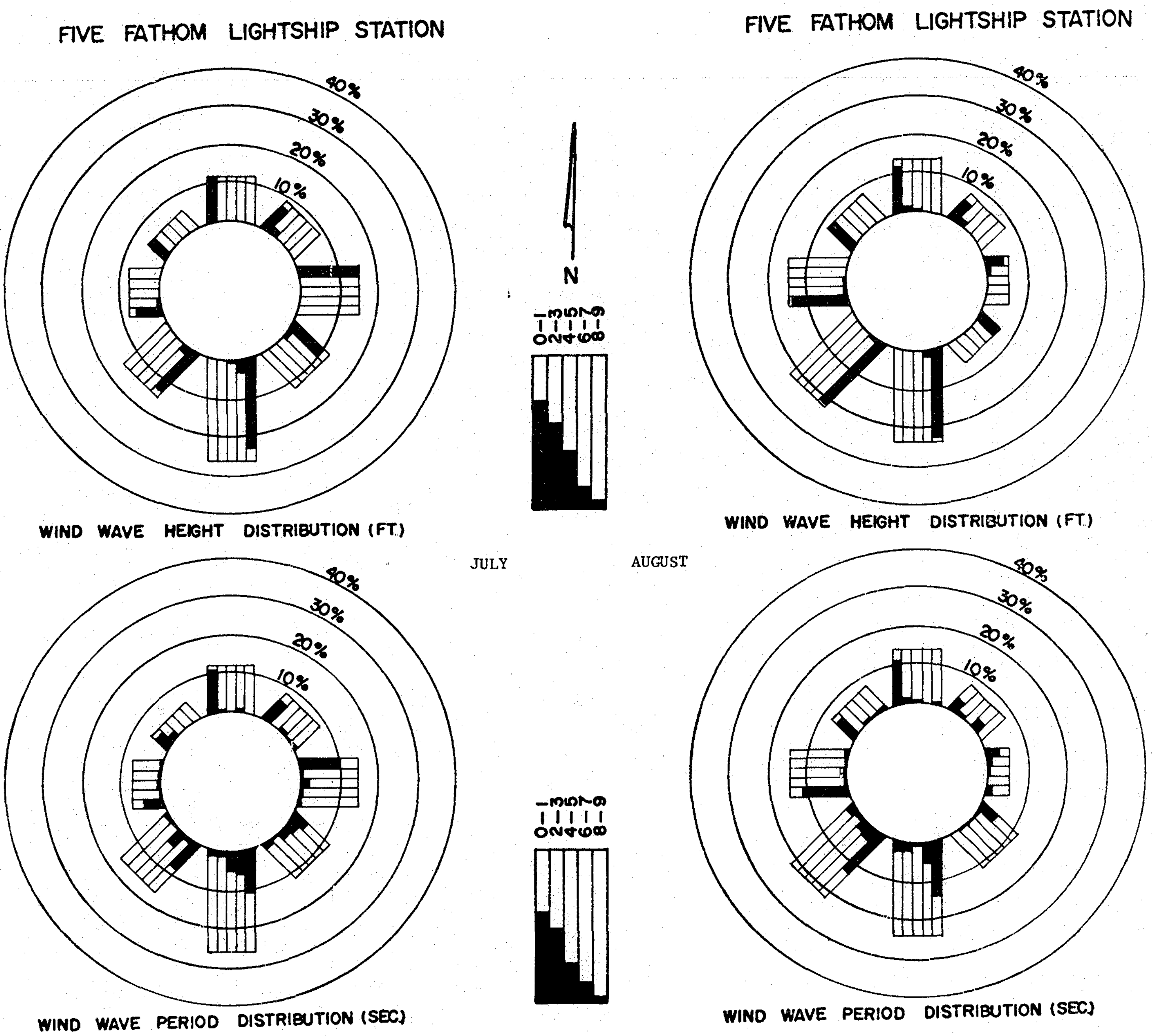


Figure 17 Monthly Wave Height and Wave Period Distributions at Five Fathom Light Station, Delaware



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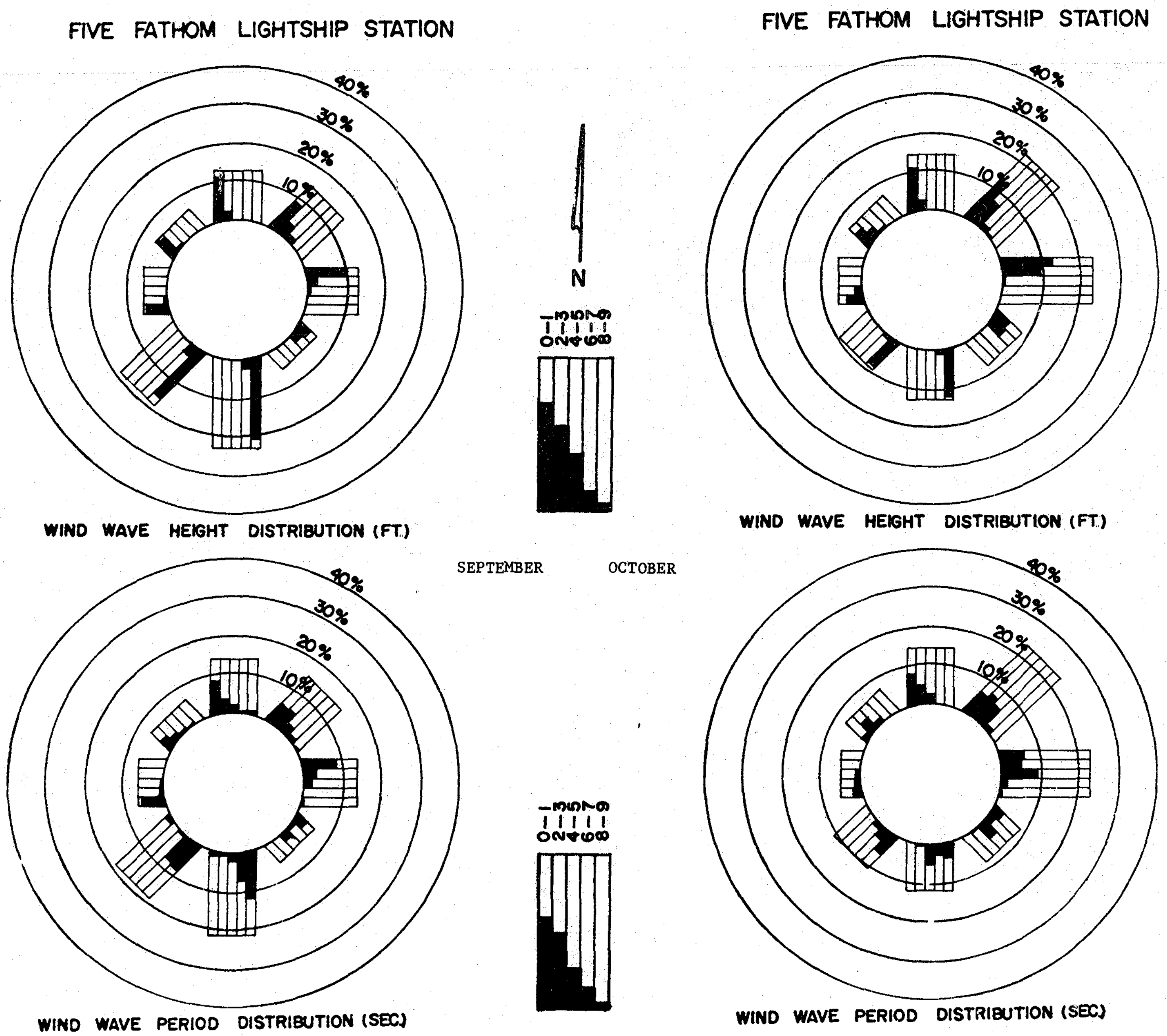

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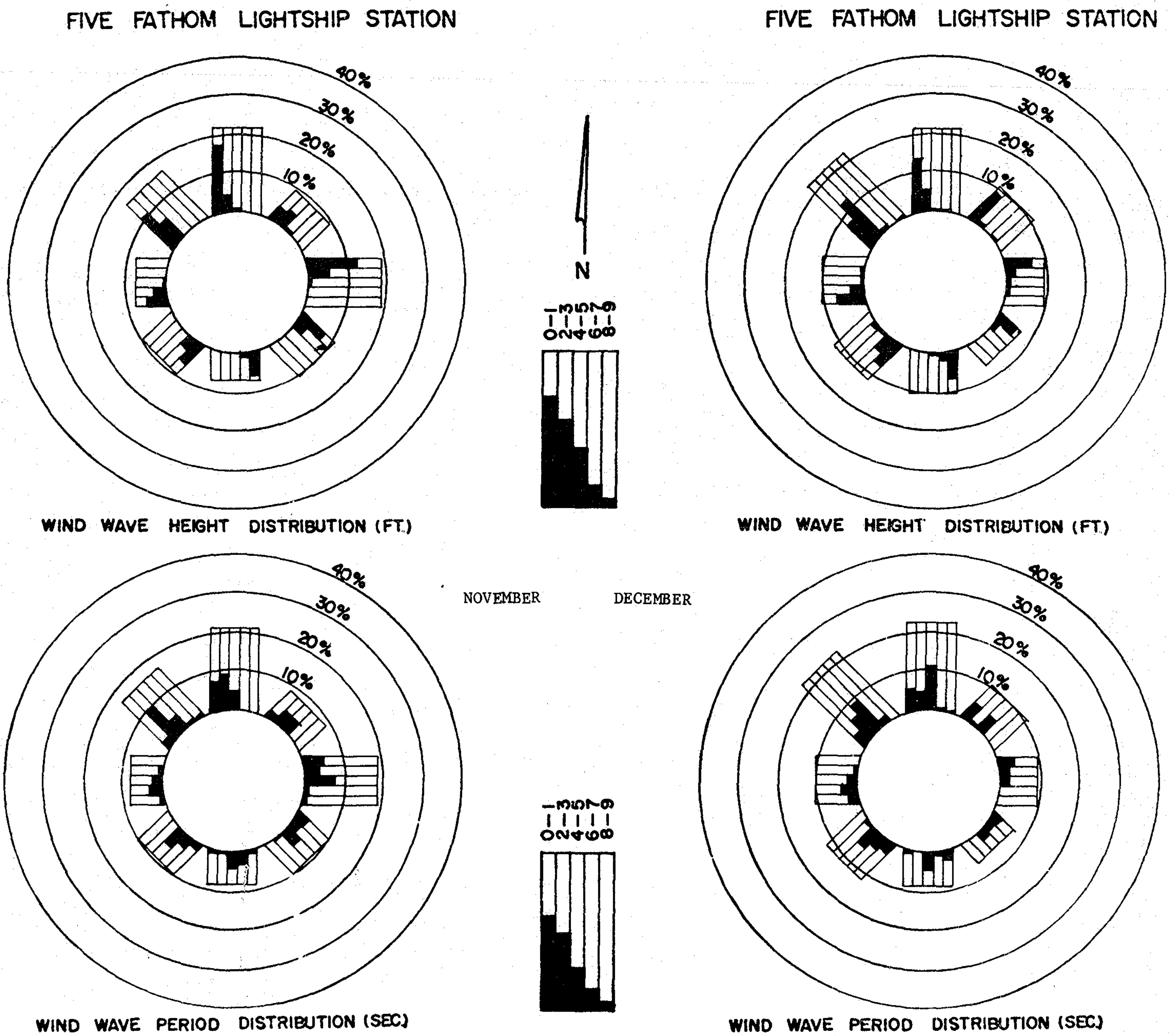


Figure 17 Monthly Wave Height and Wave Period Distributions at Five Fathom Light Station, Delaware

Swell (Direction by Height)		Swell (Direction by Period)	
Code	Actual	Code	Actual
0-1	1-1½	0-1	0-7 sec.
2-3	3-5	2-3	8-11
4-5	6½-8	4-5	12-15
6-7	4½-11	6-7	16-19
8-9	13-14	8-9	20+

Code for Swell-Height and Direction

for Figure 18 (pages 79-84)

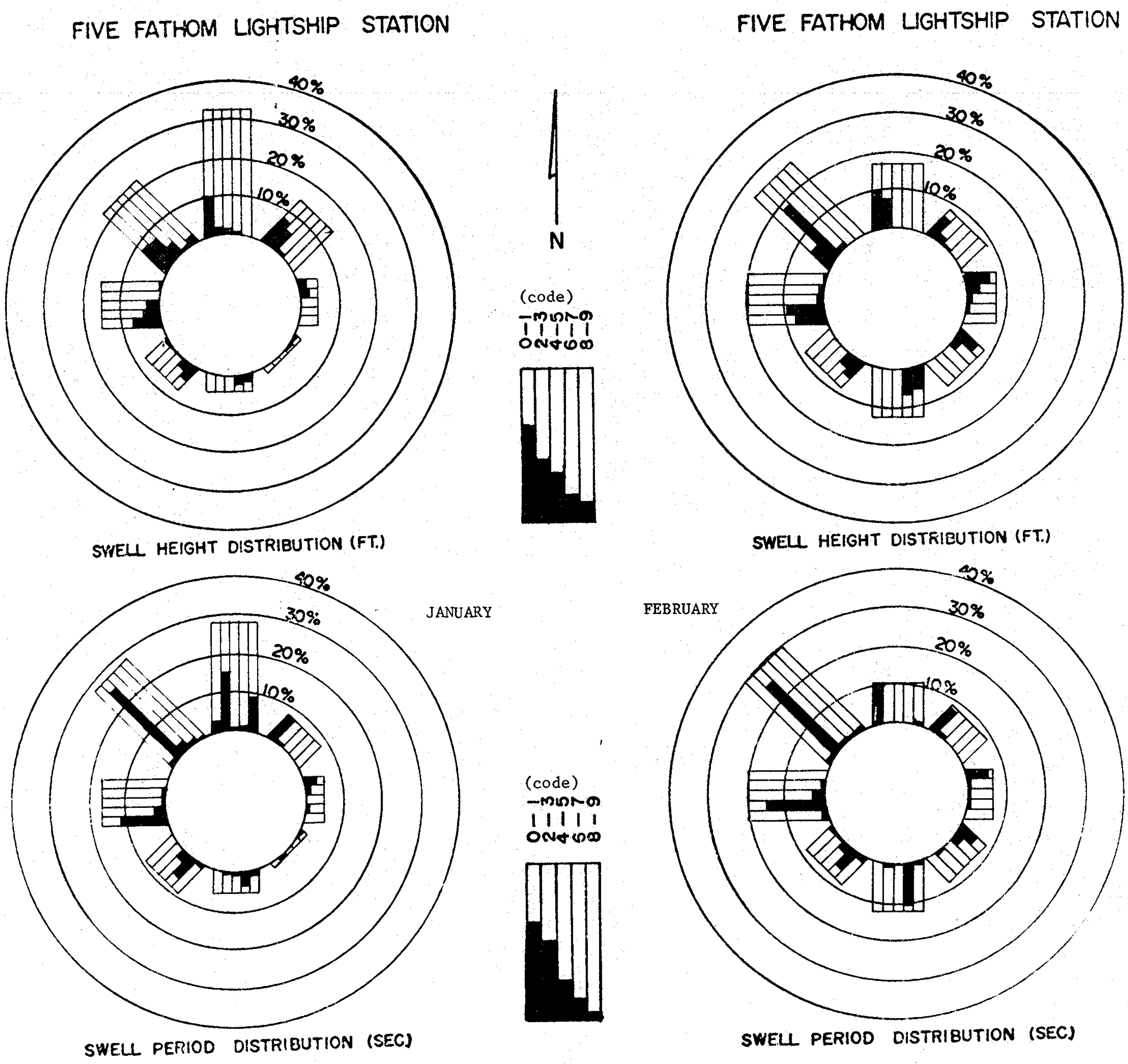


Figure 18 Monthly Swell Height and Swell Period Distribution at Five Fathom Light Station, Delaware

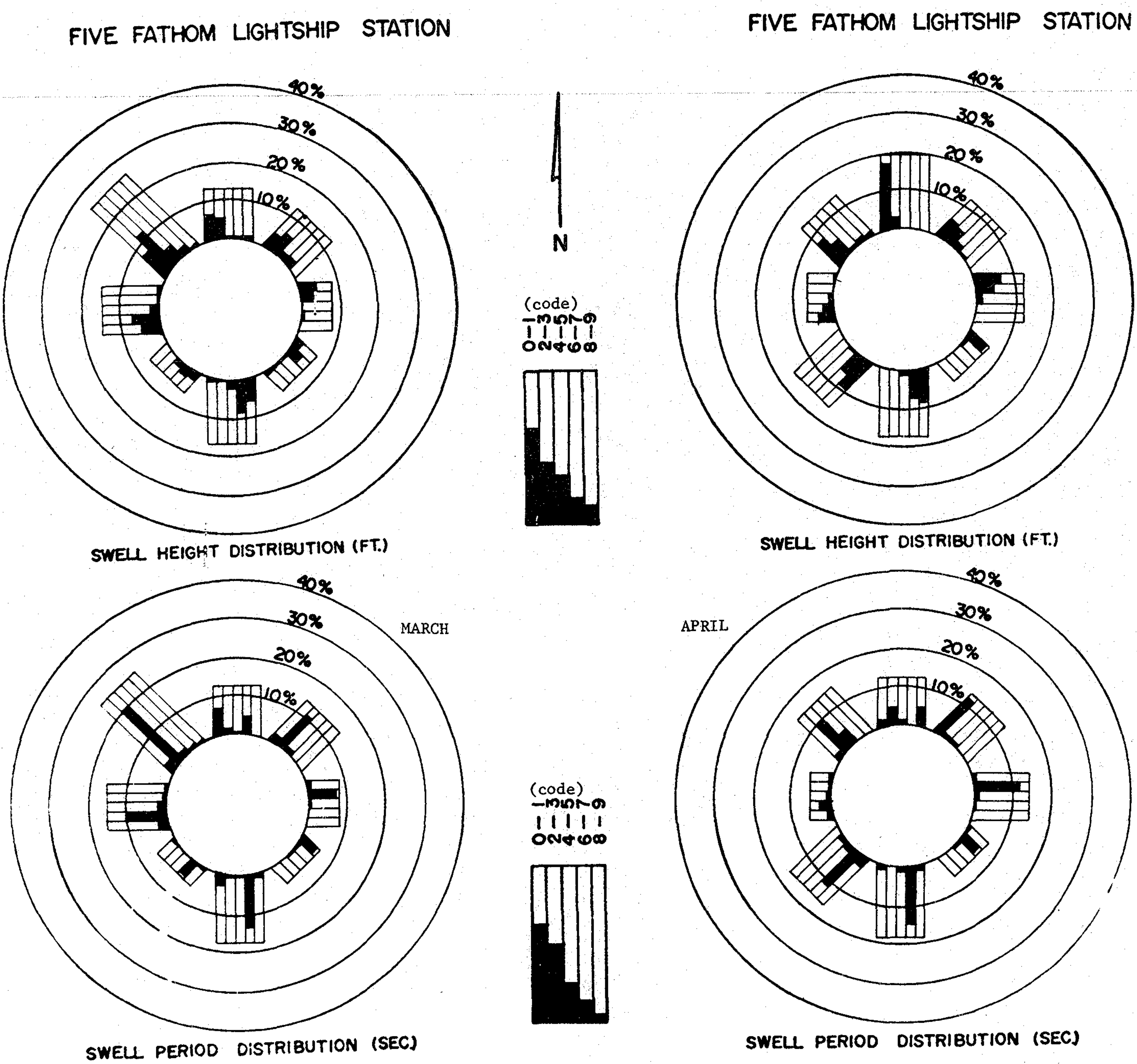


Figure 18 Monthly Swell Height and Swell Period Distribution at Five Fathom Light Station, Delaware

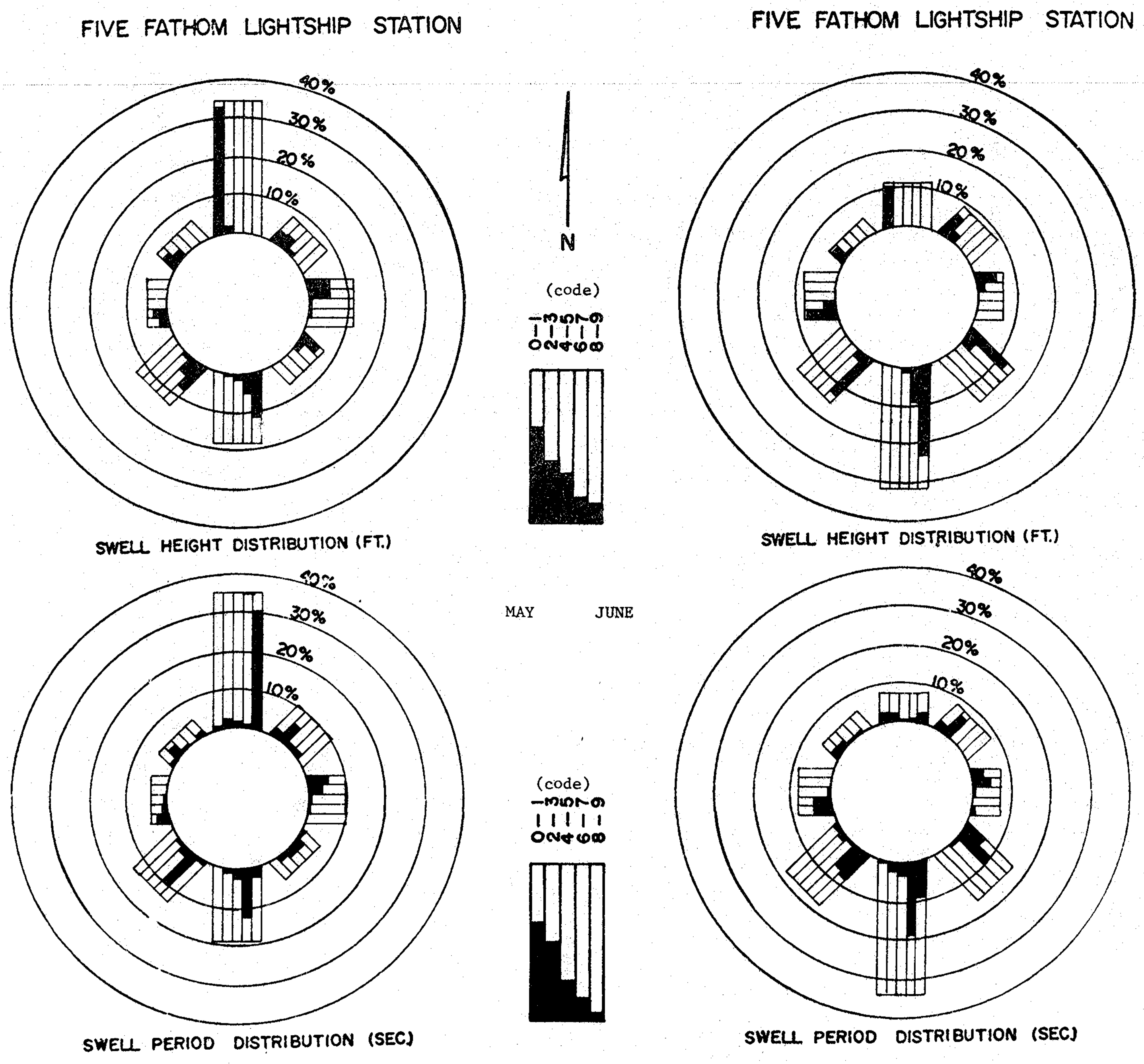
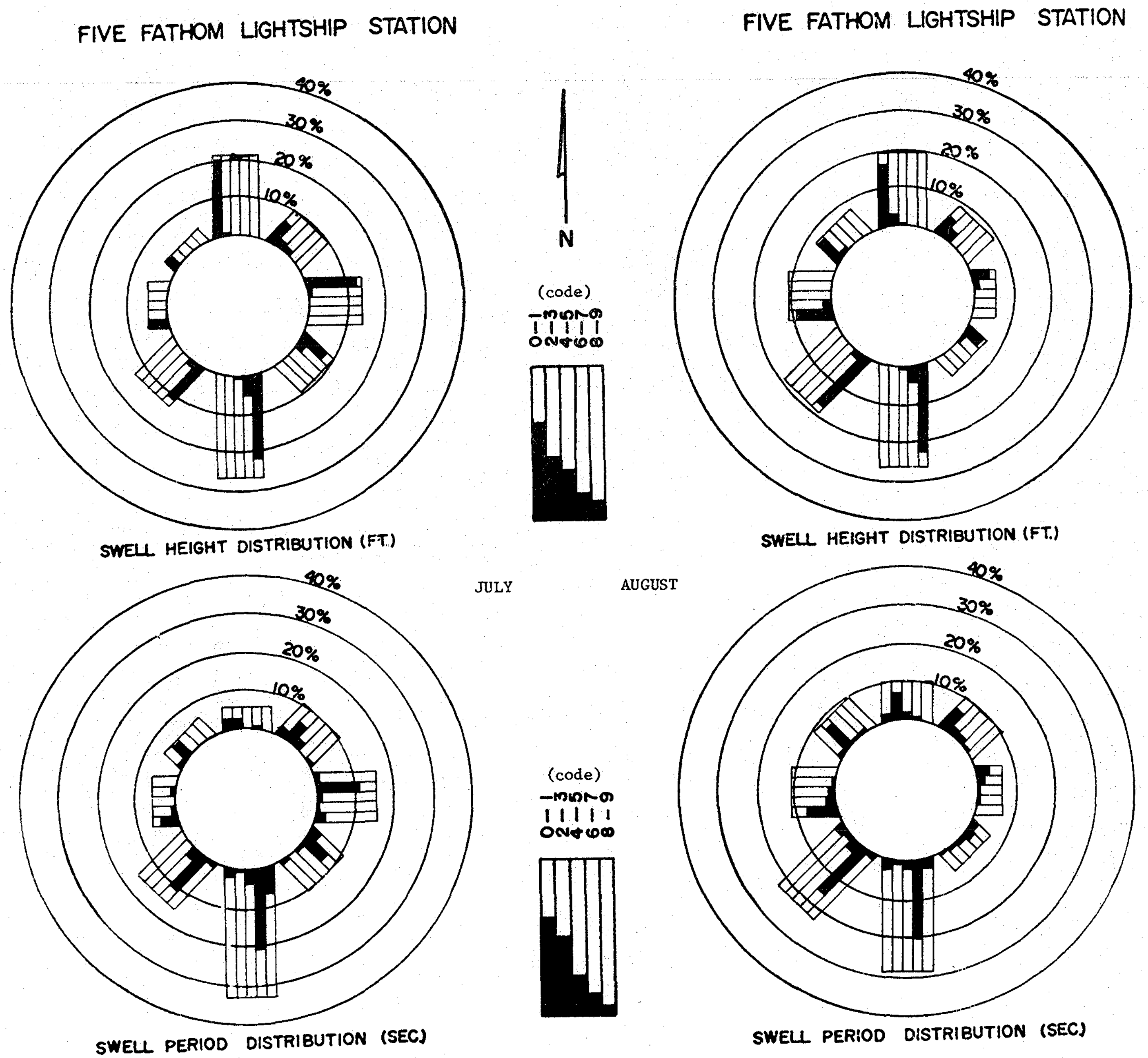


Figure 18 Monthly Swell Height and Swell Period Distribution at Five Fathom Light Station, Delaware



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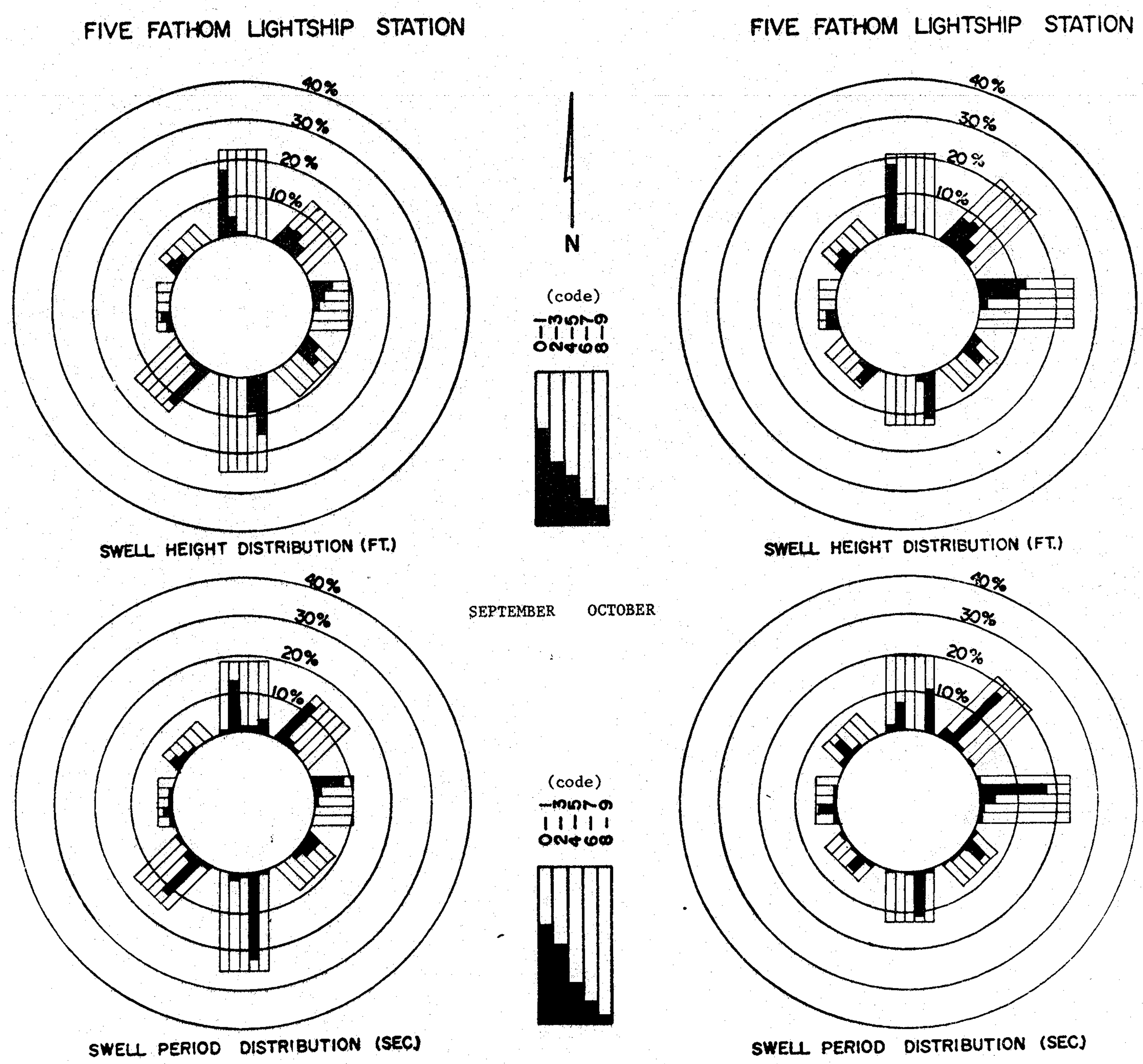

Figure 18 Monthly Swell Height and Swell Period Distribution at Five Fathom Light Station, Delaware

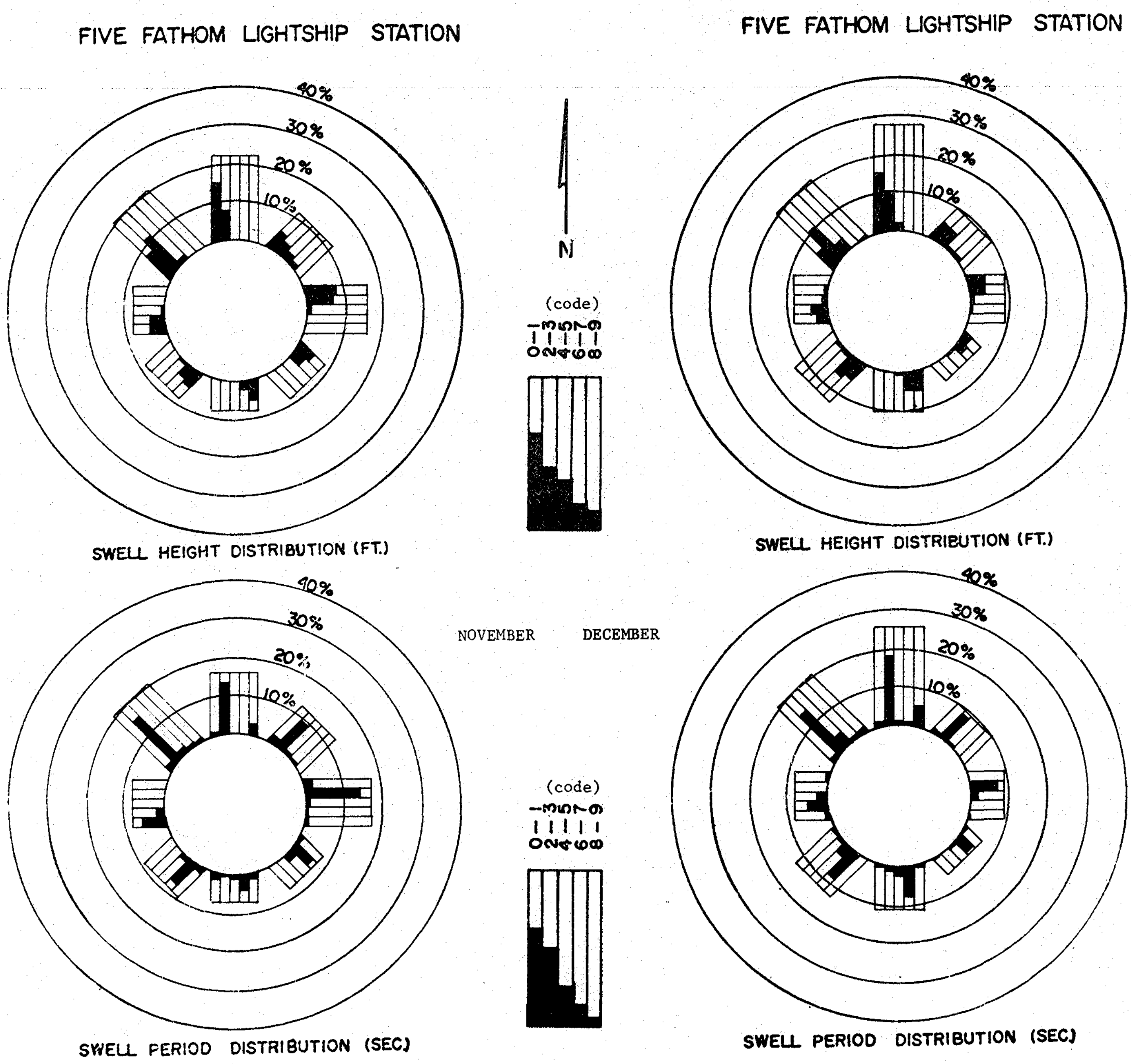

Figure 18 Monthly Swell Height and Swell Period Distribution at Five Fathom Light Station, Delaware

Table X

Average percentage frequency of occurrence of wave height direction groups at 38°55.9'N, 75°10.3'W: Delaware Bay.

(From Maurer, Don, and Hsiang Wang, 1973. Environmental vulnerability of the Delaware Bay area to supertanker accommodation, Vol. III. Draft Report submitted to The Council on Environmental Quality.)

TABLE Xa - JANUARY

Direction	Significant Wave Height Groups (Ft.) 0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-15	15 Plus	Total
N	15	3	2	0	0	0	0	20
NE	6	2	0	0	0	0	0	8
E	3	1	0	0	0	0	0	4
SE	3	1	0	0	0	0	0	4
S	7	3	0	0	0	0	0	10
SW	11	3	0	0	0	0	0	14
W	14	3	0	0	0	0	0	17
NW	10	10	3	0	0	0	0	23
Total	69	26	5	0	0	0	0	100

TABLE Xb - FEBRUARY

Direction	Significant Wave Height Groups (Ft.) 0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-15	15 Plus	Total
N	13	3	2	1	0	0	0	19
NE	5	2	0	0	0	0	0	7
E	5	1	0	0	0	0	0	6
SE	3	1	0	0	0	0	0	4
S	9	3	0	0	0	0	0	12
SW	10	2	0	0	0	0	0	12
W	14	3	0	0	0	0	0	17
NW	10	11	2	0	0	0	0	23
Total	69	26	4	1	0	0	0	100

TABLE Xc - MARCH

Direction	Significant Wave Height Groups (Ft.) 0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-15	15 Plus	Total
N	13	2	2	0	0	0	0	17
NE	8	1	0	0	0	0	0	9
E	5	1	0	0	0	0	0	6
SE	4	2	0	0	0	0	0	6
S	9	4	0	0	0	0	0	13
SW	10	3	0	0	0	0	0	13
W	13	3	0	0	0	0	0	16
NW	9	9	2	0	0	0	0	20
Total	71	25	4	0	0	0	0	100

TABLE Xd - APRIL

Direction	Significant Wave Height Groups (Ft.) 0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-15	15 Plus	Total
N	13	2	2	0	0	0	0	17
NE	9	2	0	0	0	0	0	11
E	5	1	0	0	0	0	0	6
SE	3	2	0	0	0	0	0	5
S	14	5	0	0	0	0	0	19
SW	13	3	0	0	0	0	0	16
W	12	1	0	0	0	0	0	13
NW	8	5	0	0	0	0	0	13
Total	77	21	2	0	0	0	0	100

TABLE Xe - MAY

Direction	Significant Wave Height Groups (Ft.) 0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-15	15 Plus	Total
N	11	2	1	0	0	0	0	14
NE	9	2	0	0	0	0	0	11
E	7	2	0	0	0	0	0	9
SE	5	2	0	0	0	0	0	7
S	17	3	0	0	0	0	0	20
SW	16	1	0	0	0	0	0	17
W	13	0	0	0	0	0	0	13
NW	8	1	0	0	0	0	0	9
Total	86	13	1	0	0	0	0	100

TABLE Xf - JUNE

Direction	Significant Wave Height Groups (Ft.) 0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-15	15 Plus	Total
N	9	1	0	0	0	0	0	10
NE	12	1	0	0	0	0	0	13
E	7	2	0	0	0	0	0	9
SE	6	2	1	0	0	0	0	9
S	18	2	0	0	0	0	0	20
SW	19	1	0	0	0	0	0	20
W	12	0	0	0	0	0	0	12
NW	6	1	0	0	0	0	0	7
Total	89	10	1	0	0	0	0	100

TABLE Xg - JULY

Direction	Significant Wave Height Groups (Ft.) 0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-15	15 Plus	Total
N	8	0	0	0	0	0	0	8
NE	10	2	0	0	0	0	0	12
E	6	1	0	0	0	0	0	7
SE	5	1	0	0	0	0	0	6
S	21	2	0	0	0	0	0	23
SW	24	2	0	0	0	0	0	26
W	12	0	0	0	0	0	0	12
NW	5	1	0	0	0	0	0	6
Total	91	9	0	0	0	0	0	100

TABLE Xh - AUGUST

Direction	Significant Wave Height Groups (Ft.) 0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-15	15 Plus	Total
N	13	1	0	0	0	0	0	14
NE	14	1	0	0	0	0	0	15
E	9	1	0	0	0	0	0	10
SE	7	2	0	0	0	0	0	9
S	16	4	0	0	0	0	0	20
SW	16	1	0	0	0	0	0	17
W	9	0	0	0	0	0	0	9
NW	5	1	0	0	0	0	0	6
Total	89	11	0	0	0	0	0	100

AVERAGE PERCENTAGE FREQUENCY OF OCCURRENCE OF WAVE HEIGHT DIRECTION GROUPS AT 38°55.9'N, 75°10.3'W: DELAWARE BAY

TABLE Xi - SEPTEMBER

Direction	Significant Wave Height Groups (Ft.) 0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-15	15 Plus	Total
N	14	2	1	0	0	0	0	17
NE	15	5	0	0	0	0	0	20
E	12	2	0	0	0	0	0	14
SE	5	2	0	0	0	0	0	7
S	12	1	0	0	0	0	0	13
SW	12	1	0	0	0	0	0	13
W	7	0	0	0	0	0	0	7
NW	6	3	0	0	0	0	0	9
Total	83	16	1	0	0	0	0	100

TABLE Xj - OCTOBER

Direction	Significant Wave Height Groups (Ft.) 0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-15	15 Plus	Total
N	16	3	1	0	0	0	0	20
NE	11	4	0	0	0	0	0	15
E	8	2	0	0	0	0	0	10
SE	5	2	0	0	0	0	0	7
S	9	3	0	0	0	0	0	12
SW	9	1	0	0	0	0	0	10
W	10	1	0	0	0	0	0	11
NW	10	5	0	0	0	0	0	15
Total	78	21	1	0	0	0	0	100

TABLE Xk - NOVEMBER

Direction	Significant Wave Height Groups (Ft.) 0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-15	15 Plus	Total
N	15	2	1	0	0	0	0	18
NE	9	2	0	0	0	0	0	11
E	4	1	0	0	0	0	0	5
SE	3	2	0	0	0	0	0	5
S	9	3	0	0	0	0	0	12
SW	10	2	0	0	0	0	0	12
W	15	2	0	0	0	0	0	17
NW	11	8	1	0	0	0	0	20
Total	76	22	2	0	0	0	0	100

TABLE Xl - DECEMBER

Direction	Significant Wave Height Groups (Ft.) 0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-15	15 Plus	Total
N	16	3	1	0	0	0	0	20
NE	6	1	0	0	0	0	0	7
E	3	1	0	0	0	0	0	4
SE	3	1	0	0	0	0	0	4
S	8	2	0	0	0	0	0	10
SW	10	2	0	0	0	0	0	12
W	17	2	0	0	0	0	0	19
NW	13	9	2	0	0	0	0	24
Total	76	21	3	0	0	0	0	100

AVERAGE PERCENTAGE FREQUENCY OF OCCURRENCE OF WAVE HEIGHT
DIRECTION GROUPS AT 38°55.9'N, 75°10.3'W: DELAWARE BAY

TABLE XI

EXTREME WINDS

DELAWARE BAY AREA

Mean Recurrence Interval	5 yr.	10 yr.	25 yr.	50 yr.
Maximum Sustained Wind	63 kts.	70 kts.	80 kts.	92 kts.

OFFSHORE DELAWARE BAY AREA

Mean Recurrence Interval	5 yr.	10 yr.	25 yr.	50 yr.
Maximum Sustained Wind	71 kts.	80 kts.	92 kts.	100 kts.

EXTREME WAVES

OFFSHORE DELAWARE BAY AREA

Mean Recurrence Interval	5 yr.	10 yr.	25 yr.	50 yr.
Max. Significant Wave Ht.	37 ft.	41 f..	47 ft.	53 ft.
Extreme Wave Height	60 ft.	70 ft.	85 ft.	95 ft.

DELAWARE BAY AREA

Mean Recurrence Interval	5 yr.	10 yr.	25 yr.	50 yr.
Max. Significant Wave Ht.	11 ft.	14 ft.	17 ft.	22 ft.
Extreme Wave Height	20 ft.	25 ft.	30 ft.	35 ft.

Statistical Estimates of Extremes of Winds and Waves
(from Brower, *et al.* 1972)

ENVIRONMENTAL DATA SUMMARY (PART 1)

AREA: Delaware Bay

ENVIRONMENTAL FACTORS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
WIND SPEED (KNOTS)													
01% ≤	2	2	2	2	2	2	1	1	1	2	2	3	2
Mean	11.1	11.2	11.3	10.4	9.0	8.3	7.9	7.8	8.5	9.2	10.2	10.3	9.6
99% ≤	37	35	37	32	25	24	22	22	24	33	36	36	30
Maximum observed (1871 - 1971)	Winds near 90 knots have probably occurred over Delaware Bay												
≥ 34 Knots (% freq.)	2.7	2.5	1.8	0.8	0.2	0.1	0.2	0.3	0.5	1.0	1.4	1.8	1.1
≥ 41 Knots (% freq.)	0.7	0.7	0.5	0.3	0.1	0.1	0.1	0.1	0.1	0.2	0.4	0.5	0.3
Prevailing direction	NW	NW	NW	NW	SW	SW	SW	SW	S	N	NW	W	W
WAVES (FEET)													
01% ≤	0	0	0	0	0	0	0	0	0	0	0	0	9
Mean	3	3	3	2	2	2	1	1	2	3	3	3	2
99% ≤	11	10	10	9	9	8	7	6	8	9	10	10	9
≥ 12 Feet (% freq.)	1.0	+	+	+	+	0.0	0.0	+	+	+	+	+	0.1
≥ 20 Feet (% freq.)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	+	0.0	0.0	0.0	+
VISIBILITY (% FREQ.)													
Visibility <½ N. mile	2.0	2.1	1.9	2.6	3.0	2.7	1.0	0.7	0.8	1.2	1.5	1.9	1.8
Visibility <1 N. mile	3.8	3.9	3.3	3.7	4.1	3.6	1.6	1.4	1.5	2.3	2.4	2.2	2.9
Visibility <2 N. miles	6.7	6.8	5.9	5.9	5.9	5.5	3.1	3.3	3.6	4.2	4.5	6.0	5.6
Visibility <5 N. miles	17.3	18.0	16.1	15.2	14.9	17.7	14.5	16.9	15.5	14.4	14.8	17.4	16.1
Visibility <10 N. miles	48.3	49.2	46.4	49.7	48.8	56.8	55.4	57.1	50.4	41.1	45.3	47.5	50.0

\+ = less than 0.05%

Table XII Environmental data summary; Delaware Bay area.

ENVIRONMENTAL DATA SUMMARY (PART 2)

AREA: Delaware Bay

ENVIRONMENTAL FACTORS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
FOG													
Occurrence of fog (% freq.)	7.4	11.2	11.1	12.4	13.0	13.1	9.7	10.3	10.8	10.3	9.2	10.6	11.1
Mean number of hours operation of fog signals *	57	69	53	35	32	25	17	18	16	22	31	53	428
Maximum number of hours operation of fog signals for any year (annual only)*													840
WEATHER & CLOUDS (% FREQ.)													
Precipitation	11.3	11.1	11.0	9.1	7.3	5.6	4.8	5.3	6.3	6.4	8.5	10.0	8.1
Freezing precipitation	0.5	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Frozen precipitation	3.4	2.8	1.9	0.3	0.0	+	0.0	0.0	0.0	0.0	0.4	2.0	0.9
Thunder & lightning	0.2	0.1	0.2	0.5	1.2	1.3	1.8	1.6	0.7	0.2	0.3	0.1	0.7
Sky ≤2/8	34.4	35.2	39.2	36.3	36.2	37.9	37.1	38.0	43.2	46.1	38.5	34.5	38.2
Sky overcast (8/8)	38.7	37.6	34.1	33.4	30.8	25.1	23.2	23.8	25.1	25.3	30.1	35.3	30.1
Sky obscured	5.1	6.6	8.2	9.6	12.4	11.4	4.7	3.1	2.5	2.2	2.1	2.7	6.0
Low cloud overcast	26.0	23.9	19.7	17.5	16.1	12.5	10.5	11.9	13.3	13.7	17.3	21.3	17.0
Mean cloud cover (eighths)	4.9	5.0	4.8	4.8	4.8	4.5	4.6	4.5	4.2	3.9	4.7	4.9	4.6
AIR TEMPERATURE (°F)													
Minimum	-8	-7	7	12	25	37	46	40	32	23	11	0	-8
01% ≤	16	17	25	30	46	55	65	63	53	41	30	19	39
Mean	36.0	36.4	51.4	51.6	61.1	70.0	75.5	74.2	68.2	58.3	48.2	38.2	56.1
99% ≤	53	54	73	75	78	87	90	88	87	72	61	53	73
Maximum	78	76	87	89	99	106	104	101	100	91	85	75	106
≤ 32 °F (% freq.)	60.5	68.9	30.6	8.4	+	0.0	0.0	0.0	0.1	0.2	21.9	57.0	20.6
≥ 85 °F (% freq.)	0.0	0.0	0.2	0.3	0.7	19.8	28.0	20.3	10.0	0.3	+	0.0	6.6

* Mean of Miah Maull, Ship John and Delaware Bay Shoals fog signals

\+ = less than 0.05%

Table XII Continued.

ENVIRONMENTAL DATA SUMMARY (PART 3)

AREA: Delaware Bay

ENVIRONMENTAL FACTORS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
RELATIVE HUMIDITY (%)													
Mean	72	71	71	71	73	76	77	77	77	76	74	73	74
SEA TEMPERATURE (°F)													
Minimum	28	28	27	33	40	41	54	57	56	46	38	28	27
01% ≤	28	29	33	39	42	53	63	65	58	51	44	34	45
Mean	41.2	39.8	42.5	48.6	56.7	65.8	72.0	73.4	71.0	62.9	54.2	45.5	56.1
99% ≤	57	57	60	70	72	78	82	82	80	74	65	58	70
Maximum	80	78	76	80	84	88	90	88	90	84	82	80	90
SALINITY (‰)													
Minimum	20.6	21.6	21.6	20.6	20.8	20.0	25.5	22.2	25.4	23.0	22.6	22.4	20.0
Mean	29.7	29.8	29.5	29.2	29.6	30.0	30.8	30.8	30.7	30.7	30.5	30.0	30.1
Maximum	34.5	34.1	33.6	34.2	34.6	35.0	34.6	34.1	34.1	34.0	34.1	33.6	35.0
DENSITY (ρ)													
Mean (σ_t)*	22.0	22.1	21.9	21.7	22.1	22.4	22.9	22.8	22.7	22.8	22.7	22.3	22.4
SEA-LEVEL PRESSURE (mb)													
Minimum	977	972	971	981	991	992	977	976	985	993	979	979	971
01% ≤	993	988	992	994	1000	1001	1002	1002	1001	998	994	995	997
Mean	1019	1018	1016	1015	1016	1015	1016	1016	1019	1018	1018	1019	1017
99% ≤	1042	1041	1038	1035	1034	1032	1029	1030	1036	1034	1039	1039	1036
Maximum	1045	1044	1042	1040	1037	1038	1031	1041	1043	1040	1040	1043	1045

* $\sigma_t = (\rho - 1) \times 10^3$; $\rho =$ gm cm^{-3}

Table XII **Continued.**

ENVIRONMENTAL DATA SUMMARY (PART 1)

AREA: Offshore Delaware Bay

ENVIRONMENTAL FACTORS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
WIND SPEED (KNOTS)													
01% ≤	3	3	3	3	2	2	2	3	2	3	3	4	3
Mean	15.7	14.6	14.0	12.1	10.6	10.0	9.9	10.3	11.6	13.5	14.6	15.0	12.6
99% ≤	45	44	40	38	31	30	30	31	32	38	43	44	37
Maximum observed (1871 - 1971)	Winds in excess of 100 knots have been recorded in Hurricanes and Northeasters.												
≥ 34 Knots (% freq.)	4.6	3.0	3.2	1.3	0.5	0.2	0.4	0.6	0.6	2.2	2.3	2.9	1.8
≥ 41 Knots (% freq.)	1.1	1.1	1.0	0.1	0.1	0.1	0.2	0.3	0.1	0.8	1.1	1.2	0.6
Prevailing direction	NW	NW	NW	S	S	S	S	S	NE	N	NW	NW	SW
WAVES (FEET)													
01% ≤	0	0	0	1	0	0	0	0	0	0	1	0	$<\frac{1}{4}$
Mean	4	4	4	3	3	3	3	3	3	4	4	4	4
99% ≤	18	18	15	14	11	10	9	12	17	14	16	15	14
≥ 12 Feet (% freq.)	3.7	4.9	3.9	2.0	1.0	0.8	0.2	1.1	1.7	4.0	2.7	3.4	2.5
≥ 20 Feet (% freq.)	0.2	0.6	0.5	0.2	0.0	0.0	0.0	0.1	0.2	0.2	0.2	0.2	0.2
VISIBILITY (% FREQ.)													
Visibility $<\frac{1}{2}$ N. mile	1.9	2.4	3.1	6.1	6.2	4.6	1.1	0.5	0.6	0.9	0.5	1.2	2.4
Visibility <1 N. mile	2.8	3.6	4.1	6.9	7.8	5.3	1.7	0.7	0.9	1.5	0.6	1.6	3.1
Visibility <2 N. miles	3.5	4.7	4.7	8.4	9.9	6.9	2.5	1.4	1.3	2.2	1.1	2.2	4.1
Visibility <5 N. miles	8.2	9.1	11.4	14.9	16.6	15.8	10.3	8.6	4.8	6.2	4.1	5.9	9.7
Visibility <10 N. miles	32.9	32.8	37.1	39.5	43.4	48.0	44.8	43.0	28.9	27.1	24.7	26.2	36.2

\+ = less than 0.05%

Table XII Environmental data summary; Offshore Delaware Bay area.

ENVIRONMENTAL DATA SUMMARY (PART 2)

AREA: Offshore Delaware Bay

ENVIRONMENTAL FACTORS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
FOG													
Occurrence of fog (% freq.)	3.7	4.9	5.6	12.0	13.4	11.2	5.8	2.9	3.4	3.3	2.1	2.9	5.9
Mean number of hours operation of fog signals *	41	61	59	55	41	45	32	22	29	28	21	41	475
Maximum number of hours operation of fog signals for any year (annual only)*													1059
WEATHER & CLOUDS (% FREQ.)													
Precipitation	6.9	7.9	7.8	5.1	6.0	3.6	4.0	4.2	3.5	5.6	6.3	7.3	5.7
Freezing precipitation	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	+
Frozen precipitation	1.6	1.5	0.8	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.5
Thunder & lightning	0.2	0.2	0.2	0.4	1.0	1.5	1.9	1.2	0.7	0.1	0.3	0.0	0.6
Sky ≤2/8	37.2	38.3	43.5	44.3	45.3	42.3	36.4	40.2	42.9	43.4	39.0	35.4	40.7
Sky overcast (8/8)	31.6	29.1	24.9	23.8	21.5	19.2	21.4	18.8	19.2	25.7	24.6	27.9	24.0
Sky obscured	2.3	3.5	4.5	5.2	7.0	5.7	2.6	1.4	1.0	1.0	0.8	1.1	3.0
Low cloud overcast	23.8	21.2	20.4	16.8	15.4	12.0	11.6	11.2	12.0	18.1	16.3	19.6	16.5
Mean cloud cover (eighths)	4.4	4.2	3.9	3.9	3.8	3.9	4.2	3.9	3.7	3.8	4.1	4.4	4.0
AIR TEMPERATURE (°F)													
Minimum	3	12	20	32	36	35	61	61	40	39	27	16	3
01% ≤	18	16	27	36	45	55	64	66	56	45	33	22	40
Mean	39.9	39.8	43.1	49.2	57.3	67.8	74.8	75.4	70.6	61.9	53.6	44.2	56.3
99% ≤	60	58	60	64	72	80	86	85	83	76	68	62	71
Maximum	75	77	77	80	96	88	93	92	93	99	80	74	99
≤ 32 °F (% freq.)	23.0	16.3	4.5	+	0.0	0.0	0.0	0.0	0.0	0.0	0.6	10.0	4.5
≥ 85 °F (% freq.)	0.0	0.0	0.0	0.0	0.2	0.3	2.5	1.0	0.8	+	0.0	0.0	0.4

* Brandywine and Delaware Shoals fog signals   + = less than 0.05%

Table XII **Continued**

ENVIRONMENTAL DATA SUMMARY (PART 3)

AREA: Offshore Delaware Bay

ENVIRONMENTAL FACTORS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
RELATIVE HUMIDITY (%)													
Mean	80	80	81	84	86	85	85	84	81	80	78	78	82
SEA TEMPERATURE (°F)													
Minimum	30	28	27	33	40	41	59	60	56	50	42	34	27
01% ≤	33	33	35	39	42	53	64	66	59	53	48	40	47
Mean	45.1	43.4	43.0	46.6	54.1	64.7	73.0	75.1	71.3	64.2	57.7	51.1	57.4
99% ≤	66	65	64	70	72	78	84	84	81	76	71	68	73
Maximum	80	78	76	80	84	88	90	88	90	84	82	80	90
SALINITY (‰)													
Minimum	27.1	27.5	27.5	27.3	27.1	26.8	28.6	28.5	27.8	27.7	28.0	28.0	26.8
Mean	31.4	31.4	31.2	31.1	31.4	31.6	31.9	31.6	31.6	31.6	31.5	31.4	31.5
Maximum	34.5	34.1	33.6	34.2	34.6	35.0	34.6	34.1	34.1	34.0	34.1	33.6	35.0
DENSITY (ρ)													
Mean (σ_t)*	23.1	23.2	23.1	23.0	23.2	23.5	23.6	23.5	23.4	23.4	23.4	23.2	23.3
SEA-LEVEL PRESSURE (mb)													
Minimum	977	980	981	985	995	997	981	976	990	957	981	988	957
01% ≤	994	990	992	994	1001	1001	1002	1003	1002	998	995	997	997
Mean	1018	1017	1016	1016	1017	1016	1017	1016	1018	1018	1018	1019	1017
99% ≤	1037	1038	1035	1033	1033	1029	1027	1026	1031	1033	1034	1037	1033
Maximum	1044	1044	1045	1039	1040	1030	1034	1032	1041	1040	1040	1043	1045

* $\sigma_t = (\rho - 1) \times 10^3$; ρ = gm cm^{-3}

Table XII Continued.

tidal currents tend to attain speeds of 2-2.5 knots throughout the length of the estuary. Under normal weather and river flow conditions, tidal currents would be the primary currents in the bay.

Figures 19a and 19b show the location of current observations while Tables XIII and XIIIa provide detail on the dates and methods of observation. Tidal current information we have been able to identify consists of:

1. Current observations at various locations in the bay by the former Coast and Geodetic Survey (now the National Ocean Survey - NOS). The original data is still on file in the NOS offices in Rockville, Maryland. This data is summarized in Table XIV. It forms the observational basis of the Delaware Bay Tidal Current Atlas published by NOS.
2. Tidal current predictions made by NOS at the entrance of Delaware Bay. The Tidal Current Tables give the time and velocity of maximum current and slack water time. Current predictions are made, using the current harmonic constants calculated from long term data observed off the mouth of the bay. Tidal current harmonics for the mouth of the bay are given in Table XV. Definitions and procedures for predicting currents are similar to those used in connection with Equation 1 for predicting tides. (See section on tides, above.)
3. Current measurements made by B. Oostdam (1970) at the mouth of the bay and at other select locations during 1968-70.
4. Prototype and model measurements of the upper bay made by the

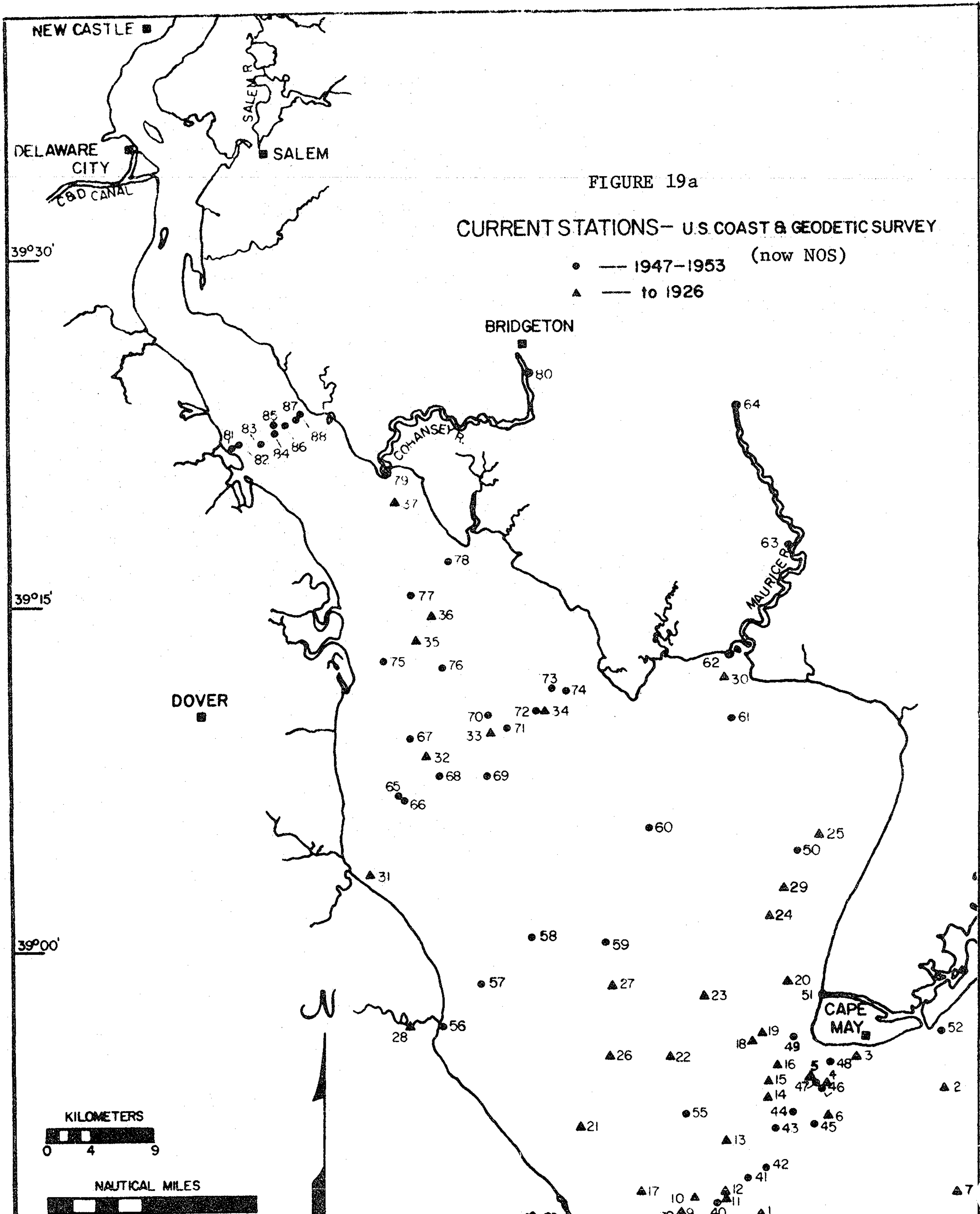
FIGURE 19a
CURRENT STATIONS— U.S. COAST & GEODETIC SURVEY
(now NOS)
— 1947-1953
— to 1926
NEW CASTLE
DELAWARE CITY
C&D CANAL
SALEM R.
SALEM
BRIDGETON
COHANSEY R.
MAURICE R.
DOVER
CAPE MAY
KILOMETERS
0 4 9
NAUTICAL MILES
0 4 9
39°30'
39°15'
39°00'
75°30'
75°15'
75°00'

FIGURE 19b

CURRENT STATIONS FROM MISCELLANEOUS SOURCES

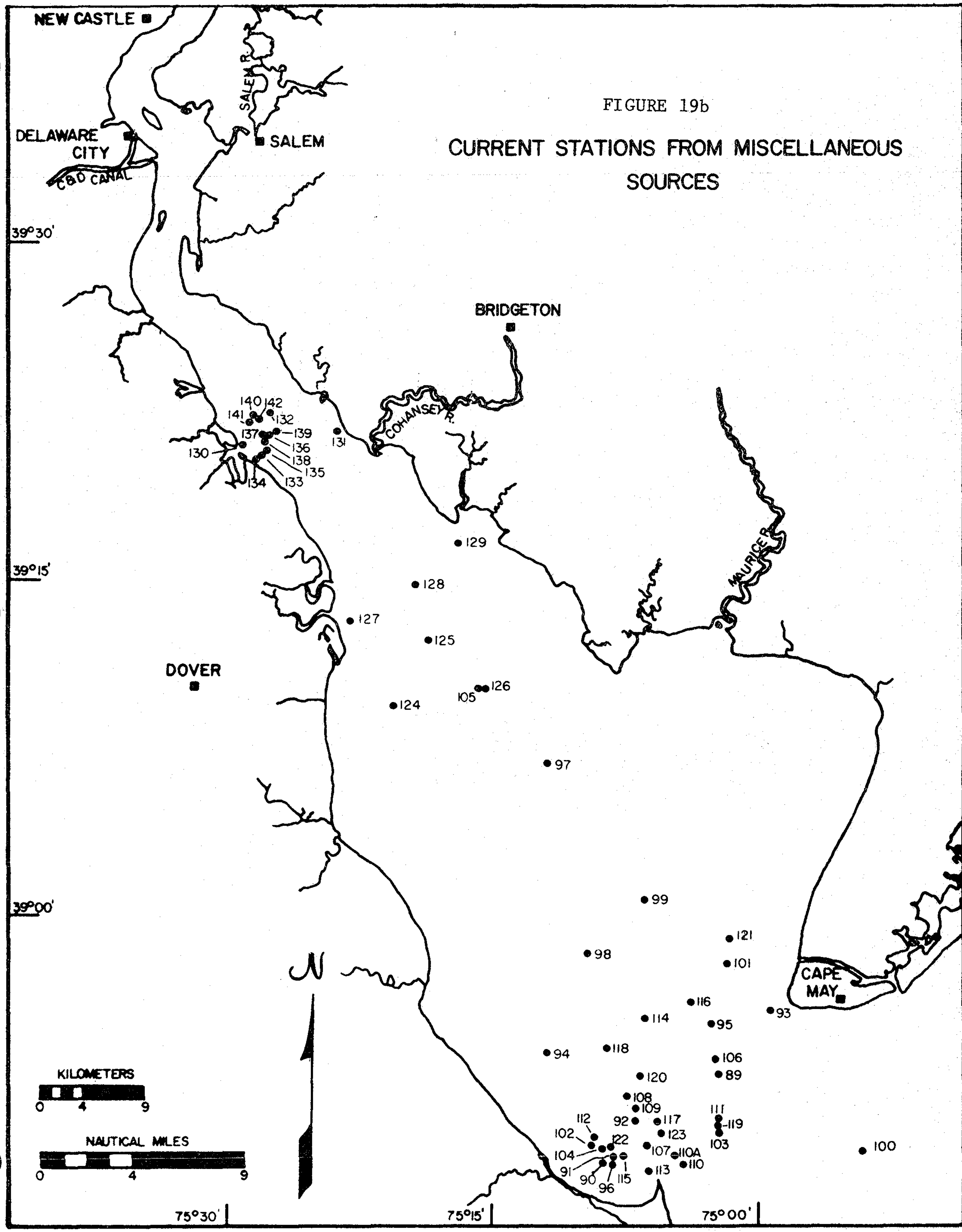

TABLE XIII

CURRENT DATA SUMMARY

#	Ref.#	N. Lat		W. Long		Date	Period Days	Method	Depth (ft)
		o	'	o	'				
1	7a	38	48.9	75	01	Aug 18-22,1925	4	PM	7,15,35,55
						1912-13, 1918-21 1925, 1940-41 See Table IIa	1552	P	7
2	9a	38	54.2	74	51.2	Sept 15-16, 1847	½	P	7
3	10a	38	55.5	74	56.0	Aug 26, 1847	½	P	7
4	11a	38	54.5	74	57.5	Sept 6-7, 1847	½	P	7
5	12a	38	58.2	74	54.6	Aug 27, 1847	½	P	7
6	13a	38	53	74	57.5	Sept 8-9, 1847	½	P	7
7	14a	38	49.8	74	50.5	Sept 16-17, 1847	½	P	7
8	15a	38	47.8	74	56	Sept 18, 1847	½	P	7
9	1a	38	48.2	75	05.5	Aug 21-22, 1924	1	P, PM	7,15,38,60
10	2a	38	49.5	75	04.9	Aug 20-21, 1924	1	P,PM	7,14,35,56
11	3a	38	49.6	75	03.2	Sept, 1847	½	P	7
12	4a	38	49.7	75	03.3	Aug, 1886	2½	P	7
13	5a	38	51.9	75	03.0	Aug 21-23, 1924	1½	P	7,8,20,32
14	6a	38	53.8	75	00.7	Sept, 1847	½	P	7
15	7a	38	54.5	75	00.7	Aug 22-23, 1924	1	P, PM	7,5,14,22
16	8a	38	55.2	75	00.1	Aug, 1947	½	P	7
17	9a	38	49.8	75	07.5	Aug, 1847	½	P	7
18	10a	38	56.2	75	01.5	Aug, 1847	½	P	7
19	11a	38	56.5	75	01.0	Aug, 1847	½	P	7
20	12a	38	59.9	74	58.8	Aug, 1847	½	P	7
21	13a	38	52.4	75	11.0	Aug 26-27, 1924	½	P, PM	7,6,15,24
22	14a	38	55.5	75	06.0	Aug, 1874	½	P	7
23	15a	38	58.0	75	04.0	Aug, 1874	½	P	7
24	16a	39	01.5	75	00.5	Aug 28-29, 1924	½	P, PM	7,5,12,20
25	17a	39	05.0	74	58.0	Sept, 1885	½	P	7

TABLE XIII

CURRENT DATA SUMMARY

#	Ref.#	N. Lat °	'	W. Long °	'	Date	Period Days	Method	Depth (ft)
26	18a	38	55.5	75	09.4	Aug, 1847	½	P	7
27	19a	38	58.6	75	07.4	Aug, 1847	½	P	7
28	20a	38	56.4	75	20.0	Aug 25, 1924	½	P, PM	7,3
29	21a	39	02.8	74	59.8	Aug 27-28, 1924	½	P	7,8,19,30
30	22a	39	11.8	75	03.0	Aug 27-28, 1924	1	P	7,3,5,12
31	23a	39	03.4	75	22.5	Aug 30-31, 1924	1	P	7,3,6
32	24a	39	08.6	75	19.2	Sept 2-3, 1924	1	P	7,T,M,B
33	25a	39	09.5	75	16.0	Sept 3-5, 1924	3	P	7,9,22,35
34	26	39	10.5	75	12.9	Sept 5-6, 1924	1	P	7,4,11,18
35	27a	39	13.6	75	20.0	Aug 20, 1924	½	P	7,5,11,18
36	28a	39	14.6	75	19.2	Aug 20, 1924	½	P	7,8,15,24
37	29a	39	19.4	75	21	Sept 8, 1924	½	P	7,6,15,24
38	1b	38	48.2	75	05.4	May 18-22, 1953	4	RCM	7,34,62
39	2b	38	48.3	75	05.3	June 25-28, 1947	3	P, PM	7,13,34,54
40	3b	38	49.2	75	03.4	May 22-24, 1953	1½	RCM	7,48,89
41	4b	38	50.2	75	01.9	May 13-16, 1953 May 18-22, 1953	7	RCM	7,17,26
42	5b	38	50.8	75	00.7	May 9-13, 1953	4	RCM	8,23,36
43	6b	38	52.4	75	00.2	May 9-13, 1953	4	RCM	6,12,17
44	7b	38	53.1	74	59.2	May 12-18, 1953	6	RCM	7,14,23
45	8b	38	52.6	74	58.2	June 18-21, 1947	3	P, PM	7,6,15,24
46	9b	38	54.2	74	57.9	June 17-20, 1947	3	P, PM	7,5,13,21
47	10b	38	54.3	74	58.1	May 5-9, 1953	4	RCM	7,14,23
48	11b	38	55.4	74	57.5	May 5-9, 1953	3	RCM	6,12,17
49	12b	38	56.3	74	59.1	June 20-23, 1947	3	P, PM	7,7,16,26
50	13b	39	04.4	74	59.0	July 10-13, 1947	3	P, PM	6,10
51	14b	38	58.0	74	57.7	Oct 31-Nov 2,	2	P, PM	3,4

TABLE XIII

CURRENT DATA SUMMARY

#	Ref.#	N. Lat °	'	W. Long °	'	Date	Period Days	Method	Depth (ft)
						1947			
52	15b	38	56.6	74	52.2	Oct 29-31, 1947	2	P	7,5,12,20
53	16b	38	47.5	75	09.5	Nov 5-7, 1947	2	P, PM	4,5
54	17b	38	47.6	75	06.5	Oct 28-31, 1947	3	P, PM	4,5
55	18b	38	53.0	75	05.3	July 28-31, 1947	3	P, PM	7,15,36,60
56	19b	38	56.8	75	18.9	Nov 7-9, 1947	2	P, PM	4,5
57	20b	38	58.7	75	16.6	June 26-29, 1947	3	P, PM	5,8
58	21b	39	00.5	75	13.9	June 23-26, 1947	3	P, PM	7,14,35,56
59	22b	39	03.3	75	09.5	June 28 - July 1 1947	3	P, PM	7,8,20,33
60	23b	39	06.4	75	07.1	July 10-13, 1947	3	P, PM	7,8
61	24b	39	10.1	75	02.5	July 13-16, 1947	3	P, PM	3,5
62	25b	39	13.0	75	02.7	Oct 23-26, 1947	3	P, PM	7,10
63	26b	39	17.2	74	59.6	Oct 20-22, 1947	2	P, PM	3,10
64	27b	39	23.7	75	02.4	Oct 12-20, 1947	1	P, PM	4,6
65	28b	39	06.9	75	20.9	May 29-30, 1953 June 3-7, 1953	4	CM	7
66	29b	39	06.6	75	20.8	June 3-7, 1953	4	RCM	7
67	30b	39	09.2	75	20.4	Aug 4-7, 1947	3	P, PM	4,6
68	31b	39	07.7	75	18.7	May 29 - June 3 1953	5	RCM	7
69	32b	39	07.6	75	16.2	May 24-29, 1953	4	RCM	7,14,21
70	33b	39	10.2	75	16.2	Aug 8-11, 1947	3	P, PM	7,6,16,26
71	34b	39	09.7	75	15.0	April 22-26, 1953	4	RCM	7,18,31
72	35b	39	10.4	75	13.4	April 22-26, 1953	4	RCM	6,12,17
73	36b	39	11.4	75	12.5	July 13-16, 1947	3	P, PM	7,10
74	37b	39	11.4	75	11.7	April 22-26, 1953	3	RCM	6,12
75	38b	39	12.8	75	21.7	Aug 5-8, 1947	3	P, PM	4,6

TABLE XIII

CURRENT DATA SUMMARY

#	Ref.#	N. Lat °	N. Lat '	W. Long °	W. Long '	Date	Period Days	Method	Depth (ft)
76	39b	39	12.4	75	18.6	Aug 8-11, 1947	3	P, PM	4,9
77	40b	39	15.4	75	20.3	Aug 16-19, 1947	3	P, PM	7,6,15,29
78	41b	39	16.9	75	18.2	Aug 13-16, 1947	3	P, PM	4,8
79	42b	39	20.9	75	21.6	Oct 24-27, 1947	3	P, PM	8,10
80	43b	39	25.6	75	14.2	Oct 17-18, 1947	1	P, PM	4,8
81	44b	39	21.8	75	29.0	Sept 6-9, 1947	3	P, PM	3,6
82	45b	39	21.8	75	28.7	June 9-13, 1953	4	RCM	7
83	46b	39	22.0	75	28.4	June 9-11, 1953 June 13-18, 1953	6	RCM	7,12,18
84	47b	39	22.4	75	27.7	June 10-14, 1953	4	RCM	7,16,25
85	48b	39	22.6	75	27.8	Aug 24-27, 1947	3	P, PM	7,16,16,26
86	49b	39	22.8	75	26.9	June 9-14, 1953	5	RCM	7,14
87	50b	39	23.0	75	26.5	Aug 21-24, 1947	3	P, PM	4,8
88	51b	39	23.1	75	26.2	June 14-18, 1953	4	RCM	7,15
89	301c	38	53.0	75	02.0	Spring (1969?)	2?		7,15
90	33c	38	49.0	75	08.6	Spring (1969?)	?		
91	55c	38	49.4	75	08.0	April 6, 1969	½		5,11,16,20,24
92	58c	38	51.0	75	06.8	Spring (1969?)	?		
93	80c	38	55.9	74	59.1	May 2, 1970	¼		
94	31c	38	53.9	75	11.9	Spring (1969?)	?		
95	84c	38	55.2	75	02.5	May 2, 1970	¼		
96	86c	38	49.0	75	08.0	May 2, 1970	?		
97	88c	39	06.9	75	12.0	May 2, 1970	?		
98	21c	38	58.3	75	09.6	Summer (1969?)	?		
99	24c	39	00.9	75	06.3	Summer (1969?)	?		
100	25c	38	49.8	74	54.0	Summer (1969?)	?		
101	40c	38	57.9	75	01.6	July 18, 1968	2/3		5,10,20,30

TABLE XIII

CURRENT DATA SUMMARY

#	Ref.#	N. Lat °	'	W. Long °	'	Date	Period Days	Method	Depth (ft)
102	41c	38	49.9	75	09.2	July 31, 1968	2/3		1,5,10,15,20
103	94c	38	50.5	75	02.0	Summer (1969?)	?		
104	96c	38	49.8	75	08.5	Summer (1969?)	?		
105	308c	39	10.1	75	15.9	Summer (1969?)	?		
106	309c	38	53.8	75	02.1	Aug 6-7, 1969	2		2,10,25,35
107	402	38	49.9	75	06.2	July 9, 1969	½		5,10.25,35,40
108	405c	38	52.0	75	07.2	July 30, 1969	¼		
109	406c	38	51.4	75	06.8	Summer (1969?)	?		
110	43c	38	49.0	75	04.0	Fall (1968?)	?		
110a	404c	38	49.3	75	04.6	Fall (1968?)	?		
111	44c	38	51.0	75	02.0	Oct 12, 1968	½+		4,10,15,19,24,27
112	57c	38	50.1	75	09.0	Fall (1968?)	?		
113	100c	38	48.7	75	06.0	Fall (1968?)	?		
114	102c	38	55.4	75	06.3	Fall (1968?)	?		
115	505c	38	49.3	75	07.4	Oct 11-12, 1969	1.2		1,5,10,15,20
116	508c	38	56.2	75	03.7	Fall (1969?)	?		
117	509c	38	50.9	75	05.5	Dec 6-7, 1969	1		10,13,23,30,45 60,70,80,85,89
118	30c	38	54.1	75	08.2	Winter (1969?)	?		
119	47c	38	50.1	75	02.0	March 16, 1969	½		1,6,11,20,25,30,34
120	82c	38	52.9	75	06.5	May 2, 1970	½		
121	702c	38	59.0	75	01.5	Feb 7-8, 1970	½+		Several
122	703c	38	94.7	75	08.1	Winter (1969?)	?		
123	704c	38	50.4	75	05.2	Winter (1969?)	?		
124	20d	39	09.5	75	20.5	?	½?		M
125	21d	39	12.3	75	18.5	?	½?		M
126	22d	39	10.1	75	15.4	?	½?		M

TABLE XIII

CURRENT DATA SUMMARY

#	Ref.#	N. Lat °	'	W. Long °	'	Date	Period Days	Method	Depth (ft)
127	24d	39	13.1	75	22.9	?	½?		M
128	25d	39	14.7	75	19.4	?	½?		M
129	26d	39	16.7	75	17.0	?	½?		M
130	28d	39	20.8	75	29.0	?	½		M
131	29d	39	21.7	75	23	?	½		M
132	30d	39	22.3	75	27.5	?	½		M
133	9A	39	20.5	75	27.0	July 8-18, 1952	½		T,M,B
134	9B	39	20.4	75	27.2	July 8-18, 1952	½		T,M,B
135	9F	39	20.6	75	26.8	July 8-18, 1952	½		T,M,B
136	8A	39	21.4	75	27.5	July 8-18, 1952	½		T,M,B
137	8B	39	21.35	75	27.7	July 8-18, 1952	½		T,M,B
138	8C	39	21.3	75	27.7	July 8-18, 1952	½		T,M,B
139	8F	39	21.5	75	27.1	July 8-18, 1952	½		T,M,B
140	7A	39	22.1	75	82.5	July 8-18, 1952	1		T,M,B
141	7B	39	22.0	75	28.6	July 8-18, 1952	1		T,M,B
142	7F	39	22.1	75	28.4	July 8-18, 1952	1		T,M,B

The Ref. # indicates the number of the station in the document where it was found, while the letter indicates the source. Thus:

a. Zeskind & LeLacheur (1926)
b. National Ocean Survey Unpublished
c. Oostdam (1971)
d. U.S. Army Corps of Engineers (1956)

The locations were generally scaled off of charts and figures and their accuracy should be interpreted accordingly. The period is generally to the nearest tidal cycle of 12.42 hours ($\simeq$ 1/2 day.) A question mark after a period indicates that the period of observation is at least that given. In the method column "P" indicates pole and log line, "PM" is Price current meter with telephone attachment, "RCM" is recording current meter. The depths are those given in the sources, except in series (c) where representative values were scaled from graphs. "T" indicates top, "M" mid-depth and "B" bottom.

Table XIIIa

CURRENT DATA SERIES AT OVERFALLS LIGHT VESSEL* (STATION 1, Figure 19a)

Nov. 7, 1912 - Feb. 6, 1913	92	days
Sept. 13 - Dec. 18, 1918	98	"
Feb. 22 - May 2, 1919	70	"
July 1, 1919 - Jan. 17, 1920	201	"
Mar. 21, 1920 - Jan. 20, 1921	316	"
Mar. 13 - July 31, 1921	141	"
Aug. 18, 1924 - May 14, 1925	270	"
Apr. 17, 1940 - Apr. 21, 1941	369	"

* Compiled from Zeskind and LeLacheur (1926) and unpublished sources

Table XIV

Delaware Bay Tidal Current Parameters

Station No.	Depth	FLOOD Direction	FLOOD Mean Velocity	FLOOD Duration	FLOOD Max. Velocity	FLOOD Time Difference		EBB Direction	EBB Mean Velocity	EBB Duration	EBB Max. Velocity	EBB Time Difference		SLACK WATER Time Difference Low Water		SLACK WATER Time Difference High Water	
	Feet	°	Knots	Hours	Knots	h.	m.	°	Knots	Hours	Knots	h.	m.	h.	m.	h.	m.
38	7	311	2.00	5.58	2.0	-0	10	134	2.34	6.84	2.7	-0	15	-0	25	-0	45
	34	280	1.74	6.13	1.6	-0	50	108	2.39	6.29	2.4	-0	15	-0	40	-0	30
	62	294	1.57	5.92	1.1	-0	40	128	2.36	6.50	2.7	-0	20	-0	40	-0	45
39	7	292	1.94	5.56	1.8	-0	05	113	2.19	6.86	2.1	-0	40	-0	20	-0	45
	13	-	2.03	5.85	2.0	-0	20	-	2.25	6.57	2.2	-0	30	-0	30	-0	40
	34	-	1.65	6.45	1.5	-0	35	-	2.07	5.97	1.9	-0	30	-0	50	-0	20
	54	-	1.56	6.57	1.6	-0	45	-	1.78	5.85	1.7	-0	40	-1	00	-0	25
40	7	346	2.02	5.72	1.8	+0	20	145	2.68	6.70	2.3	+0	40	+0	20	+0	05
	48	352	2.05	5.85	1.8	-0	15	148	1.72	6.57	1.3	+0	50	-0	00	-0	05
	89	346	1.91	6.85	1.9	-0	10	148	1.31	5.57	1.2	+0	15	-0	30	+0	20
41	7	302	1.35	5.98	1.7	-0	45	156	1.43	6.44	2.0	-0	15	-0	30	-0	30
	17	290	1.65	6.16	1.8	-0	45	175	1.55	6.26	2.1	-0	20	-0	45	-0	30
	26	298	1.28	6.14	1.8	-0	35	149	1.11	6.28	1.7	-0	20	-0	35	-0	25
42	8	287	1.17	6.25	1.7	-0	45	149	1.65	6.17	2.2	-0	45	-1	00	-0	40
	23	295	1.19	6.14	1.7	-0	45	166	1.35	6.28	1.8	-0	40	-0	55	-0	45
	36	296	1.30	6.44	2.3	-0	40	147	1.25	5.98	1.8	-0	40	-1	05	-0	35
43	6	322	1.36	6.18	1.9	-1	05	137	1.61	6.24	2.2	-1	30	-1	10	-0	55
	12	307	1.26	6.26	1.8	-1	10	133	1.42	6.16	1.8	-1	15	-1	15	-0	55
	17	300	1.23	6.35	1.7	-1	05	129	1.26	6.07	1.7	-1	15	-1	20	-0	55
44	7	303	1.49	6.63	2.2	-1	05	145	1.35	5.79	1.9	-0	50	-1	30	-0	50
	14	289	1.61	6.65	2.1	-1	00	151	1.36	5.77	1.9	-1	00	-1	25	-0	45
	23	301	1.40	6.69	2.1	-0	55	132	1.18	5.73	1.7	-1	10	-1	35	-0	50
45	7	295	0.95	6.46	1.4	-0	55	137	1.47	5.96	1.9	-0	45	-1	05	-0	45
	6	-	1.25	6.63	1.8	-0	55	-	1.74	5.79	2.3	-0	45	-1	10	-0	45
	15	-	1.23	6.41	1.7	-0	55	-	1.57	6.01	2.1	-0	40	-1	10	-0	40
	24	-	1.21	6.51	1.7	-0	50	-	1.36	5.91	1.9	-0	45	-1	10	-0	45
46	7	296	1.42	6.20	2.1	-1	15	138	2.45	6.22	3.0	-1	00	-0	55	-0	45
	5	-	1.59	6.07	2.3	-1	15	-	2.62	6.35	3.3	-1	00	-0	55	-0	50
	13	-	1.54	6.41	2.2	-1	10	-	2.34	6.01	3.0	-0	55	-1	15	-0	45
	21	-	1.46	6.35	2.2	-1	10	-	2.06	6.07	2.7	-0	50	-1	15	-0	50
47	7	336	1.63	5.93	1.7	-1	50	156	6.49	6.49	2.7	-1	15	-1	20	-1	20
	14	295	1.56	6.27	1.7	-1	45	169	6.15	6.15	2.3	-1	15	-1	30	-1	10
	23	334	1.59	6.15	1.8	-1	35	142	6.27	6.27	2.0	-1	10	-1	20	-1	10
48	6	298	1.65	6.37	1.8	-1	35	113	1.86	6.05	2.1	-1	35	-1	40	-1	20
	12	288	1.48	6.19	1.9	-1	45	099	1.76	6.23	2.0	-1	40	-1	45	-1	30
	17	294	1.54	6.52	1.6	-1	40	106	1.66	5.90	1.9	-1	35	-1	50	-1	15
49	7	343	1.97	6.22	2.3	-1	00	169	2.22	6.20	2.7	-1	05	-0	55	-0	40
	7	-	2.04	6.22	2.8	-1	00	-	2.37	6.20	2.9	-1	05	-1	00	-0	45
	16	-	1.85	6.13	2.2	-1	00	-	1.87	6.29	2.4	-1	00	-1	00	-0	50
	26	-	1.60	6.24	2.2	-1	00	-	1.52	6.18	2.0	-1	00	-1	05	-0	50
50	6	007	0.96	6.42	1.0	-0	40	186	0.99	6.00	1.1	-0	05	-0	45	-0	15
	10	-	1.20	6.21	1.2	-0	30	-	1.30	6.21	1.3	-0	10	-0	40	-0	25
51	3	264	0.56	5.75	0.7	-2	00	089	0.24	6.67	0.3	-2	20	-1	45	-2	00
	4	-	0.81	6.05	0.9	-2	05	-	0.59	6.37	0.8	-2	15	-2	05	-2	00

Table XIV

Delaware Bay Tidal Current Parameters

Station No.	Depth	FLOOD Direction	FLOOD Mean Velocity	FLOOD Duration	FLOOD Max. Velocity	FLOOD Time Difference		EBB Direction	EBB Mean Velocity	EBB Duration	EBB Max. Velocity	EBB Time Difference		SLACK WATER Time Difference Low Water		SLACK WATER Time Difference High Water	
	Feet	°	Knots	Hours	Knots	h.	m.	°	Knots	Hours	Knots	h.	m.	h.	m.	h.	m.
52	7	333	1.62	6.70	2.3	-0	55	150	2.12	5.72	2.8	-1	30	-1	40	-1	00
	5	-	1.91	6.65	2.7	-1	45	-	2.29	5.77	3.0	-1	35	-1	45	-1	05
	12	-	1.76	6.69	2.4	-1	50	-	2.19	5.73	2.9	-1	40	-1	50	-1	05
	20	-	1.70	6.75	2.4	-1	50	-	1.97	5.67	2.5	-1	30	-1	50	-1	05
53	4	206	0.60	-	0.7	+2	20	030	1.02	-	1.2	+1	00	--		--	
	5	-	0.71	-	0.8	+2	05	-	1.11	-	1.2	+0	50	--		--	
54	4	266	0.73	5.67	1.0	-0	45	078	0.85	6.75	1.1	-0	40	-0	50	-1	05
	5	-	0.80	5.93	1.1	-0	50	-	0.90	6.49	1.2	-0	30	-1	00	-1	05
55	7	344	1.72	6.10	1.7	+0	40	173	1.89	6.32	1.8	+0	45	+0	30	+0	40
	15	-	2.22	6.77	2.1	+0	40	-	1.97	5.65	1.8	+0	45	+0	10	+1	00
	36	-	1.96	7.30	2.0	+0	40	-	1.56	5.12	1.5	+0	35	-0	20	+1	00
	60	-	1.39	6.25	1.4	+0	25	-	1.19	6.17	1.1	0	00	+0	10	+0	30
56	4	025	1.35	5.39	1.5	+2	35	190	0.68	7.03	0.8	+1	55	+2	35	+2	00
	5	-	1.65	5.35	1.9	+2	25	-	0.58	7.07	0.7	+1	50	+2	30	+1	55
57	5	326	0.56	6.22	0.5	-0	45	145	0.80	6.20	0.8	-0	35	-0	45	-0	30
	8	-	0.82	6.13	0.8	-0	55	-	0.97	6.29	1.0	-0	30	-0	45	-0	35
58	7	331	1.22	6.66	1.4	+0	40	152	1.46	5.76	2.0	+1	20	+0	30	+1	15
	14	-	1.42	7.09	1.7	+0	40	-	1.56	5.33	2.0	+1	10	+0	10	+1	20
	35	-	1.42	6.52	1.5	+0	25	-	1.24	5.90	1.4	+0	45	+0	15	+0	50
	36	-	1.08	6.77	1.2	+0	20	-	1.10	5.65	1.4	+0	25	-0	10	+0	35
59	7	339	1.30	6.46	1.5	+0	20	174	1.47	5.96	1.4	+0	45	+0	15	+0	45
	8	-	1.39	6.39	1.4	+0	15	-	1.64	6.03	1.6	+0	50	+0	10	+0	35
	20	-	1.21	6.45	1.2	+0	10	-	1.37	5.97	1.4	+0	25	+0	05	+0	30
	33	-	1.08	7.12	1.1	+0	10	-	0.93	5.30	0.9	+0	05	-0	35	+0	35
60	7	355	0.59	6.50	0.7	-0	30	150	0.61	5.92	0.7	-0	50	-0	50	-0	20
	8	-	0.84	6.47	0.8	-0	20		0.85	5.95	0.8	-0	50	-0	55	-0	25
61	3	340	0.45	6.93	0.7	-0	20	159	0.25	5.49	0.4	+0	15	-0	25	+0	30
	5	-	0.59	7.14	0.8	+0	10	-	0.55	5.28	0.6	+0	20	-0	30	+0	40
62	7	012	1.04	6.34	0.9	+0	45	192	1.00	6.08	0.8	+1	20	+0	55	+1	15
	10	-	1.11	6.36	0.9	+0	45	-	1.06	6.06	0.9	+1	10	+0	45	+1	10
63	3	(000)	2.38	6.48	1.8	+1	30	(180)	2.15	5.94	1.5	+1	05	+1	00	+1	30
	10	-	2.42	6.50	1.8	+1	25	-	2.16	5.92	1.4	+1	10	+1	00	+1	30
64	4	(000)	0.22	-	0.2	+2	40	(180)	0.32	-	0.3	+2	30	-		-	
	6	-	0.23	-	0.2	+2	30	-	0.43	-	0.4	+2	25	-		-	
65	7	312	0.67	6.26	1.0	-0	05	209	0.67	6.16	0.9	+0	45	0	00	+0	15
66	7	300	0.59	6.05	0.9	0	00	177	0.64	6.37	0.7	+0	40	+0	15	+0	15
67	4	316	0.93	3.09	1.0	+0	35	158	0.91	5.99	1.0	+0	55	+0	20	+0	50
	6	-	1.20	3.10	1.2	+0	25	-	1.20	6.18	1.3	+0	45	+0	35	+0	50
68	7	335	1.12	5.87	1.6	+0	05	154	1.09	6.55	1.4	+0	55	+0	30	+0	20
69	7	336	0.98	5.92	1.4	+0	50	162	1.23	6.50	1.9	+1	35	+1	05	+1	05
	14	331	1.68	6.24	1.9	+0	40	170	1.38	6.18	1.7	+1	35	+0	50	+1	05
	21	351	1.36	7.10	1.6	+0	15	134	1.07	5.32	1.3	+1	10	+0	15	+1	25

Table XIV

Delaware Bay Tidal Current Parameters

Station No.	Depth	FLOOD Direction	FLOOD Mean Velocity	FLOOD Duration	FLOOD Max. Velocity	FLOOD Time Difference	EBB Direction	EBB Mean Velocity	EBB Duration	EBB Max. Velocity	EBB Time Difference	SLACK WATER Time Difference Low Water	SLACK WATER Time Difference High Water
	Feet	°	Knots	Hours	Knots	h. m.	°	Knots	Hours	Knots	h. m.	h. m.	h. m.
70	7	329	1.19	5.25	1.3	+1 25	164	2.18	7.17	2.1	+2 05	+1 50	+1 10
	6	-	1.37	5.21	1.4	+1 25	-	2.47	7.21	2.4	+2 00	+1 40	+0 50
	16	-	1.38	5.71	1.4	+0 50	-	2.04	6.71	2.0	+1 15	+1 10	+0 50
	26	-	1.25	6.40	1.3	+0 50	-	1.17	6.02	1.2	+1 30	+0 50	+1 15
71	7	005	1.49	6.27	1.5	+0 20	171	1.59	6.15	1.5	+1 00	+0 35	+0 55
	18	344	1.81	6.86	1.9	+1 00	170	1.36	5.56	1.3	+0 50	+0 25	+1 15
	31	348	1.27	6.96	1.3	+0 35	140	0.84	5.46	0.8	+0 05	-0 25	+0 35
72	6	358	1.63	5.91	1.6	+0 50	165	1.76	6.51	1.8	+1 05	+0 50	+0 45
	12	350	1.37	6.27	1.5	+0 35	168	1.27	6.15	1.2	+0 55	+0 25	+0 40
	17	348	1.23	6.54	1.2	+0 30	165	1.06	5.88	1.0	+0 50	+0 05	+0 40
73	7	342	0.83	6.39	1.2	+0 30	158	1.00	6.03	1.2	+0 45	+0 20	+0 45
	10	-	0.96	6.12	1.3	+0 25	-	1.22	6.30	1.4	+0 45	+0 35	+0 45
74	6	341	1.22	5.52	1.1	-0 20	151	1.43	6.90	1.2	+0 45	+0 30	+0 05
	12	(360)	1.44	5.55	1.4	-0 15	166	1.59	6.87	1.6	+0 30	+0 20	-0 05
75	4	348	0.80	5.92	0.8	+0 55	164	1.06	6.50	1.1	+0 50	+0 55	+0 50
	6	-	1.02	6.08	1.0	+0 50	-	1.24	6.34	1.3	+0 55	+0 45	+0 55
76	4	320	0.85	6.61	1.1	+0 50	160	1.19	5.81	1.2	+1 25	+0 55	+1 35
	9	-	1.38	7.24	1.4	+0 45	-	1.27	5.18	1.5	+1 15	+0 30	+1 45
77	7	318	1.52	5.58	2.5	+1 45	146	2.31	6.84	3.0	+2 35	+2 15	+1 50
	6	-	1.66	5.35	2.7	+1 40	-	2.52	7.07	3.3	+2 30	+2 20	+1 45
	15	-	1.55	5.87	2.5	+1 40	-	2.22	6.55	2.8	+2 25	+1 55	+1 50
	24	-	1.40	6.30	2.2	+1 35	-	1.80	6.12	2.3	+2 20	+1 40	+2 00
78	4	308	1.09	6.29	1.4	+1 00	122	0.74	6.13	1.0	+0 55	+1 00	+1 20
	8	-	1.38	6.52	1.7	+1 00	-	0.90	5.90	1.2	+1 00	+0 50	+1 25
79	8	074	1.07	6.07	1.1	+1 20	254	1.25	6.35	1.3	+1 30	+1 35	+1 40
	10	-	1.27	6.22	1.2	+1 20	-	1.47	6.20	1.4	+1 25	+1 25	+1 40
80	4	(000)	0.21	-	0.2	+2 20	(180)	0.21	-	0.2	+2 30	- -	- -
	8	-	0.27	-	0.3	+2 35	-	0.42	-	0.4	+2 30	- -	- -
81	3	314	1.17	6.69	1.3	+2 10	147	1.19	5.73	1.3	+1 45	+1 30	+2 15
	6	-	1.37	6.40	1.5	+2 20	-	1.41	6.02	1.4	+1 45	+1 50	+2 15
82	7	300	1.36	5.87	2.0	+2 15	183	1.52	6.55	1.9	+2 10	+2 10	+2 05
83	7	332	1.86	5.69	2.2	+2 35	165	2.25	6.73	2.7	+2 55	+2 40	+2 20
	12	310	1.88	5.72	2.1	+2 15	131	2.15	6.70	2.7	+3 05	+2 35	+2 20
	18	347	1.77	5.88	2.1	+2 05	112	1.77	6.54	2.0	+3 00	+2 20	+2 15
84	7	342	1.96	5.30	2.6	+2 15	167	1.90	7.12	2.3	+2 20	+2 35	+1 55
	16	348	1.91	5.84	2.4	+2 05	155	1.74	6.58	2.2	+2 10	+2 15	+2 10
	25	342	1.77	5.93	2.2	+2 25	136	1.56	6.49	2.1	+2 10	+2 05	+2 05
85	7	327	2.09	5.59	1.8	+2 30	150	2.49	6.83	2.0	+2 45	+2 35	+2 10
	6	-	2.18	5.34	2.0	+2 40	-	2.74	7.08	2.2	+2 50	+2 45	+2 05
	16	-	2.17	5.91	1.7	+2 05	-	2.14	6.51	1.8	+2 15	+1 55	+1 50
	26	-	1.68	6.50	1.4	+1 50	-	1.52	5.92	1.2	+2 00	+1 35	+2 05
86	7	302	1.07	5.77	1.4	+1 00	154	1.23	6.65	1.6	+1 40	+1 30	+1 15
	14	312	1.13	6.08	1.4	+1 10	130	1.17	6.34	1.6	+1 50	+1 15	+1 25
87	4	316	1.26	5.81	1.2	+1 15	144	1.06	6.61	1.0	+1 05	+1 30	+1 20
	8	-	1.48	5.95	1.3	+1 10	-	1.31	6.47	1.2	+1 10	+1 30	+1 25
88	7	311	1.29	5.77	1.5	+1 10	185	1.24	6.65	1.2	+1 25	+1 25	+1 15
	15	312	1.37	6.32	1.3	+1 15	152	1.13	6.10	1.1	+1 15	+1 00	+1 20

FORM C&GS-444 (11-67)

TABLE XV

U.S. DEPARTMENT OF COMMERCE
ESSA- COAST AND GEODETIC SURVEY

~~TIDES~~ CURRENTS STANDARD HARMONIC CONSTANTS FOR PREDICTION

STATION Delaware Bay Entrance

Lat. 38° 48′ N.
Long. 75° 01′.4 W
Long. 75° 02 W.

Component	H Amplitude (ft. kn.)	κ Epoch (°)	A κ′ − κ (°)	B 1.10×H (ft. kn.)	C 360° − κ′ (°)	D −κ′ (°)
M_2	1.570	188.8	5.1	1.661	+	−193.9
S_2	0.230	203.8	0.0	0.253	+	−203.8
N_2	0.268	166.4	7.8	0.295	+	−174.2
K_1	0.118	65.0	−0.2	0.130	+	−64.8
M_4	0.034	37.0	10.2	0.037	+	−47.2
O_1	0.054	61.1	5.3	0.059	+	−66.4
M_6	0.031	137.8	15.4	0.034	+	−153.2
$(MK)_3$	—	—			+	−
S_4	—	—			+	−
$(MN)_4$	—	—			+	−
ν_2	(0.052	169.4)	7.5	0.057	+	−176.9
S_6	—				+	−
μ_2	0.084	340.4	10.2	0.092	+	−350.6
$(2N)_2$	(0.036	144.0)	10.6	0.040	+	−154.6
$(OO)_1$	—	—			+	−
λ_2	(0.011	195.8)	2.8	0.012	+	−198.6
S_1	0.042	40.8	0.0	0.046	+	−40.8
M_1	—				+	−
J_1	—	—			+	−
Mm	—	—			+	−
Ssa					+	−
Sa	—	—			+	−
MSf	—	—			+	−
Mf	—	—			+	−
ρ_1	—	—			+	−
Q_1	(0.010	59.2)	8.0	0.011	+	−67.2
T_2	(0.014	203.8)	0.2	0.015	+	−204.0
R_2	—	—			+	−
$(2Q)_1$	—				+	−
P_1	0.033	28.5	0.2	0.036	+	−28.7
$(2SM)_2$	—	—			+	−
M_3	—	—			+	−
L_2	0.160	213.0	2.4	0.176	+	−215.4
$(2MK)_3$	—	—			+	−
K_2	0.083	245.0	−0.4	0.091	+	−244.6
M_8					+	−
$(MS)_4$					+	−

REMARKS

Time meridian 75° W. = +5 h.
Extreme range .... { ft. kn.
Dial ....
Marigram gear ....
Marigram scale ....
Z_0 .... ft.
Permanent current − 0.070 kn.
The DATUM is a plane .... ft. below mean { low water springs / lower low water

short period components increased 10 %

use analysed values ≥ 0.030
use inferred values ≥ 0.010

f = 305° true e = 140° true

Source of constants C+GS analysis of 369 days beginning April 17, 1940.

Compiled by des 2-25-69 (Date) Verified by Rae 6-18-69 (Date)

USCOMM-DC 50160-P67

Corps of Engineers (1956b) in connection with the River Model Study.

5. Dye dumps made by the Delaware Department of Natural Resources and Environmental Control, in cooperation with CMS, in connection with the study of the effects of spoil disposal at the Lewes Ferry Terminal.

6. Drogue studies performed on the New Jersey side of the bay by Rutgers University. (We have not been able to inspect these data.)

Wind and river flow cause the observed currents to differ from current predictions made using the harmonic constants; however, Kupferman and Polis's two-dimensional single-layer computer model of Delaware Bay is capable of making predictions of the effects of river flow and meteorological effects on the vertically integrated current.

The direct effect of river discharge on tidal flow is quite small in the lower bay; however, the bay is observed to change its estuarine circulation type when the river flow changes the bay's salinity structure. In general, as the discharge increases, there will develop a stronger two-layered "estuarine" circulation due to the combined effects of fresh water overriding sea water. The circulation will be generally inland at the north and bottom, and seaward on the south and top. This is illustrated in Figure 30, showing the transport at the mouth of the bay as calculated by Salter and Polis (See Appendix) from NOS Data.

In order to understand the extent of estuarine circulation present at any time, it is necessary to examine the temperature and, especially, the salinity distributions in the water column. (See section on salinity below.) For almost all the observations of currents in the bay, there are no concurrent temperature and salinity data. Thus, at the present time (1972), it is impossible to say how representative the net current observed at any station is. It is the net current which is largely responsible for the transport of substances through the bay.

The NOS observations noted above under Item 1 comprise the bulk of the data. They have concurrent observations of wind speed and direction, but as each station was occupied only once for 3-4 days, and the stations were occupied successively rather than simultaneously, they do not provide sufficient data for deducing the response of the current system to meteorological factors.

SALINITY

Salinity is the total weight of dissolved solids in a thousand-gram sample of estuary water.[1] The unit is parts per thousand ($^{o}/oo$). Salinity in the Delaware Estuary varies from a value characteristic of coastal ocean water (30 - 33 $^{o}/oo$) to a value of about 0.1 $^{o}/oo$ in the river. In the upper reaches of the tidal river, concentrations of the major species of dissolved ions are generally close to but somewhat smaller than world and North American river averages (Table XVI).

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1 For a more scientifically precise definition, see R. A. Cox (1965).

Table XVI

Concentrations of the Principal Ions in River Water

Ion	Delaware River at Trenton, N J October 1950–September 1951[1]	Mean composition of North American rivers[2]	Mean composition of world rivers[2]
Silica (SiO_2)	4.7	9	13.2
Iron (Fe)	0.06	0.16	0.67
Calcium (Ca)	14	21	15
Magnesium (Mg)	4.7	5	4.1
Sodium (Na)	4.4	9	6.3
Potassium (K)		1.4	2.3
Bicarbonate (HCO_3)	38	68	58.4
Sulfate (SO_4)	21	20	11.2
Chloride (Cl)	4.7	8	7.8
Fluoride (F)	0.1	....	....
Nitrate (NO_3)	2.8	1	1
Total dissolved solids	[3]94	142	120

[1]Average river flow over this period was 14,730 cubic feet per second
Source: Durfor, C N., and W B Keighton, Chemical characteristics of Delaware River water, Trenton to Marcus Hook 1954, page 45. Water-Supply Paper 1262. U.S. Geological Survey, Department of Interior, Washington, D.C.
[2]Source: Livingstone, D. A., Chemical composition of rivers and lakes, 1963, page 41. Professional Paper 440G. U.S. Geological Survey, Department of Interior, Washington, D.C.
[3]Recomputed from original figures

The salinity value at any point in the Delaware Estuary indicates the approximate degree of dilution of ocean water by river water. Ketchum (1952) has made use of this fact to determine the total amount of fresh water in the Delaware Estuary. With this, and river-flow data, he has determined the value of a quantity known as the residence time. While there is no generally accepted precise definition of residence time, Ketchum defines it as the time required for the rivers to input an amount of fresh water equal to the total amount of fresh water in the estuary. He had found that the residence time for the fresh water in the estuary depends upon the rate of river flow, and varies between

60 and 120 days, averaging 100 days. He also calculated residence times for various segments of the estuary (Figure 20). These are the best estimates which are presently available. The whole problem is in urgent need of attention. Residence times, also referred to as flushing times, are useful in obtaining rough estimates of the levels of suspended and dissolved pollutants to be expected in various parts of the estuary from the known input rates of these pollutants. Harold Haskin (1972) has made some very rough analyses of the correlation of river flow with salinity. He found that salinity at a given station for a given river flow is higher now than it was in the past. However, these analyses are rough in that no attempt was made to analyze for the effects of tidal flow on salinity, or even to take into account the fact that the salinity at any point in time depends on past rather than present river flow. One would expect on theoretical grounds that the salinity at a given station at a given tidal stage would depend on past river flow. As mentioned above, Ketchum (1952) has shown that a characteristic time for this phenomenon is typically 100 days, depending on river flow and station location. Thus salinity in the bay being correlated with the river flow at Trenton on the day of observation has no causal significance. A more sophisticated analysis was carried out by the Corps (1959) for the tidal river.

We have analyzed long-term density data from the National Ocean Survey and have found that there is an annual reversal in the transverse salinity gradient near the mouth of the bay. This is shown in Figure 21. The analysis consisted in subtracting the monthly mean densities at Breakwater Harbor and Cape May for each month for which

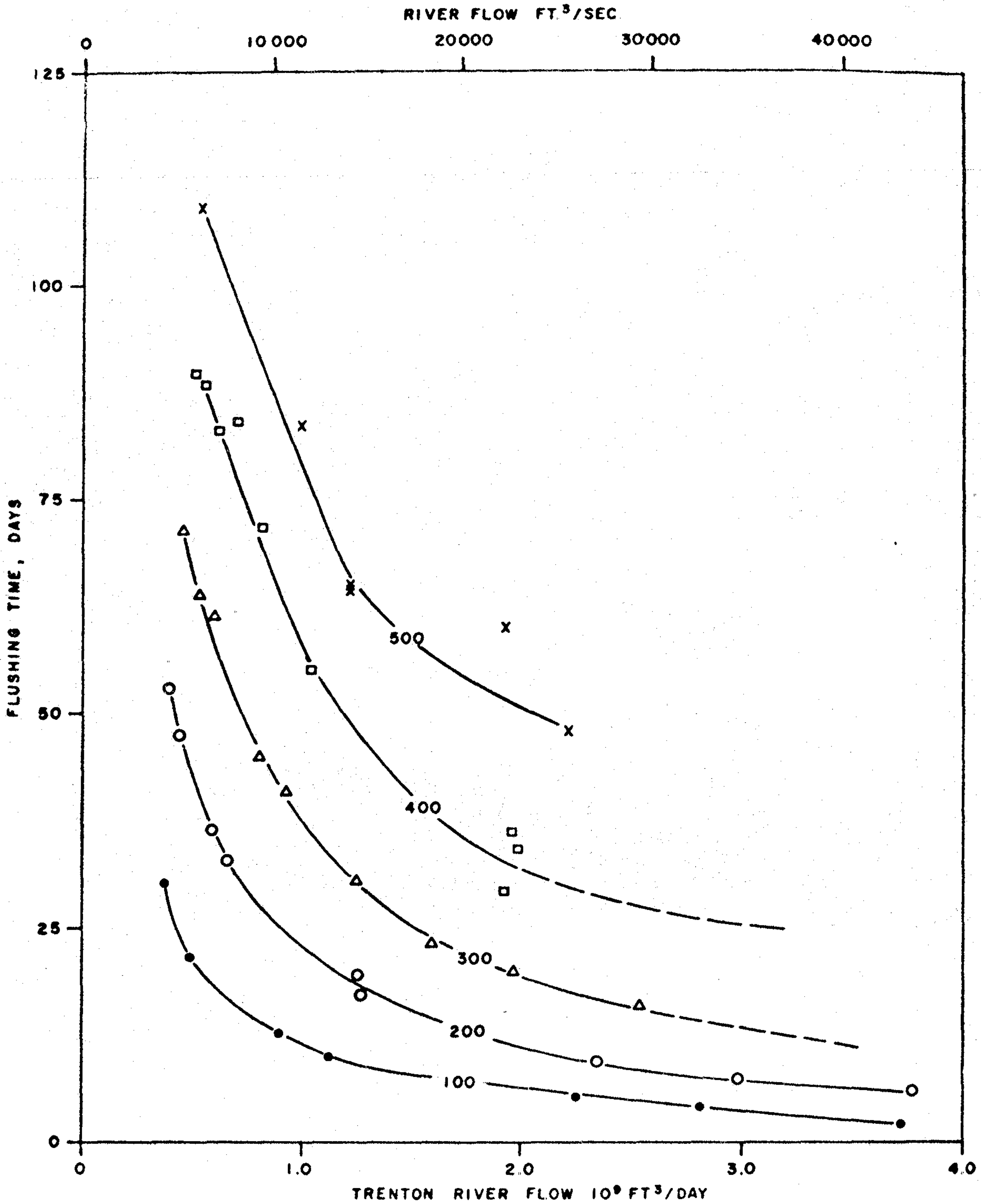


Figure 20

The cumulative flushing times between Trenton and various boundaries in the Delaware Estuary as a function of river flow at Trenton. The numbers on the curves represent the Channel Station at the outer boundary of the part of the estuary considered (from Ketchum 1952). For locations of Channel Stations see Figure 2.

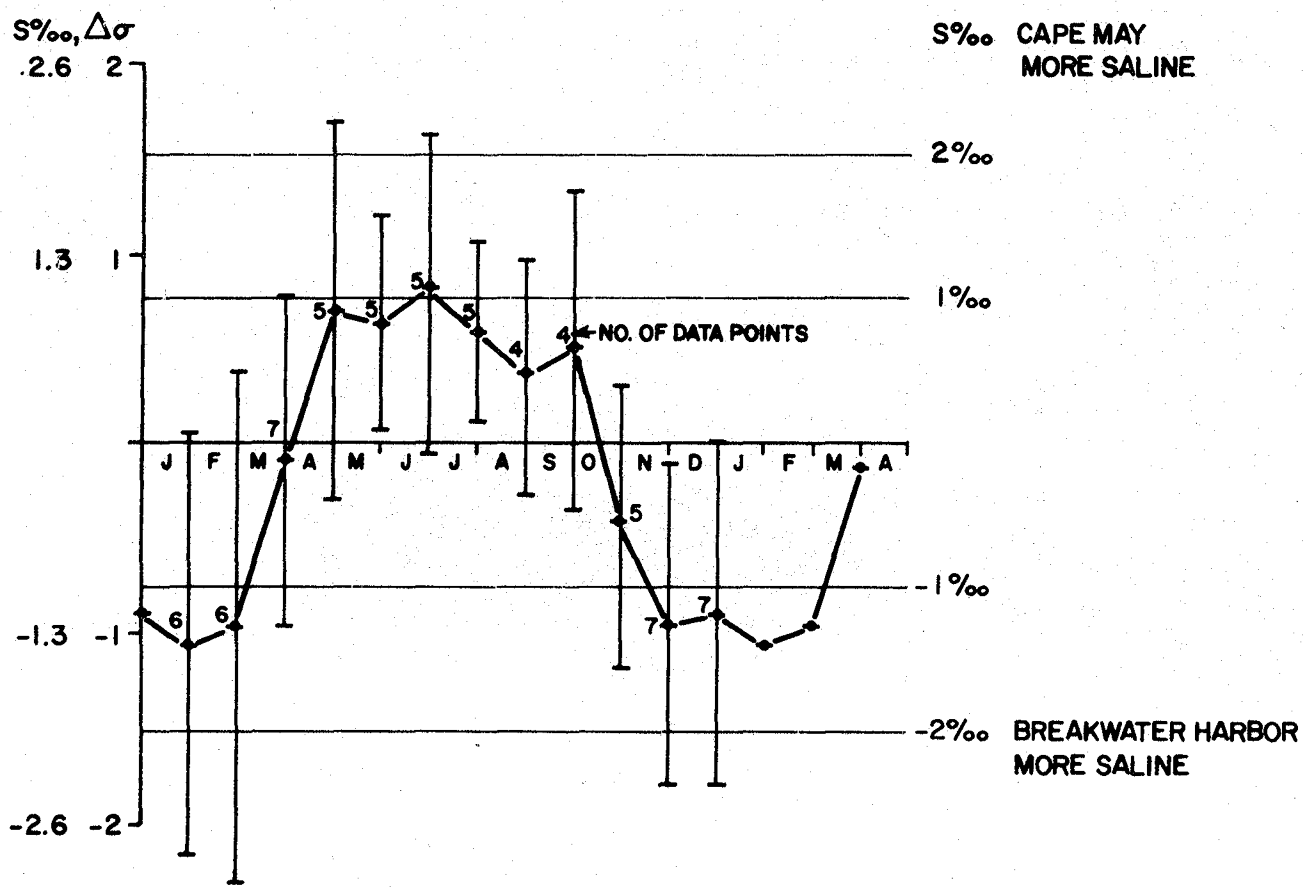

S‰, Δσ
2.6 2
1.3 1
-1.3 -1
-2.6 -2
S‰ CAPE MAY MORE SALINE
2‰
1‰
-1‰
-2‰ BREAKWATER HARBOR MORE SALINE
NO. OF DATA POINTS
J F M A M J J A S O N D J F M A

Figure 21

data was available at both stations, and plotting the means and standard deviations. The exact explanation of this phenomenon is not known. It may involve wind mixing, seasonal variations in river discharge and possibly a reversal in the offshore surface current.

Figure 22, taken from Cronin (1954) shows the salinity along the navigation channel measured on nine different cruises (the Delzoop cruises). The variation in salinity from cruise to cruise is due primarily to changes in the flow rate of the river. The river flow can be as much as twenty-five times larger, or ten times smaller than its long-term average value.

Figure 23, taken from Cronin, et al. (1962) shows the vertical distribution of salinity along the navigation channel for various seasons of the year. As we mentioned in our discussion of currents, the fresher water tends to override the more saline water, causing stratification. This is seen most clearly in the spring, the season when the river flow is at its peak. The phenomenon occurs because pure ocean water is about 2-1/2% denser than fresh water and therefore tends to move along the bottom. The degree to which stratification occurs has been used as the basis of systems of estuary classification. These systems depend ultimately on the intensity of the mixing taking place in the estuary. If there were no mixing between river water and ocean water, an estuary would be filled with ocean water capped by a thin layer of fresh water. The fresh water would move through the estuary from the river to the sea just fast enough to remove the discharge of the river. Such an estuary is called a stratified estuary. At the other

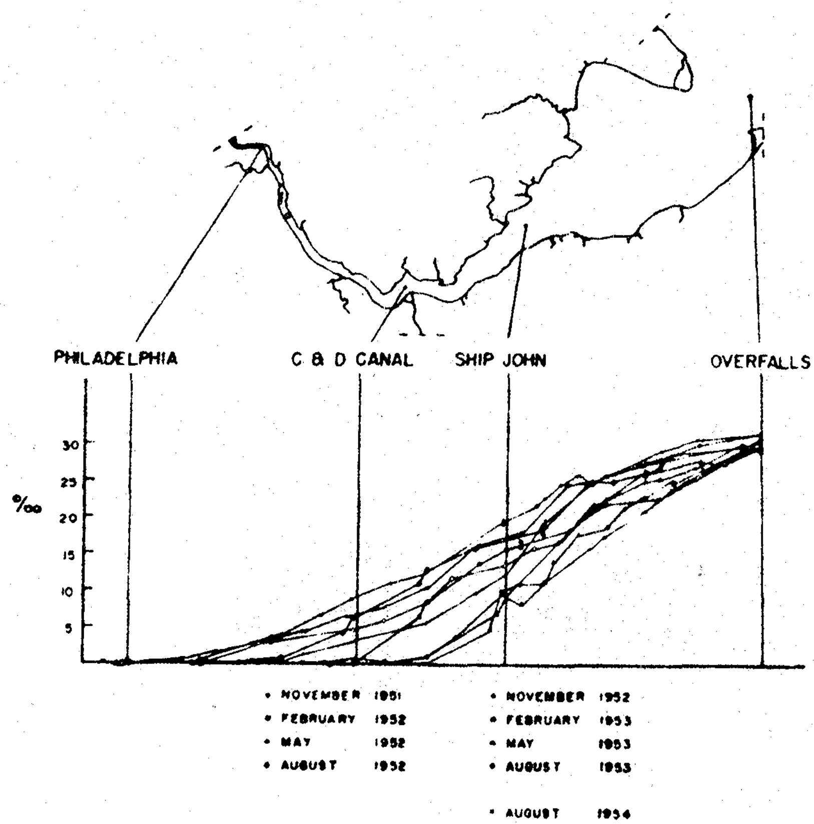
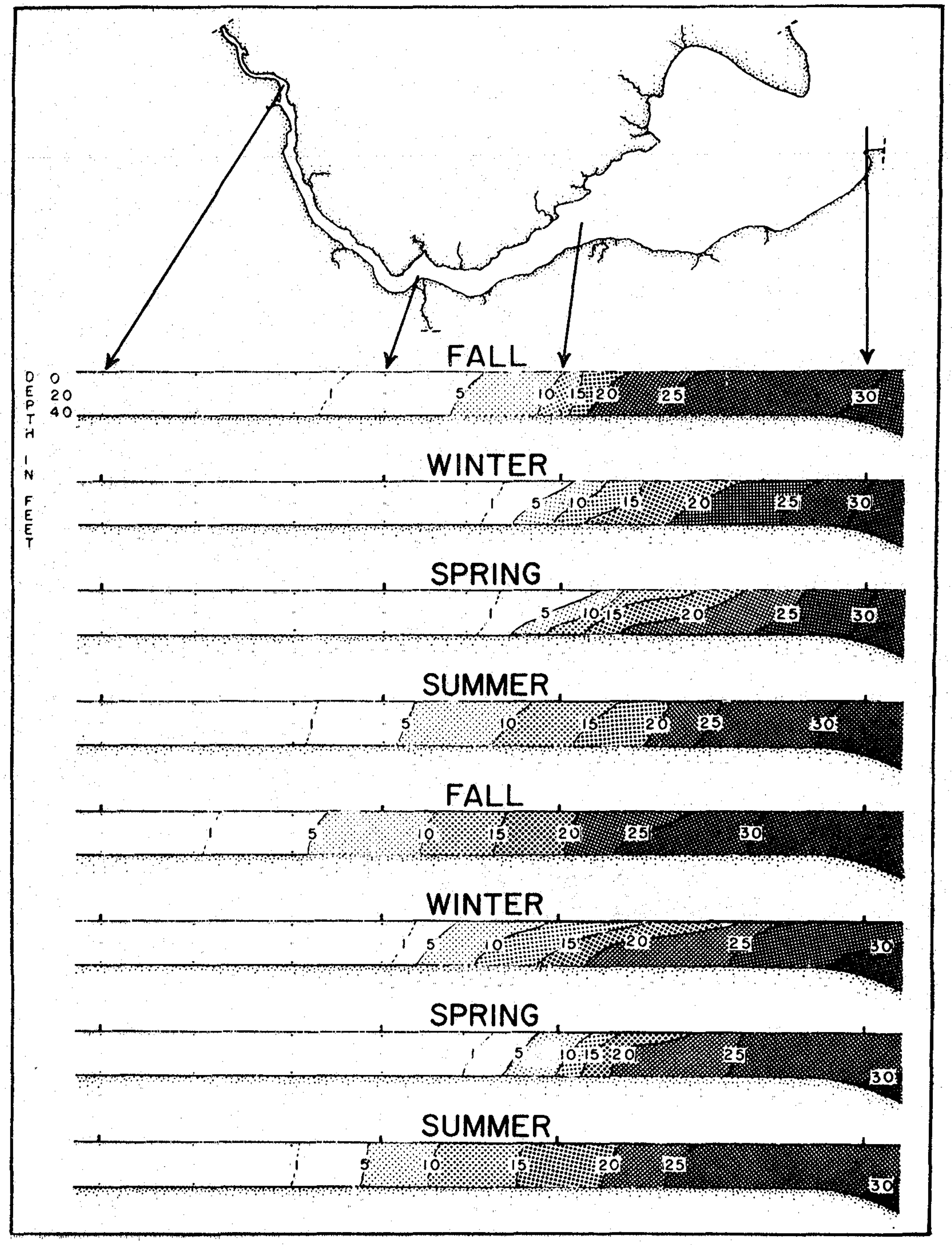


Figure 22

Average Channel Salinity in the Delaware Estuary, from Eight Delzoop Cruises and one JD Cruise



From Cronin, Daiber, and Hulbert (1962)

Figure 23

Salinity in the Delaware Estuary for each cruise. Location of isohalines and their degree of horizontal stratification both reflect recent flows into the estuary.

extreme is the vertically mixed estuary which has the same salinity from top to bottom; the water has a net seaward flow at all levels. The factors which tend to induce mixing are the tidal motions, the roughness of the boundaries, wide shallow basins and the wind stresses on the surface. Opposing factors are high river flow and narrow deep channels. The effect of increased flow is to increase the stratification of the water column. This means that while the surface salinity will decrease with increased river flow, bottom salinity will not decrease as rapidly and under some circumstances may actually increase. The data indicates that the bay actually changes estuarine type with variations in discharge, going from a vertical homogeneous to a partially mixed configuration. In addition to the effect of river flow, salinity is effected to a lesser extent by monthly variations in tidal height and by changes in mean sea level. In the bay, the variations in the salinity of coastal water moving down the New Jersey coast must also be considered.

One point that has not yet been discussed is the presence of rapid spatial variations of salinity in the bay. This phenomenon is currently under study (Szekielda, Kupferman, Klemas and Polis, 1972). During the winter of 1971, horizontal variations up to four parts per thousand in one meter were observed. On one occasion, such a front moved through a station being occupied. Had the station been taken 15 minutes earlier or later the front would not have been observed. This implies that smooth isohalines drawn from station data must be interpreted with caution. The biological effects of these sudden changes on the immobile benthic populations can only be guessed at present.

Availability of Data:

A large amount of salinity data is available for the bay and consists of:

1. Data obtained during the Delzoop, J-D, and Winterim cruises covering the period of 1951-1959 and January, 1972. The dates of these cruises are shown in Table XVII. The general location of the stations are shown in Figures 24a and 24b. Surface isohalines plotted from J-D Cruise data are shown in Figures 25a through 25n (corrected to high tide at the Capes).
2. Extensive salinity recordings made by the Corps of Engineers in connection with the Delaware River Estuary model study (Commonwealth of Pennsylvania, 1934). The recordings (USACE 1930-39) covered the period 1930-1939 and were made by the Philadelphia District.
3. An hourly time series of salinity measurements made by the Corps of Engineers for the period 25 January to 8 February 1932 for the following locations: Ship John, abreast Ben Davis Gas Buoy, abreast Elbow of Cross Ledge Light House, abreast Miah Maull and abreast Brandywine Shoal.
4. Daily recordings made by the Delaware River Master (1954 to date) since 1954 at Reedy Island, Delaware Memorial Bridge and Chester.
5. Hourly salinity recordings at Ship John for the period 1969-present by the U. S. Geological Survey.

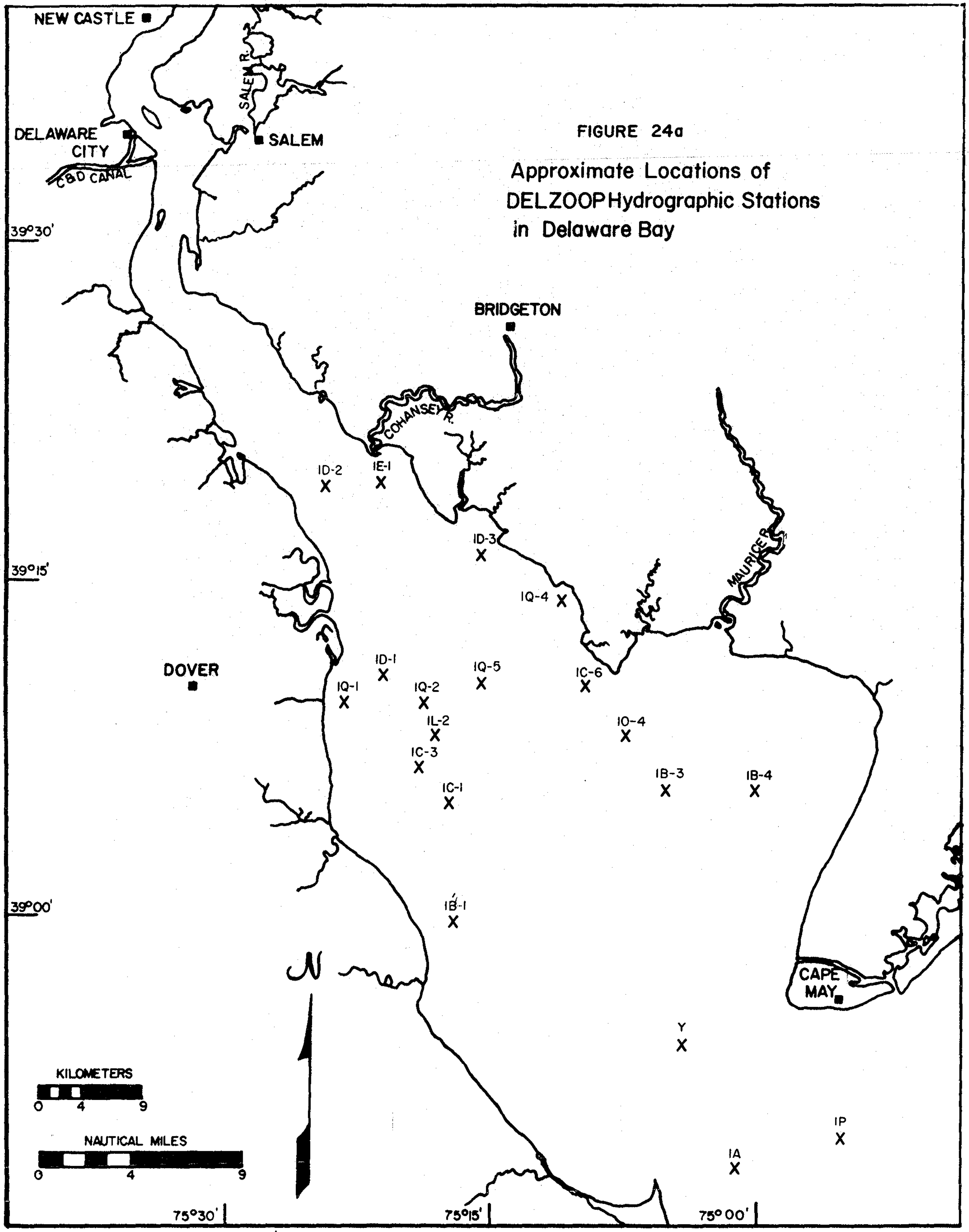
Table XVII

Hydrographic Cruises
in Delaware Bay

Cruise	Date
DELZOOP I	10 Oct. - 10 Nov. 1951
DELZOOP II	30 Nov. - 3 Dec. 1951
DELZOOP III	1-6 Feb. 1952
DELZOOP IV	22-29 May 1952
DELZOOP V	18-22 Aug. 1952
DELZOOP VI	10-17 Nov. 1952
DELZOOP VII	5-12 Feb. 1953
DELZOOP VIII	30 May - 6 June 1953
DELZOOP IX	20-25 Aug. 1953
J-D I	9-13 Aug. 1954
J-D II	18-20 Oct. 1954
J-D III	7-14 March 1955
J-D IV	1-3 Aug. 1955
J-D IV A	22 Aug. 1955
J-D IV B	29 Aug. 1955
J-D V	24-29 Sept. 1955
J-D VI	6, 8, 9 Feb. and 3 March 1956
J-D VII	27 July - 2 Aug. 1956
J-D VIII	27-8 Feb and 3, 6, 11, 14 March 1957
J-D IX	? Winter 1957
J-D X	?? 10-25 July 1958 (Spring 1957?)
J-D XI	?
J-D XI A	21-29 Aug. 1957
J-D XII	30-31 Oct. and 7 Nov. 1957
J-D XIII	5, 6, 10 March 1958
J-D XIV	30 April 1958 and 1, 7, 12, 26 May '58
J-D XV	Sept. 1958
J-D XVI	4, 5, 12 Nov. 1958
J-D XVII	25-27 Feb. 1959 and 3-5 March 1959
Winterim	10-12, 19 Jan. 1972

FIGURE 24a

Approximate Locations of DELZOOP Hydrographic Stations in Delaware Bay



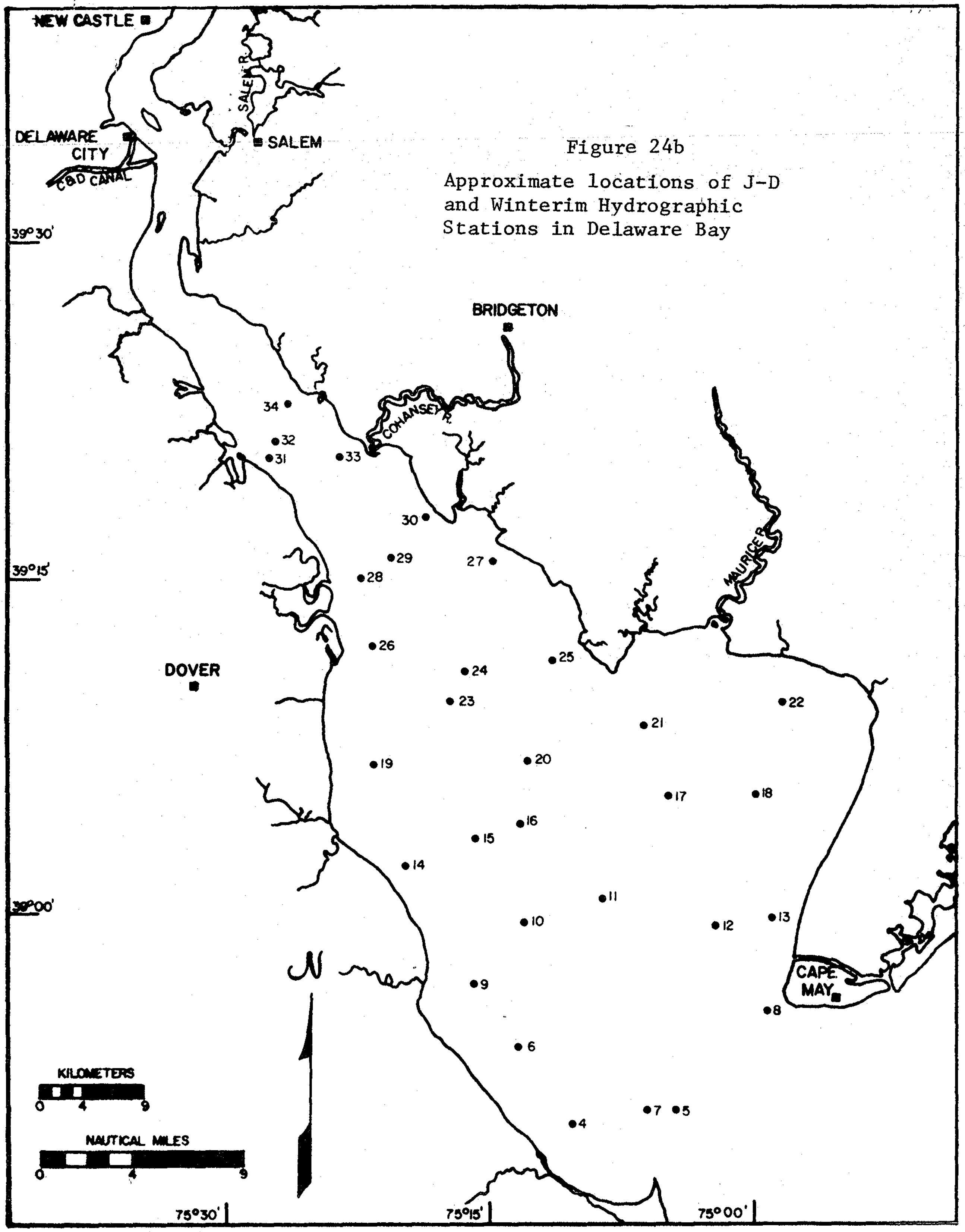


Figure 24b

Approximate locations of J-D and Winterim Hydrographic Stations in Delaware Bay

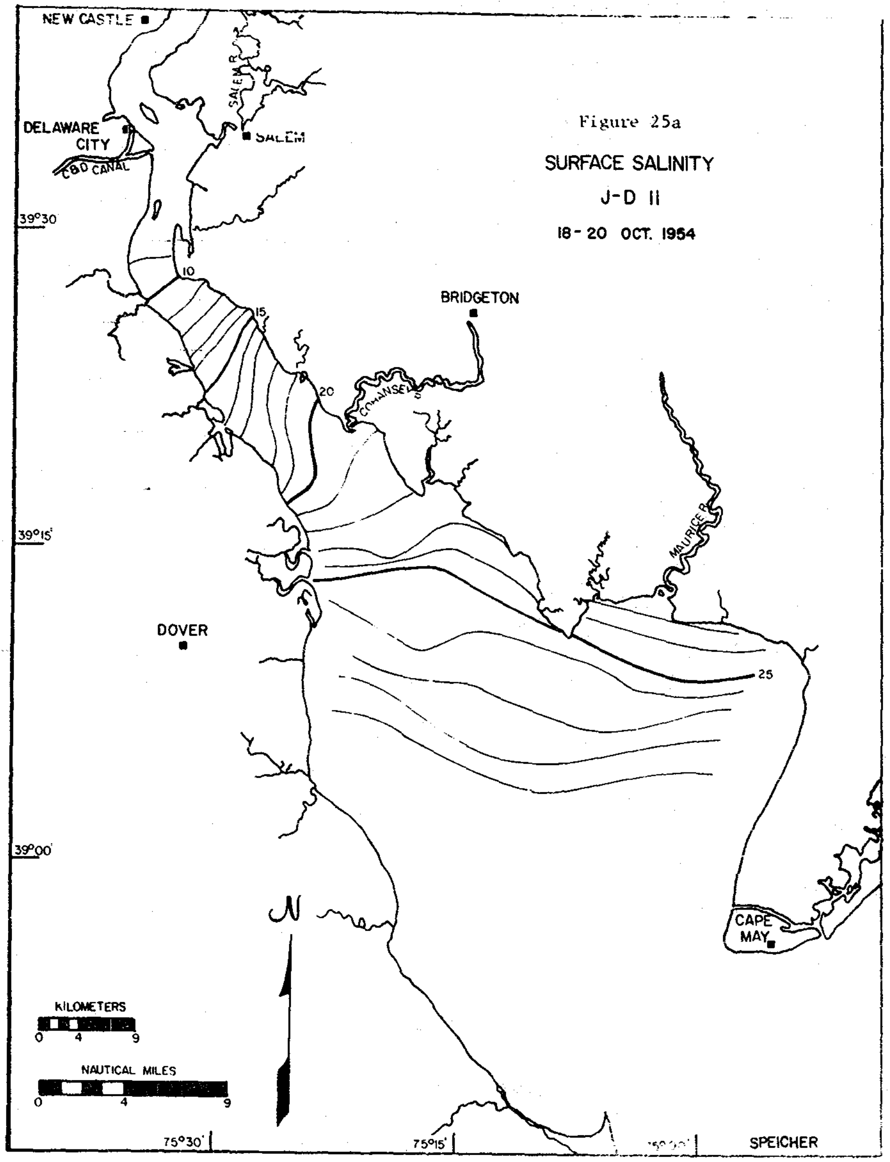


Figure 25a
SURFACE SALINITY
J-D II
18-20 OCT. 1954

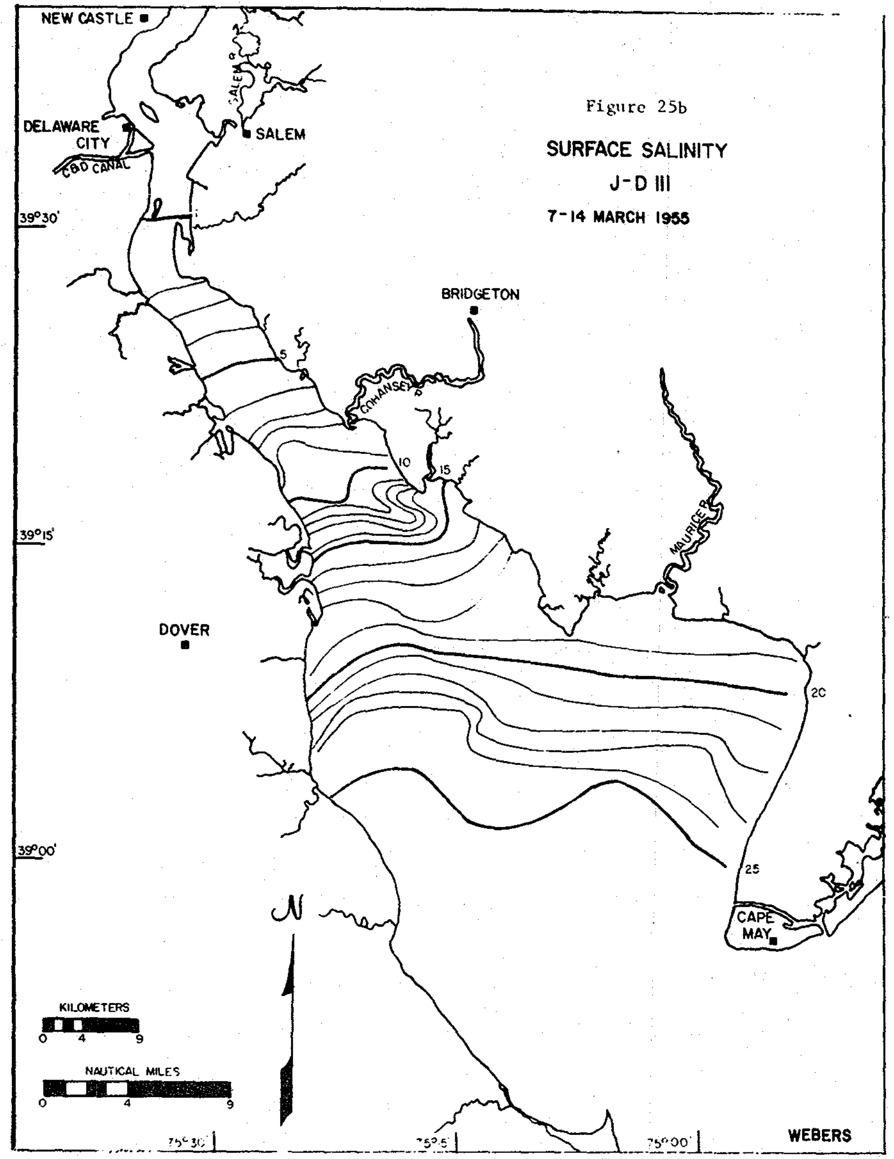


Figure 25b
SURFACE SALINITY
J-D III
7-14 MARCH 1955

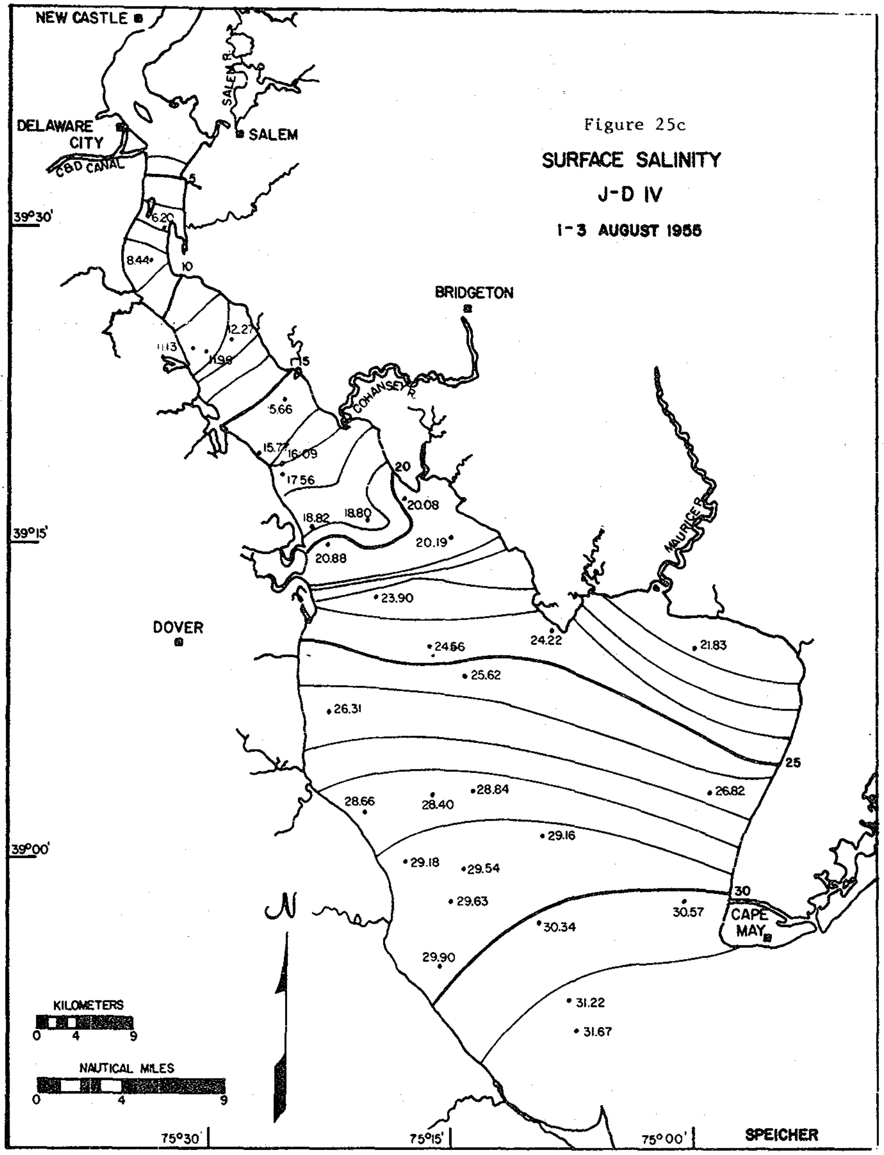


Figure 25c

SURFACE SALINITY

J-D IV

1-3 AUGUST 1955

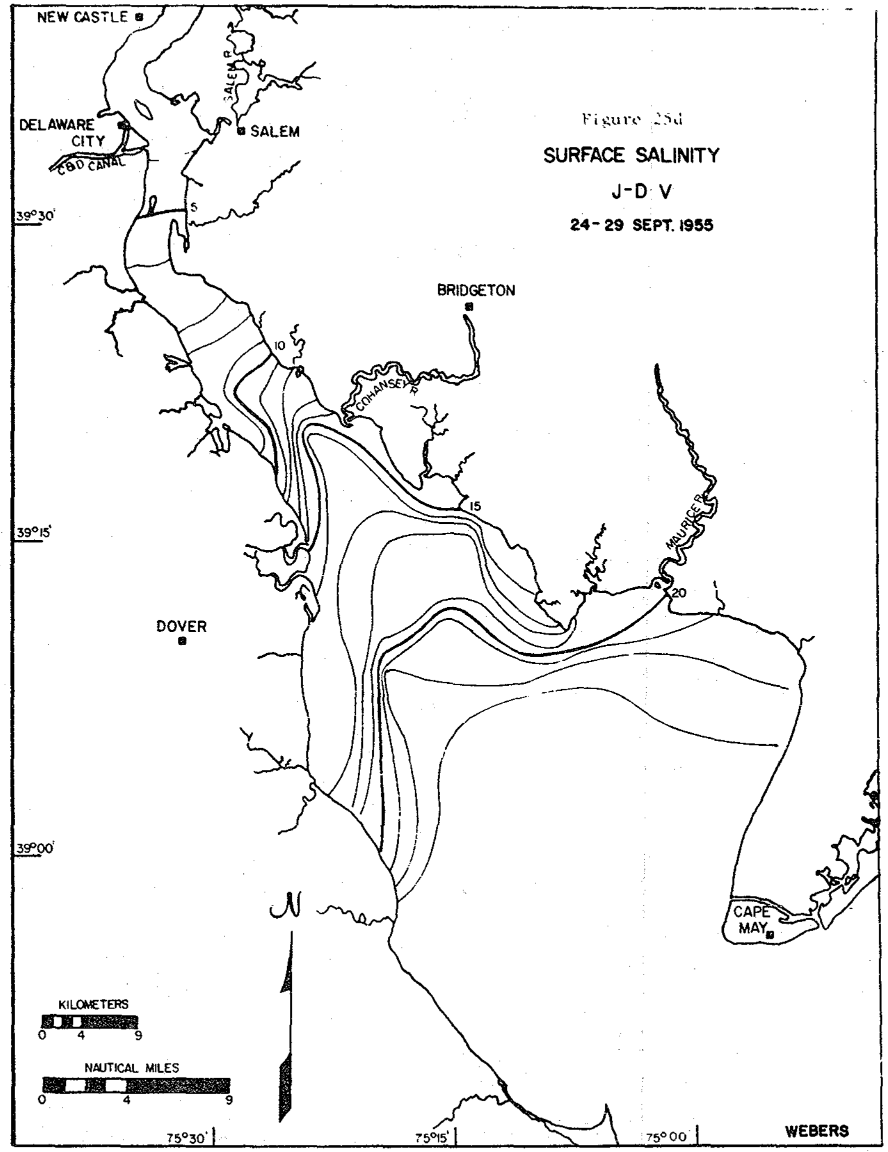


Figure 25d

SURFACE SALINITY

J-D V

24-29 SEPT. 1955

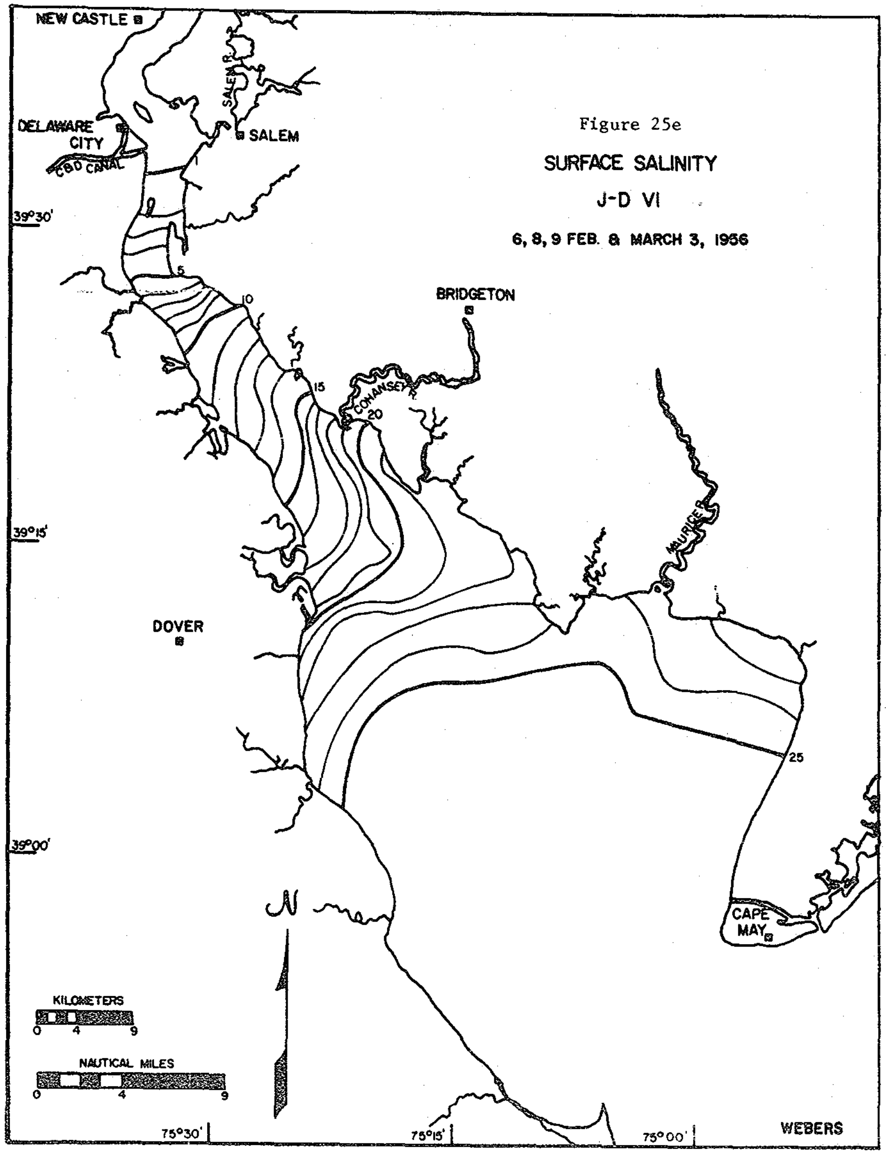


Figure 25e

SURFACE SALINITY

J-D VI

6, 8, 9 FEB. & MARCH 3, 1956

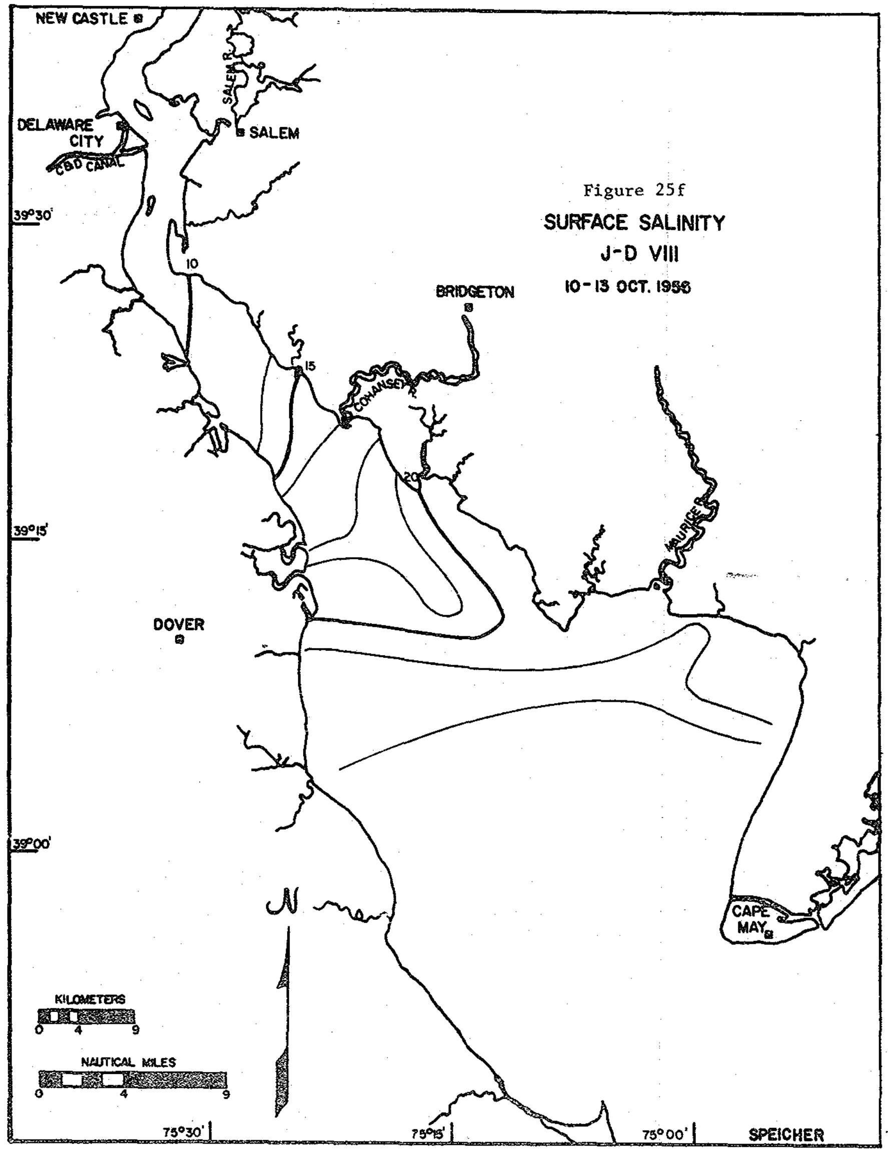


Figure 25f

SURFACE SALINITY

J-D VIII

10-13 OCT. 1956

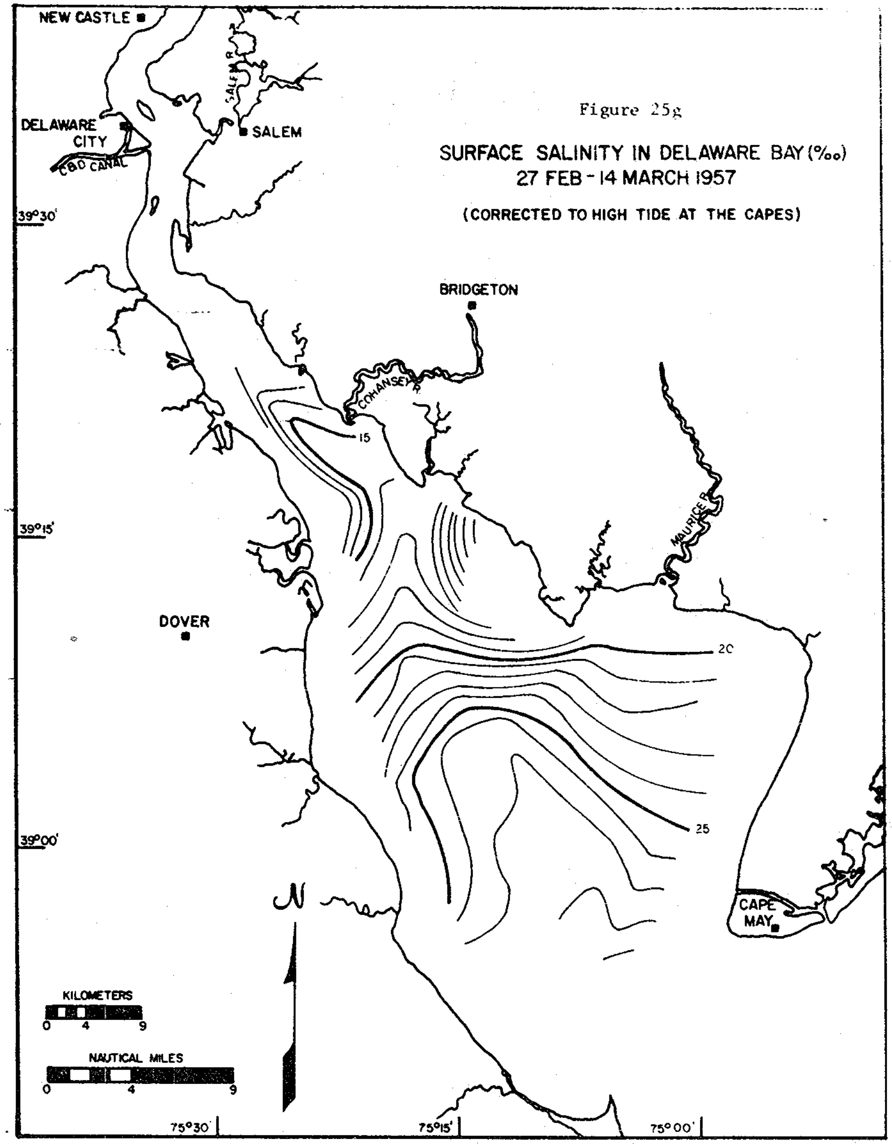


Figure 25g

SURFACE SALINITY IN DELAWARE BAY (‰)
27 FEB - 14 MARCH 1957

(CORRECTED TO HIGH TIDE AT THE CAPES)

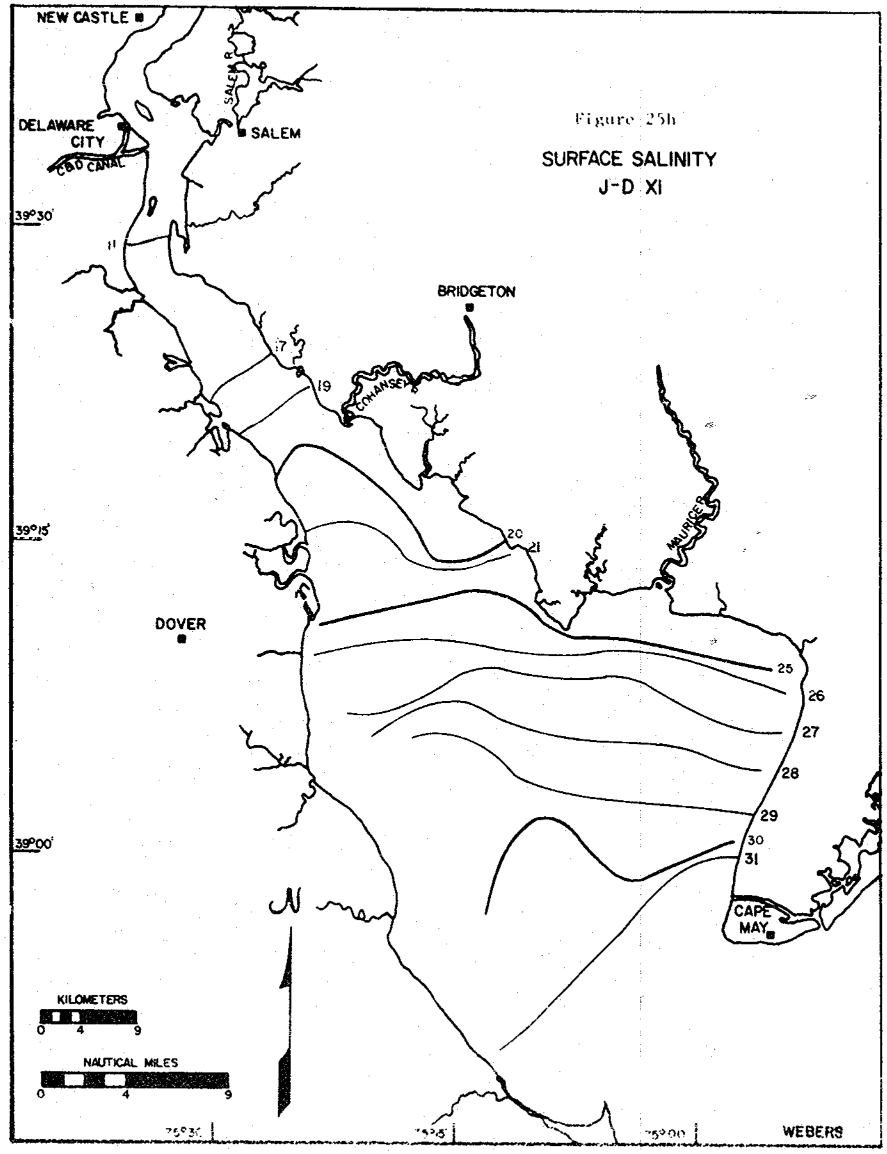


Figure 25h

SURFACE SALINITY
J-D XI

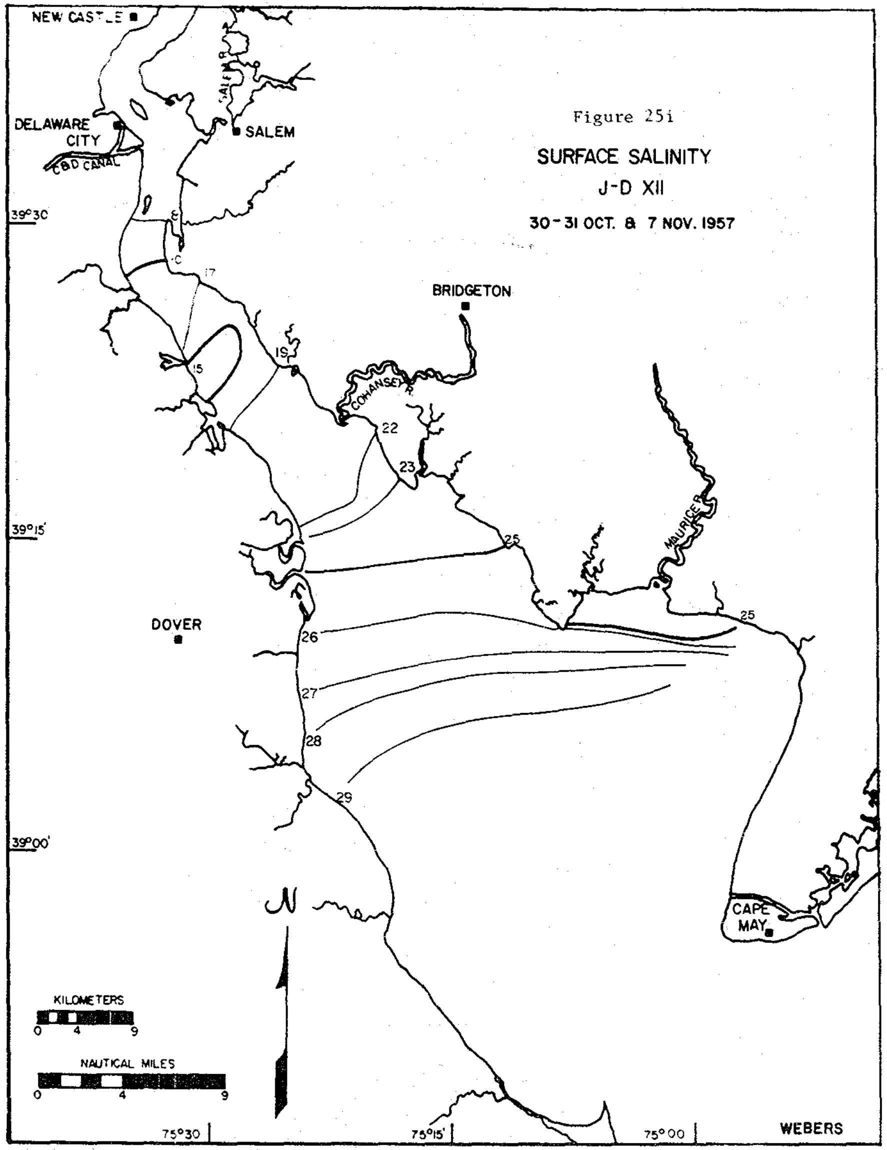


Figure 25i

SURFACE SALINITY
J-D XII
30-31 OCT. & 7 NOV. 1957

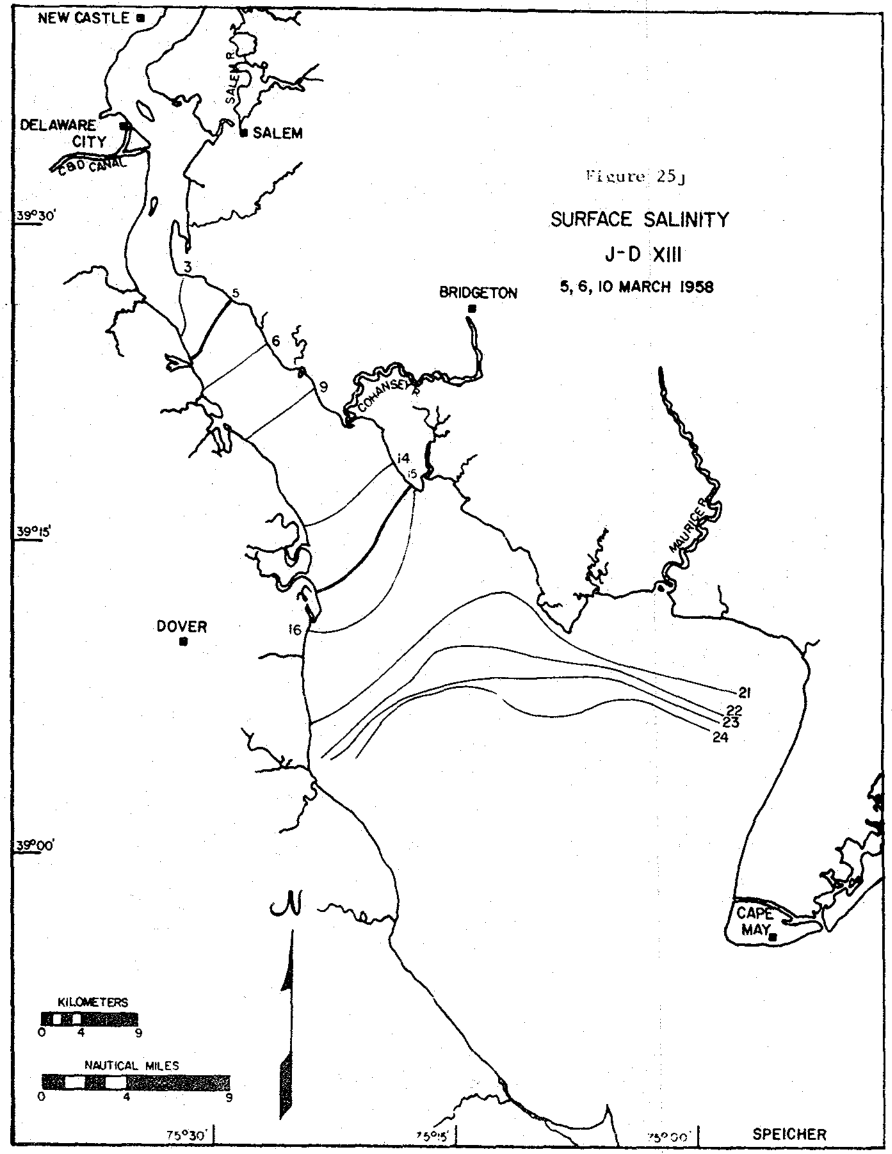


Figure 25j

SURFACE SALINITY
J-D XIII
5, 6, 10 MARCH 1958

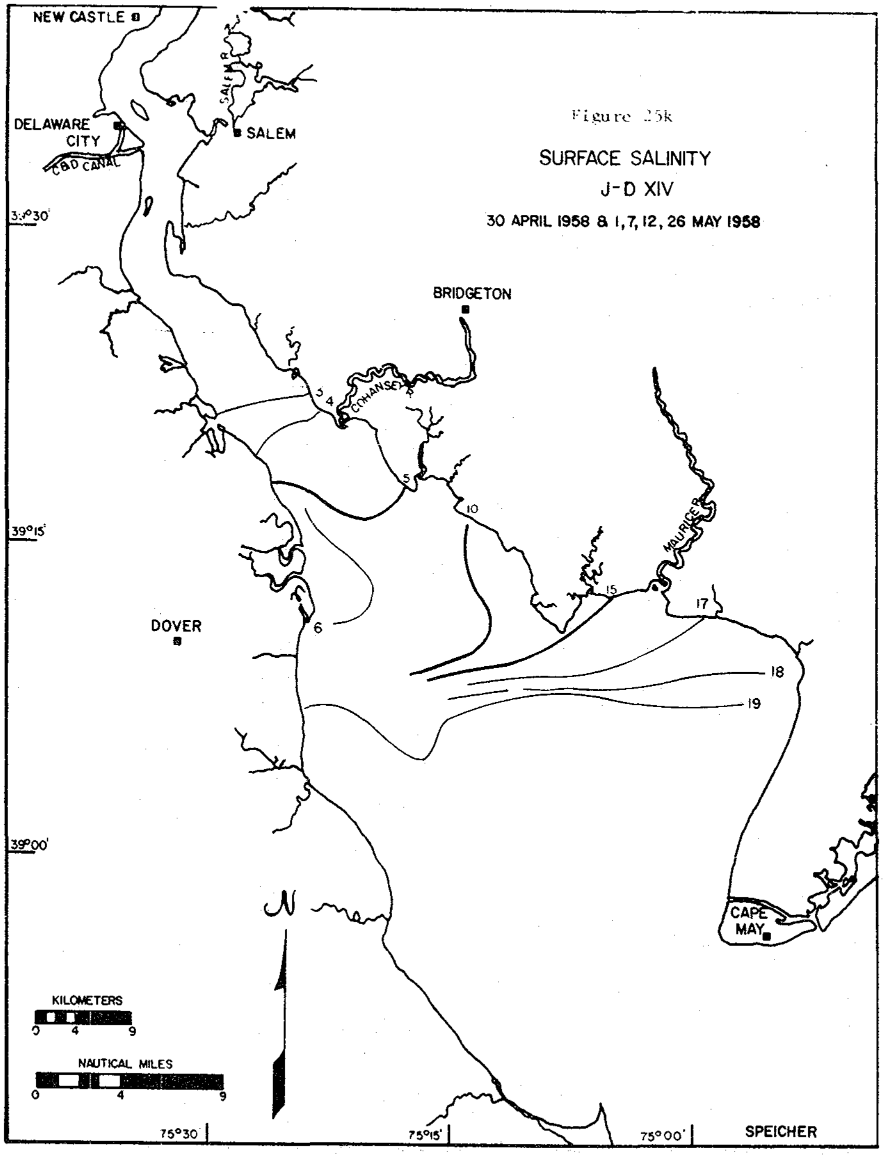


Figure 25k

SURFACE SALINITY
J-D XIV
30 APRIL 1958 & 1, 7, 12, 26 MAY 1958

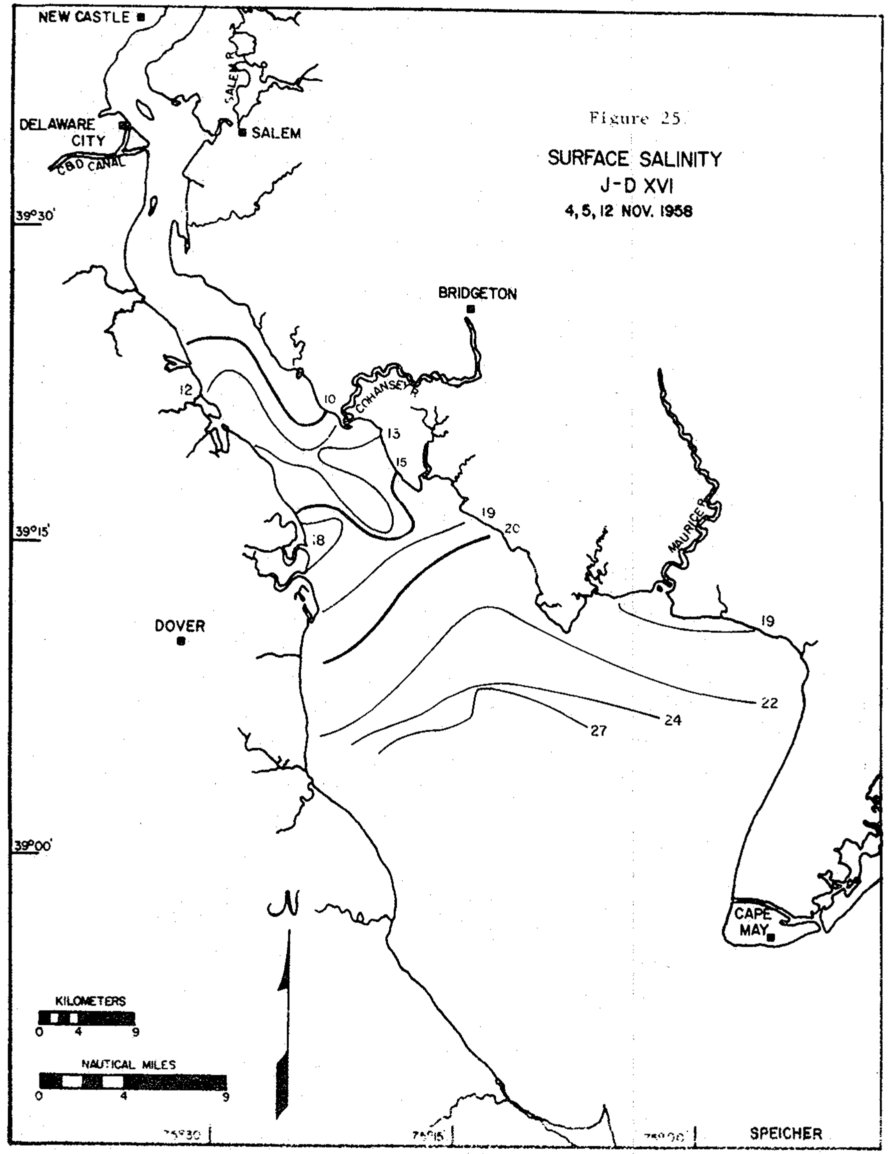


Figure 25

SURFACE SALINITY
J-D XVI
4, 5, 12 NOV. 1958

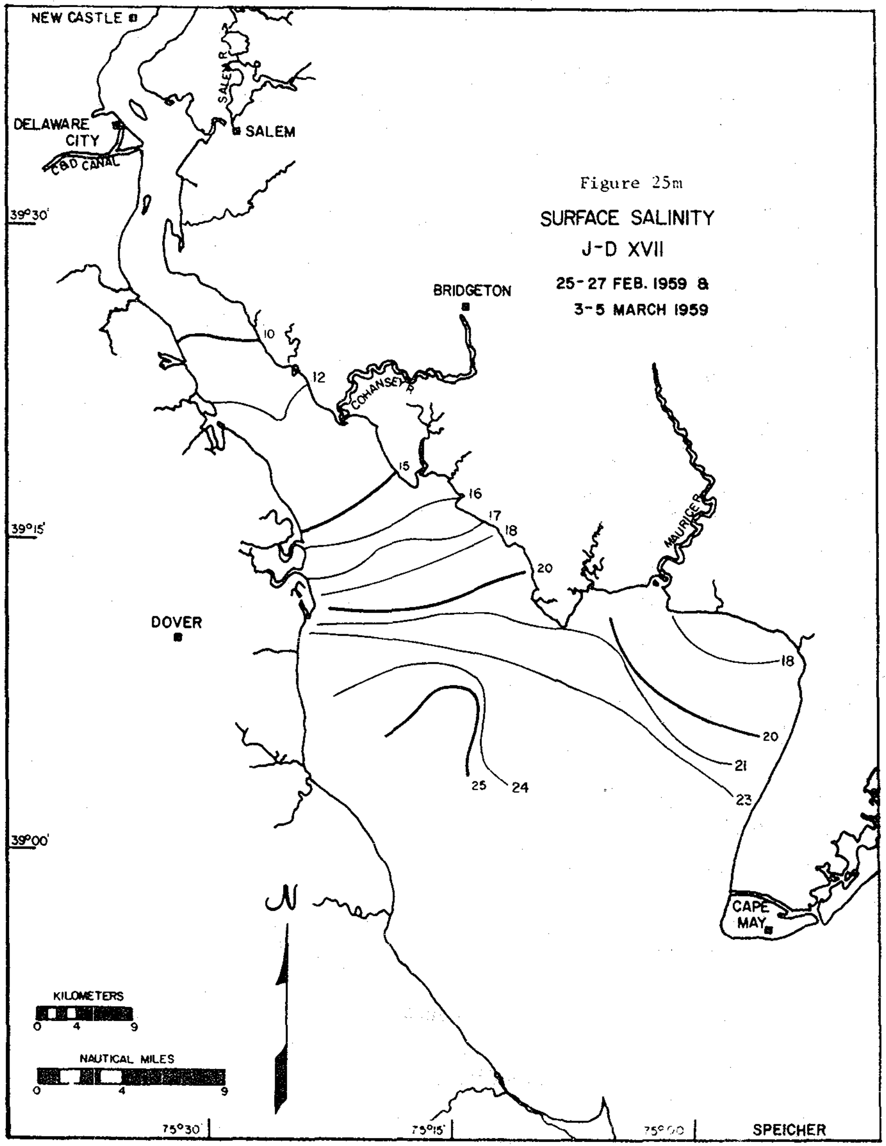


Figure 25m
SURFACE SALINITY
J-D XVII
25-27 FEB. 1959 &
3-5 MARCH 1959

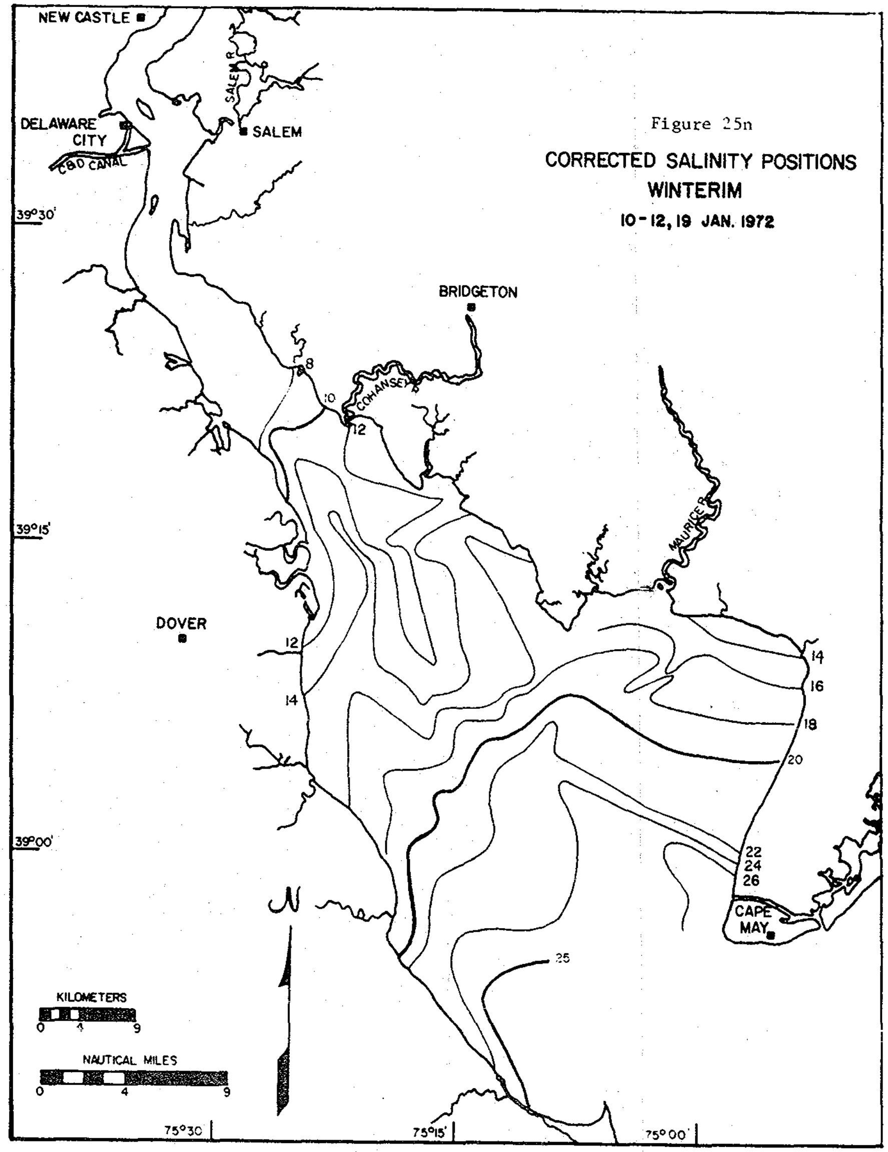


Figure 25n
CORRECTED SALINITY POSITIONS
WINTERIM
10-12, 19 JAN. 1972

6. Observations on salinity variation with depth (Oostdam 1971).
7. Density observations made by NOS at Breakwater Harbor in a broken series from 1919 to the present, as well as a shorter series at Cape May. (See Table XVIII.)
8. Data taken in connection with biological cruises of Delaware Bay, a typical example being that of de Sylva (1958), Figure 26.
9. Hydrography surveys of the Harbor of Refuge area made by Whitney (1968, 1970).

The data presently available are probably adequate to provide a historical baseline on the salinity distributions in Delaware Bay prior to the widening of the C & D Canal. Since that time, there has been only one systematic hydrographic cruise (Winterim 1972). However, there have been data taken at the fixed continuous stations listed under items (4) and (5) above, which could be analyzed to find the effects on the salinity distribution of the navigation improvements on the canal.

TEMPERATURE

In the lower estuary, temperature generally increases with depth in the winter and decreases with depth in the summer. Slight lateral

Table XVIII - Surface Water Temperatures and Densities
Means and Extremes (NOS Data)

Years	January Temp. °C	January Dens. σ_{15}	February Temp. °C	February Dens. σ_{15}	March Temp. °C	March Dens. σ_{15}	April Temp. °C	April Dens. σ_{15}	May Temp. °C	May Dens. σ_{15}	June Temp. °C	June Dens. σ_{15}	July Temp. °C	July Dens. σ_{15}
							CAPE MAY, NEW JERSEY							
1965	--	--	--	--	--	--	--	--	--	--	--	--	--	--
1966	2.1	20.6	1.1	21.2	6.2	21.6	9.0	21.7	14.5	22.6	19.3	22.4	22.4	23.1
							BREAKWATER HARBOR, DELAWARE							
1919-1923	3.1	21.0	2.3	20.9	6.8	20.6	9.6	20.2	14.5	20.9	20.0	20.8	22.9	21.8
--														
1947-1949	3.1	20.0	3.4	20.1	5.9	20.0	10.7	20.4	15.4	20.5	21.1	20.8	23.0	21.7
	5.5	20.8	4.9	20.7	6.8	20.9	11.0	20.1	15.9	20.4	20.3	20.6	23.7	21.7
	2.4	20.6	2.8	21.0	5.6	20.6	9.9	19.9	15.4	20.5	20.1	21.3	22.7	22.2
1960	4.2	19.3	3.9	20.0	1.7	19.8	10.9	20.3	15.8	21.0	20.8	20.8	21.6	21.9
1961	1.8	21.4	1.6	21.1	5.9	19.5	10.0	18.6	14.5	19.3	18.2	21.1	22.6	22.2
1962	2.6	20.9	--	--	4.2	20.0	--	--	--	--	--	--	--	--
1963	0.6	21.2	-0.3	21.6	5.4	21.0	10.8	19.9	14.3	21.6	--	--	--	--
1964	2.1	21.8	3.1	21.5	-- -	--	--	--	--	--	--	--	--	--
1965	3.3	22.3	1.8	22.4	5.1	22.2	8.4	21.4	16.3	22.7	18.6	23.3	21.8	23.5
1966	2.4	22.2	1.3	22.3	5.7	22.1	8.4	22.0	14.2	22.0	19.1	22.4	22.9	23.1
Mean	3.1	20.9	2.8	21.0	5.7	20.6	10.0	20.2	15.3	20.8	20.1	21.2	22.8	22.1
Maximum	10	23.2	8	23.3	16	23.2	16	24.1	21	23.9	28	23.9	30	24.3
Mean Max.	5.5	22.2	5.1	22.2	18.7	21.9	13.1	21.8	18.3	21.8	23.6	22.3	25.1	22.9
Mean Min.	0.6	19.1	0.7	19.2	2.9	18.3	6.6	18.0	11.8	19.3	17.0	19.6	20.8	21.1
Minimum	-2	15.0	-2	15.7	-1	15.7	2	15.0	9	15.1	14	14.5	19	18.7

Years	August Temp. °C	August Dens. σ_{15}	September Temp. °C	September Dens. σ_{15}	October Temp. °C	October Dens. σ_{15}	November Temp. °C	November Dens. σ_{15}	December Temp. °C	December Dens. σ_{15}	Means Temp. °C	Means Dens. σ_{15}	Maximum Temp. °C	Maximum Dens. σ_{15}	Minimum Temp. °C	Minimum Dens. σ_{15}
							CAPE MAY, NEW JERSEY									
1965	--	--	--	--	--	--	10.3	21.9	5.9	21.5	--	--	--	--	--	--
1966	22.9	23.2	20.6	23.3	16.2	22.0	10.8	22.0	6.5	20.9	12.6	22.0	26	24.8	-1	15.2
							BREAKWATER HARBOR, DELAWARE									
1919-1923	22.3	22.2	21.5	22.3	17.1	22.5	10.6	22.2	5.2	21.4	13.0	21.4	26	24.1	-2	16.6
--																
1947-1949	23.5	21.8	21.8	21.9	19.3	21.8	11.7	21.8	6.1	21.5	13.6	21.0	30	23.9	-2	15.4
	23.6	22.3	22.3	22.3	17.3	22.3	11.3	22.1	6.8	21.1	14.1	21.3	27	23.9	1	14.5
	23.3	22.1	22.2	22.1	16.9	21.9	11.6	21.2	5.7	20.8	13.2	21.2	28	24.3	-2	15.0
1960	24.1	21.5	23.0	20.4	16.6	19.9	12.0	21.0	3.9	21.2	13.2	20.6	26	22.7	-1	17.3
1961	23.7	22.4	22.2	22.2	17.2	21.5	11.2	21.8	5.7	21.6	12.9	21.1	26	23.1	-2	16.2
1962	--	--	--	--	--	--	--	--	3.6	20.9	--	--	--	22.2*	0*	17.5*
1963	22.6	22.6	19.0	21.9	16.9	22.4	11.4	22.2	3.4	22.5	--	--	26*	23.6*	-2	15.3*
1964	__	__	__	__	14.7	22.9	12.1	22.8	6.2	22.6	--	--	--	23.4*	-2	20.5*
1965	21.2	23.9	21.4	24.1	15.8	23.5	10.1	23.2	6.2	23.2	12.5	23.0	24	24.6	-1	18.5
1966	--	--	--	--	15.8	22.8	11.2	22.8	5.4	21.8	--	--	25*	23.9*	-2	20.9*
Mean	23.1	22.2	21.9	22.1	16.8	22.1	11.3	21.9	5.6	21.4	13.2	21.4				
Maximum	28	24.3	27	24.6	23	24.1	16	23.8	12	23.7			30	24.6		
Mean Max.	25.3	23.0	24.7	23.0	20.2	22.9	14.5	22.8	9.1	22.4						
Mean Min.	21.0	21.0	19.0	21.1	13.0	20.8	7.6	20.3	2.2	20.1						
Minimum	19	16.2	13	18.6	10	16.8	4	16.5	-2	16.3					-2	14.5

*Observations for the year are incomplete; extremes are for the months shown.

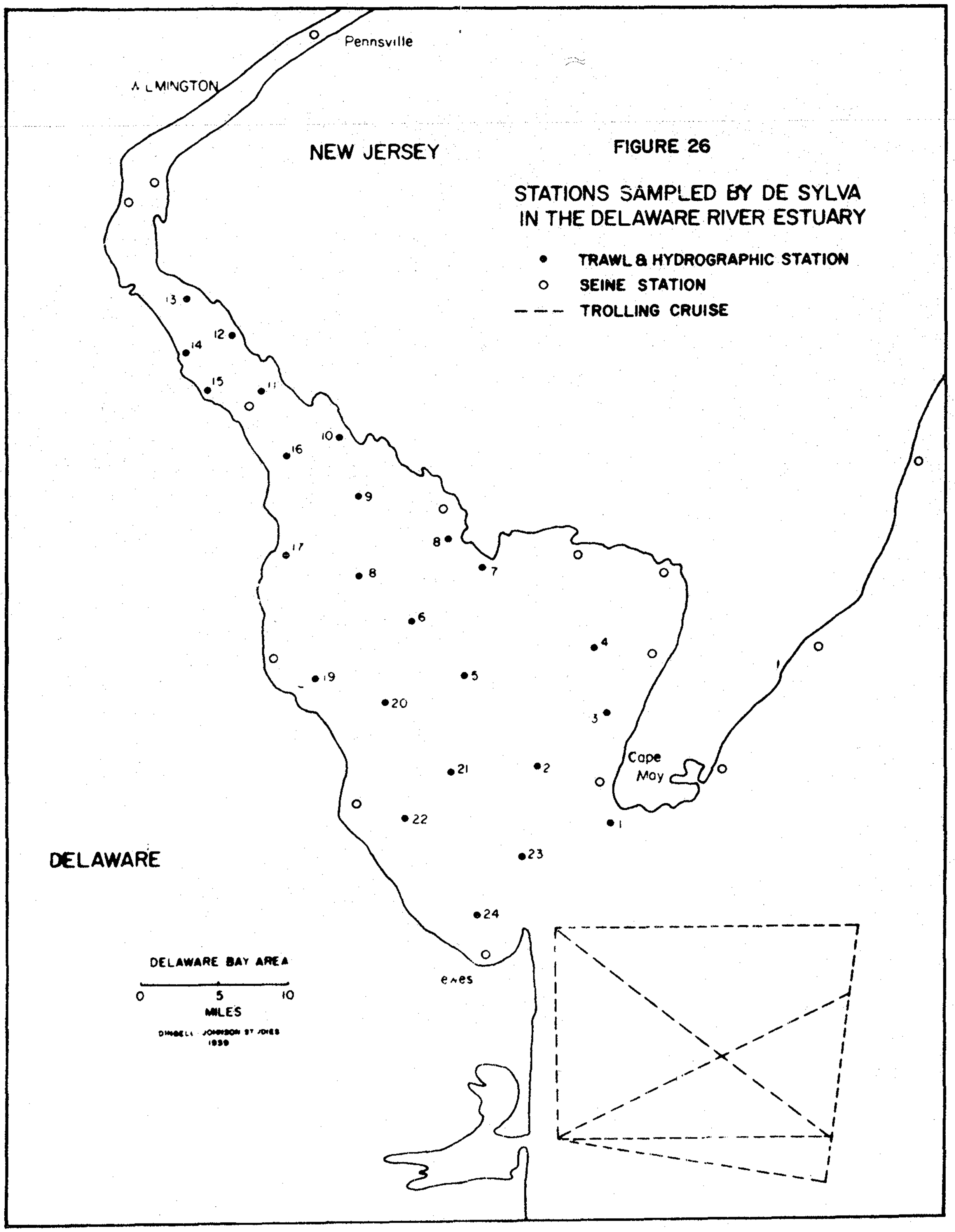


FIGURE 26

STATIONS SAMPLED BY DE SYLVA IN THE DELAWARE RIVER ESTUARY variations also occur. Temerpature has some slight affect on the density of the water and therefore on the circulation pattern of the bay; however, this affect is generally negligible in comparison with that of salinity. More important is the effect of temperature on the biota, where it is often a controlling factor.

In the upper estuary, temperature is controlled primarily by air temperature and solar radiation and is relatively constant along the estuary. Vertical distributions of water temperature along the navigation channel for various seasons of the year are shown in Figure 27. Monthly mean temperature and density curves at Breakwater Harbor and Philadelphia are shown in Figure 28. Figure 29 shows a typical surface temperature distribution in fall.

Availability of Data

Temperature data available is slightly less extensive than that for salinity and consists of:

1. Observations made during Delzoop, J-D, and Winterim cruises.
2. Temperature recordings made in conjunction with biological cruises, as for example de Sylva, et al. (1962), Daiber and Wockley (1968) Raney et al. (1972).
3. Mean monthly temperature for Delaware Estuary collected by the U. S. Coast and Geodetic survey in references USGS (1963a) and USGS (1963b), and summarized in Table XVIII.

The data on temperature are believed adequate to the foreseeable short-term needs. They should be particularly useful for power plant siting studies. The possibility and effects -- both physical and

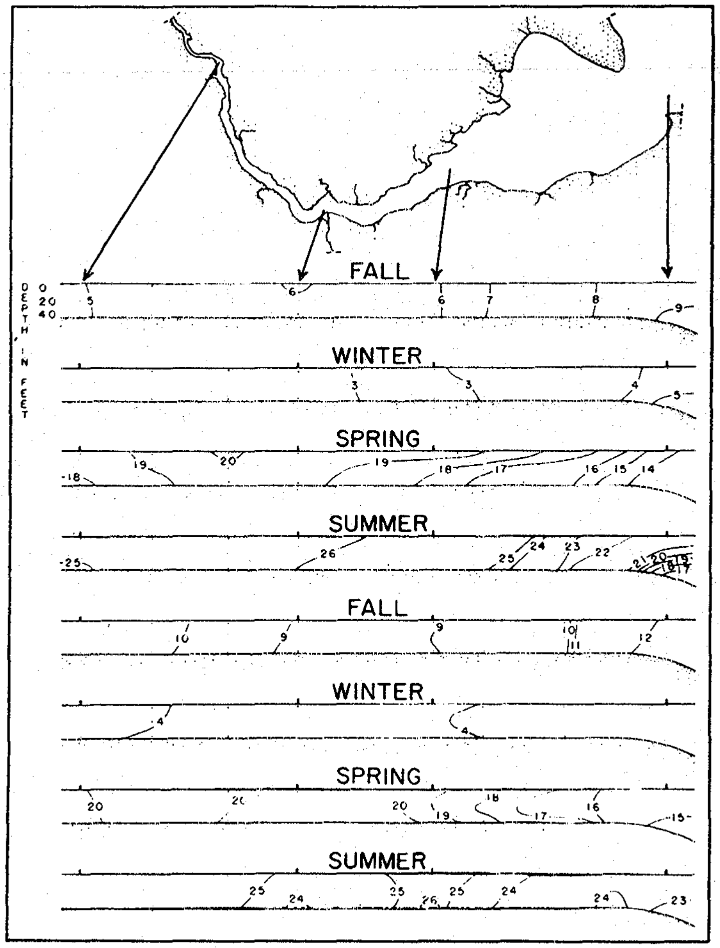


Figure 27

Temperatures (Centigrade) in the Delaware Estuary for each cruise. Upstream portions most nearly reflect air temperatures, while the lower estuary is always tempered by the more stable Atlantic ocean. (From Cronin, Daiber, and Hulbert, 1962) biological -- of changes in the temperature regime should be the object of special attention in such studies. Massive amounts of hot water effluents could have the effect of further stabilizing the water column against turbulent mixing. The effect of this would be to increase stratification and alter the circulation pattern and salinity balance of the bay. A biological consequence might be the further invasion of oyster drills than might otherwise be the case.

Mean Temperature and Density Curves

Monthly mean surface water temperatures (in degrees Celsius) and densities (σ_{15}) are presented graphically to show the seasonal variation.

——— Temperatures - - - - - Densities

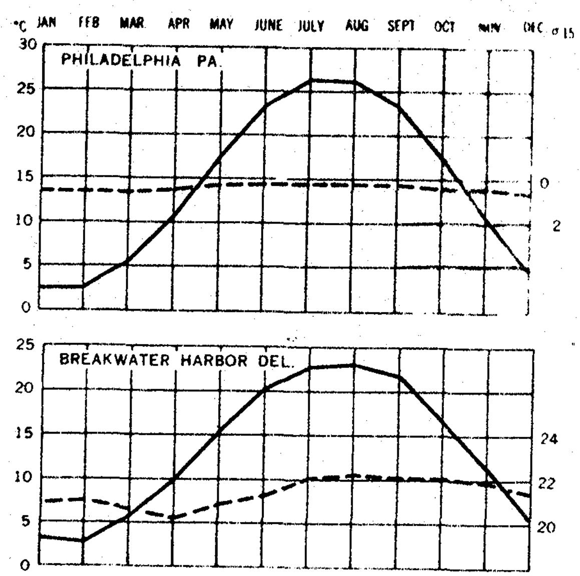


Figure 28

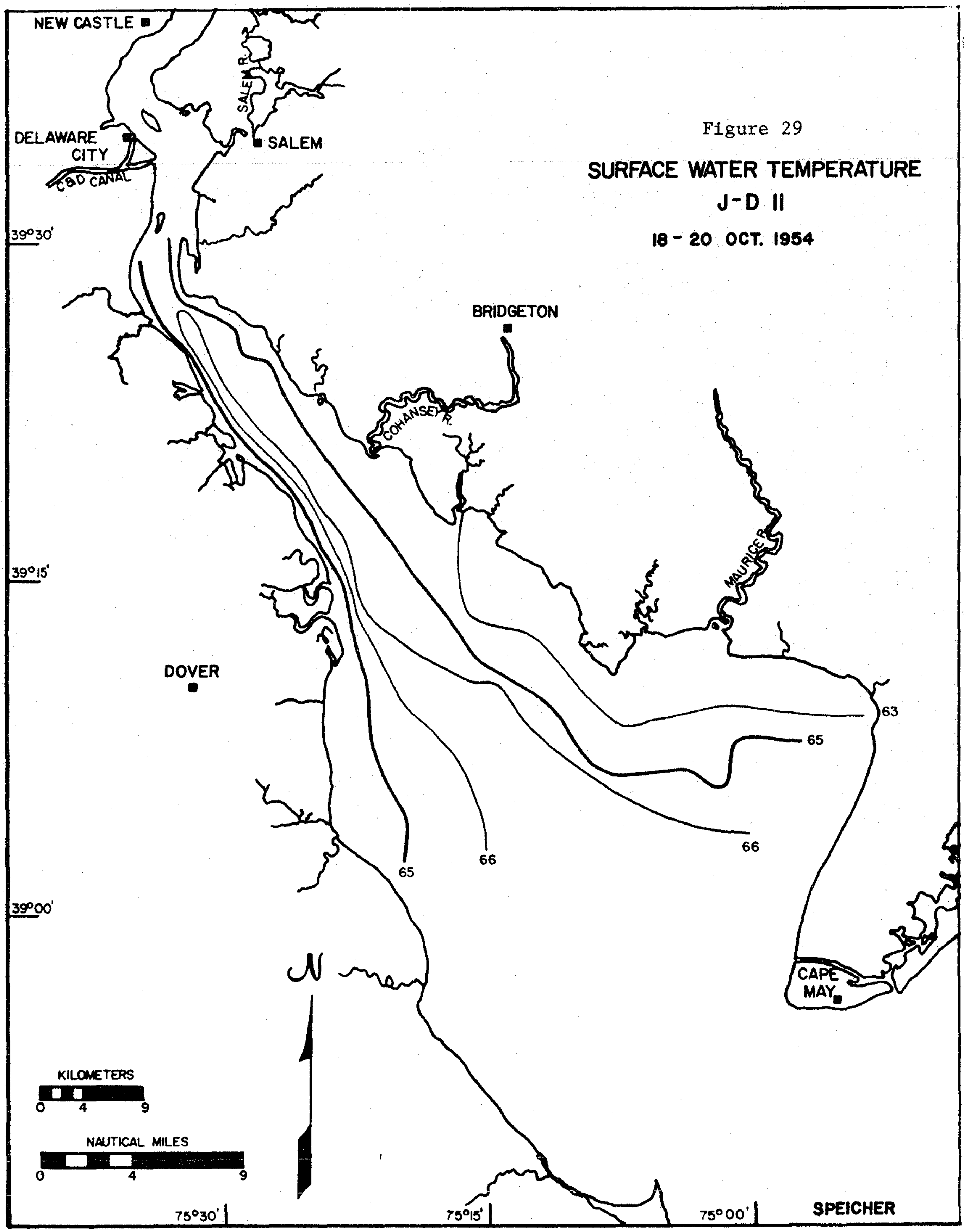


Figure 29
SURFACE WATER TEMPERATURE
J-D II
18 - 20 OCT. 1954
NEW CASTLE
SALEM R.
SALEM
DELAWARE CITY
C&D CANAL
39°30'
BRIDGETON
COHANSEY R.
MAURICE R.
39°15'
DOVER
63
65
66
66
65
39°00'
CAPE MAY
N
KILOMETERS
0 4 9
NAUTICAL MILES
0 4 9
75°30'
75°15'
75°00'
SPEICHER

APPENDIX

Net Transport of Water Through the Mouth of Delaware Bay*

The net transports shown in Figure 30 were computed from current data compiled by the National Ocean Survey (formerly the Coast and Geodetic Survey) during May and June of 1947, and May and June 1953. The data were taken at eleven stations across the mouth of the bay. These stations were not collinear, but the cross section was chosen as shown in Figure 31 in an effort to keep errors to a minimum. In the case where two stations correspond to the same transport box, the data were averaged. The data at each point were presented in the following manner:

(1) Location of station (degrees latitude & longitude)

(2) Date measurements were taken

(3) Depth of date point (feet)

(4) Flood/ebb duration (hours)

(5) Mean velocity (knots)

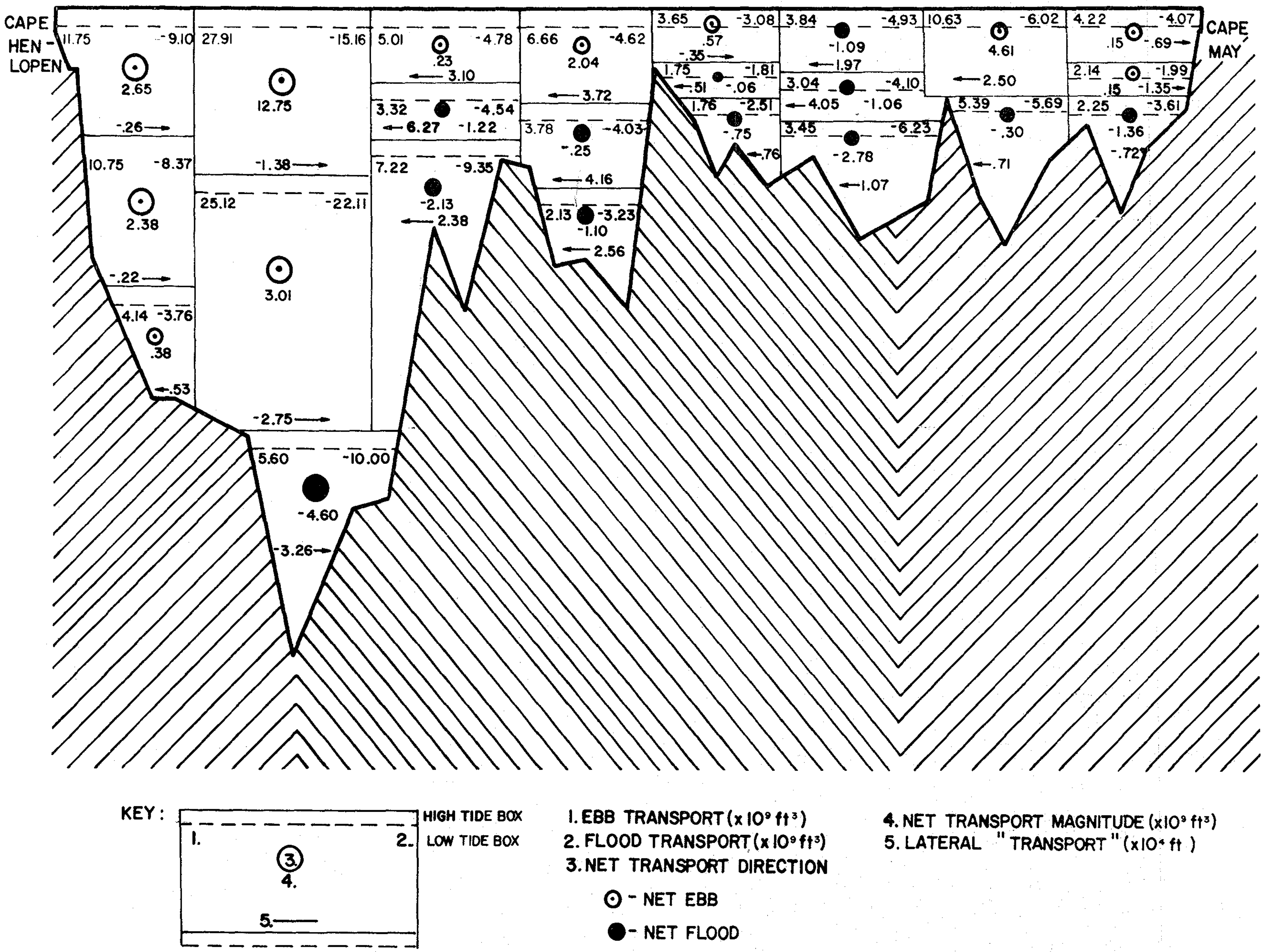
(6) Mean current direction

Each box area is slightly adjusted to take into account the increased total cross-sectional area at the mouth of the bay due to the rise of sea level during flood. That is, the tidal heights averaged over the flood and ebb durations were used. We find that the average tidal height during flood is four feet higher than that during ebb. The volume transported in each box was computed as follows:

---

* Prepared by Michael Salter.

Figure 30


CAPE HENLOPEN
CAPE MAY
KEY:
HIGH TIDE BOX
LOW TIDE BOX
1. EBB TRANSPORT (x 10⁹ ft³)
2. FLOOD TRANSPORT (x 10⁹ ft³)
3. NET TRANSPORT DIRECTION
- NET EBB
- NET FLOOD
4. NET TRANSPORT MAGNITUDE (x10⁹ ft³)
5. LATERAL "TRANSPORT" (x10⁴ ft)

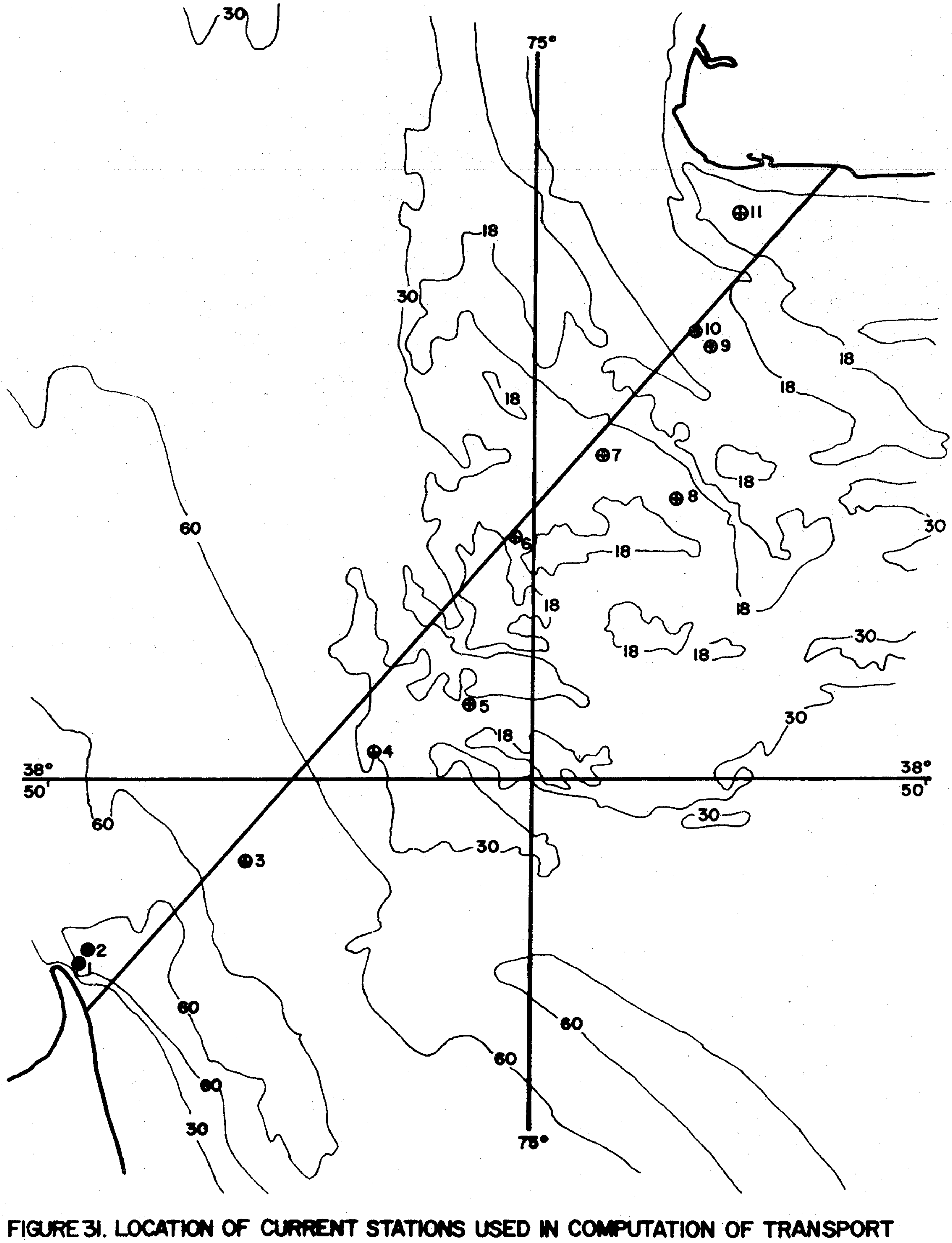


FIGURE 31. LOCATION OF CURRENT STATIONS USED IN COMPUTATION OF TRANSPORT

Volume transported along axis of bay (ft^3)

= Velocity component along axis of bay (ft/sec)

x Cross-sectional area of box (ft)

x Duration of flood/ebb (seconds)

By subtracting the ebb transport from the flood transport we obtain the net transport: positive values correspond to net flood transport, negative values correspond to net ebb transports.

Looking at the gross features of the cross section we notice a net ebb transport on the Cape Henlopen side, and a net flood transport on the area to the Cape May side of the center. This feature is accounted for by considering the effects of the Coriolis force on tides in a semi-enclosed body of water. Another interesting feature is the net transport of water into the Delaware Bay through the deep channel. This is what we would expect to find in a partially mixed estuary such as Delaware Bay is in the spring.

The lateral "transports" represent the time integral of the velocity and therefore should not be compared to the longitudinal transports.

The total ebb transport is 152.65×10^9 ft^3 while the total flood transport is 143.09×10^9 ft^3. The difference between these values is 9.56×10^9 ft or 6.5%. Since the average river discharge over a tidal cycle is 0.86×10^9 ft^3,the above difference represents the uncertainty in the calculation.

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CHEMICAL OCEANOGRAPHY

by

Karl-Heinz Szekielda

INTRODUCTION

Ketchum (1967) defined an estuary ". . . as a body of water in which the river water mixes with and measurably dilutes sea water." Pritchard (1967) provides a similar definition: "An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage."

These definitions are not sufficient for a discussion of the chemistry and biology of the Delaware Bay estuary since they both emphasize a description based on dilution of ocean water with river water and not vice versa. Especially with respect to land runoff, sewage disposal and industrial effluents, the transport of dissolved and particulate matter by fresh water significantly influences the observed chemistry and biology in the Delaware Bay estuary. With respect to sewage disposal, or generally speaking pollution of a natural water body, moreover, these definitions are not sufficient for a discussion of the many biological and chemical processes involved in the water of an estuary where salinity changes range from that of fresh water to concentrations close to that of the neighboring ocean. The approach of Kühl and Mann (1968) is more specific in a nonstratified estuary like the Delaware estuary, because it considers the degree of mixing between the two major sources of water. Although their description of the different parts of an estuary is a qualitative one, it has some advantages in regard to describing the chemistry and the biology of an estuary. The general scheme according to these authors is given in Figure 1.

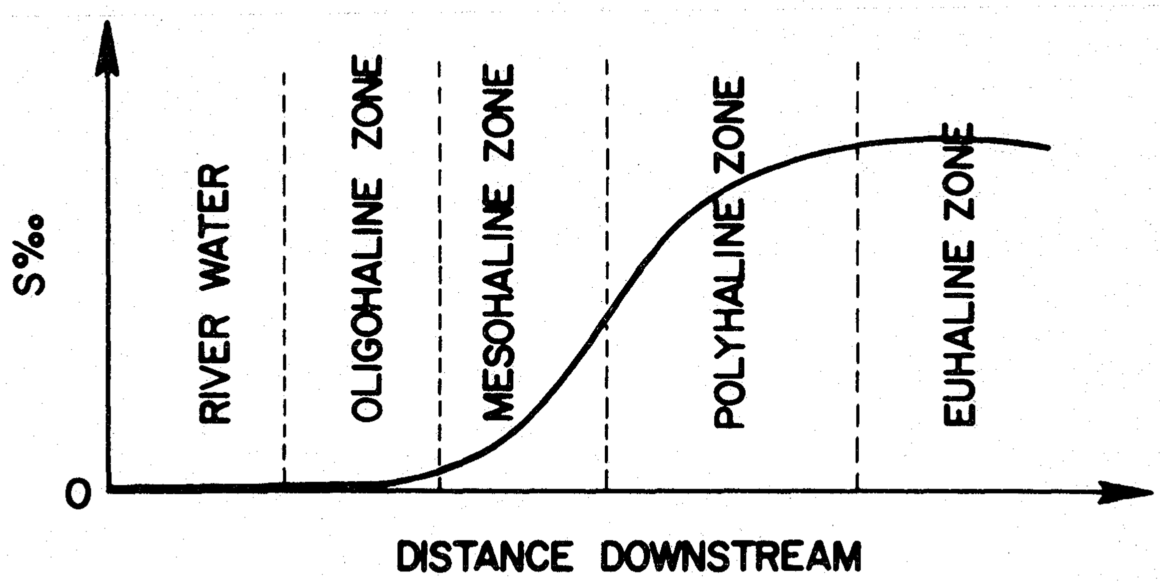


Figure 1: Estuary segments as a function of salinity according to H. Kühl and H. Mann (1968).

The purpose of the following report is to derive some general outlines, for the Delaware estuary. Since only a few publications cover chemical data, the hydrography and the chemistry of this bay are not well defined.

MATERIAL

All data presented in this report are available as a computer printout from the Federal Water Quality Administration and were reported by the Delaware Department of Natural Resources and Environmental Control. Most of the analytical methods are common in the analysis of natural waters (for example, see Klein, 1959). The initial evaluation of the data indicated, however, that the quality of the data and the natural heterogeneity in the distribution of the parameters make it difficult to draw a general picture of the Delaware estuary. Therefore all data were averaged over a period of two years. The following data were summarized in separate analysis as a function of the distance along the estuary.

TABLE I: TOTAL OF ANALYZED PARAMETERS

Parameter	No. of Analysis
Chloride	2819
Chromium	2676
Iron	2787
Chlorophyll	2126
Phenols	534
Oxygen	3159
Phosphate	2723
Nitrite	2982

The results were plotted as distance in miles upriver (Trenton near mile 135). The position of the stations may be derived from Figure 2.

RESULTS

Salinity

The mean chloride concentration in the Delaware river system shows that the river water extends to Philadelphia (Figure 3).

DATA POINTS, DELAWARE RIVER STUDY

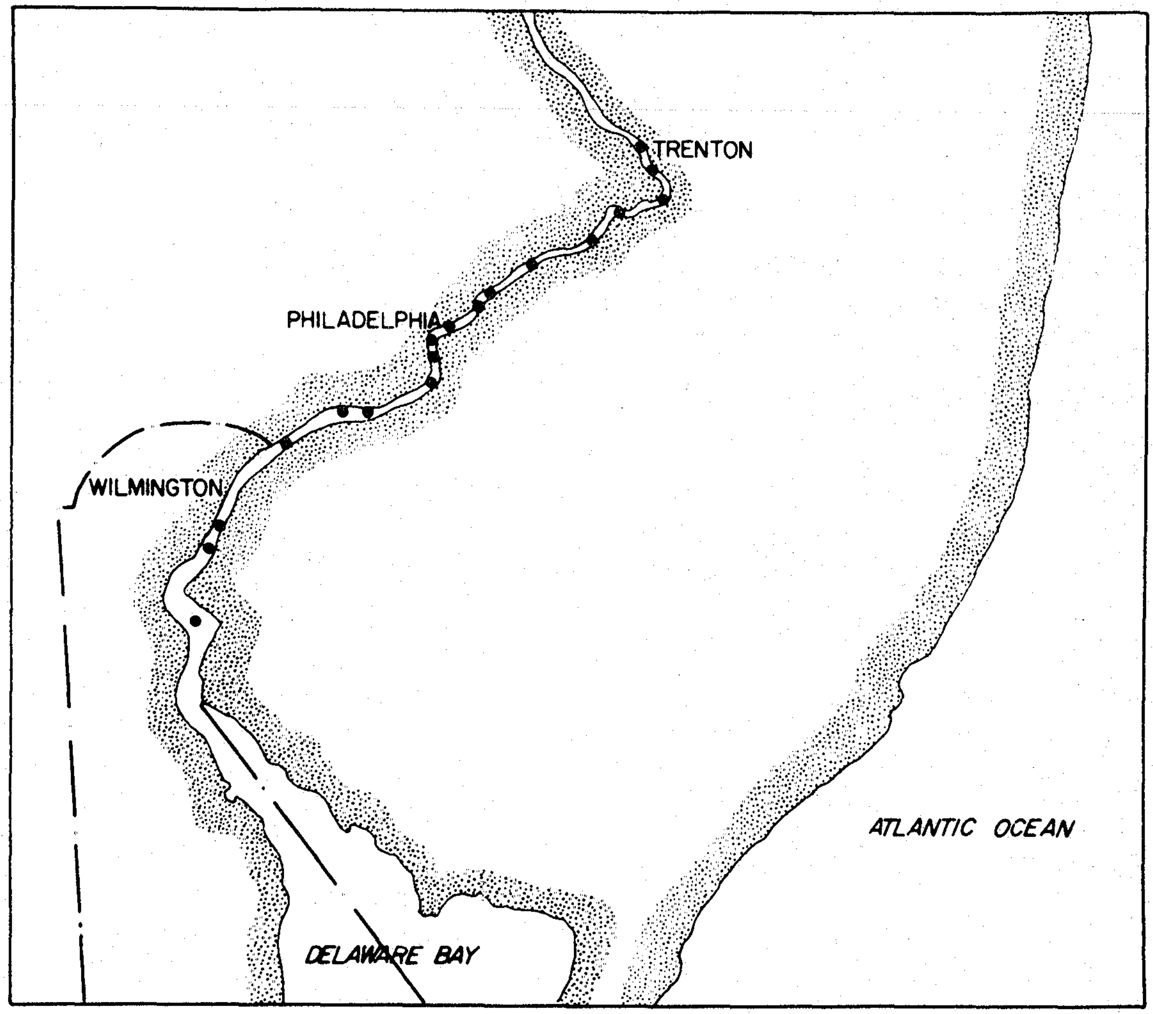


Figure 2: Sample location in the Delaware Estuary.

The mean location of the oligohaline zone and the mesohaline zone is between Gloucester and Delaware City. Similar conclusions can be drawn from the total residue in the water. Salinity data from the Delaware Bay (Figure 4) indicates that the bay is already part of the polyhaline and the euhaline zone. This classification of the

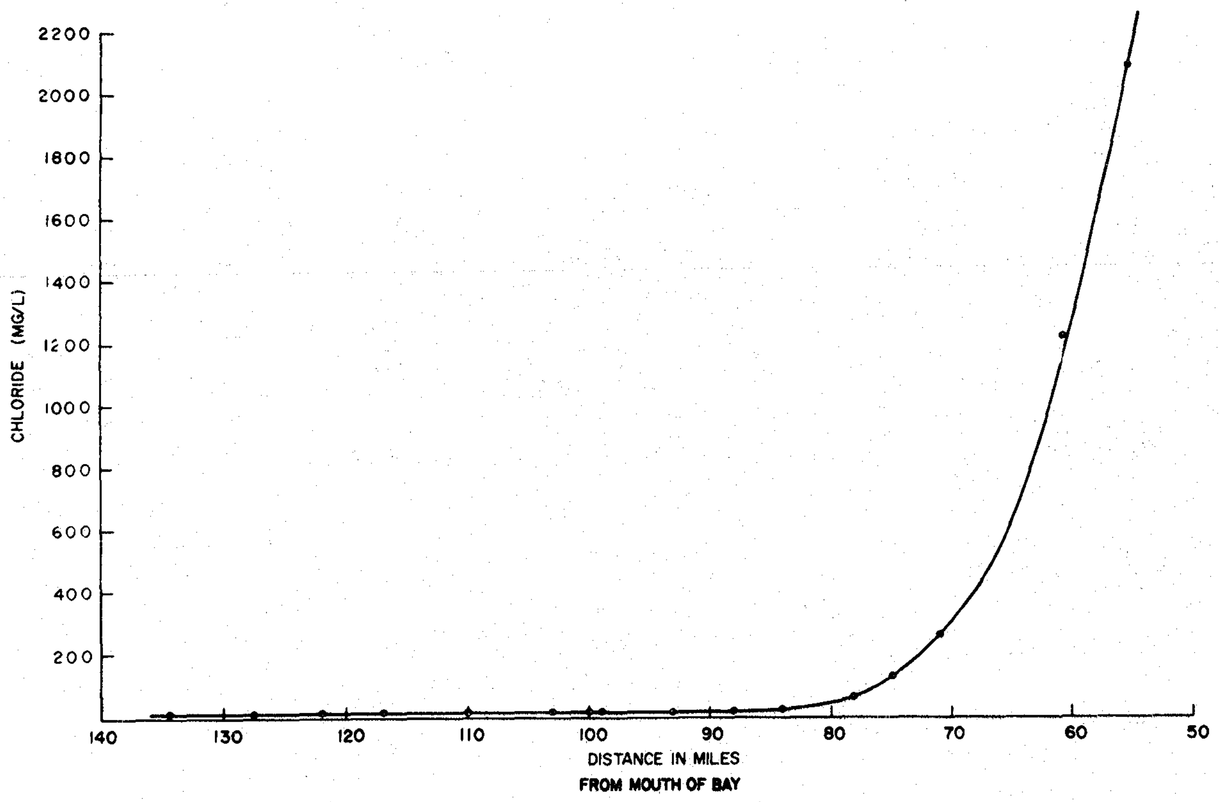


Figure 3: Chloride distribution in the Delaware Estuary.

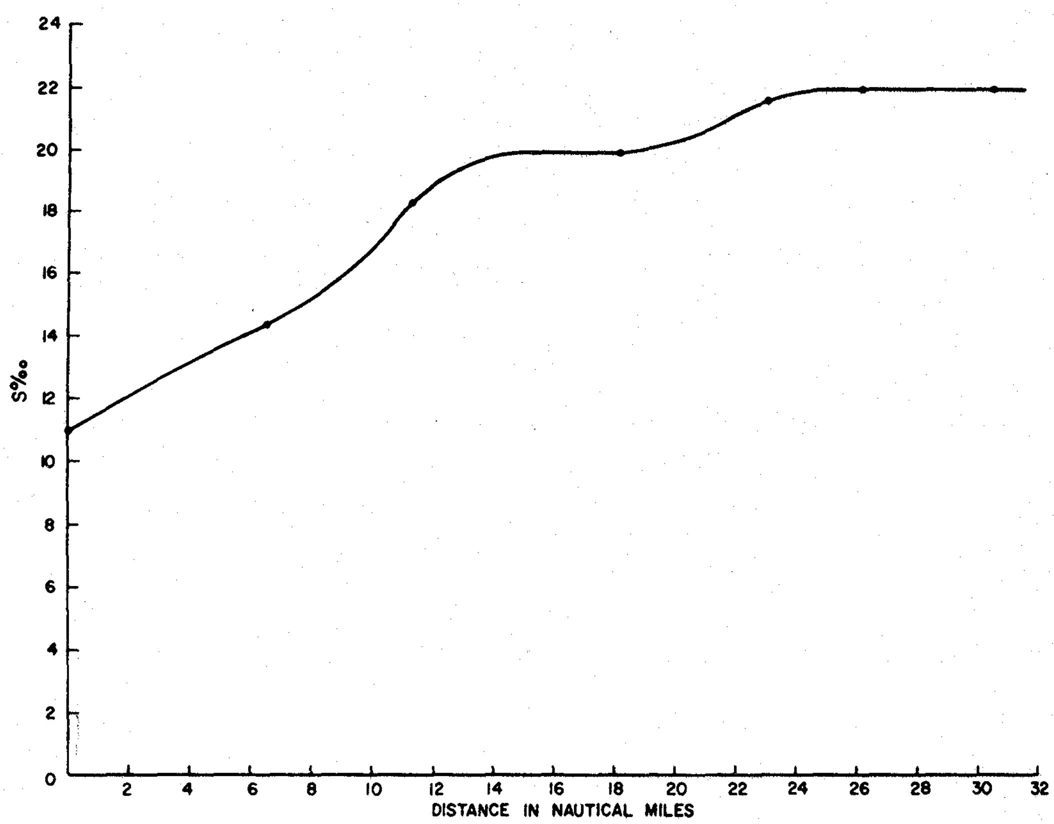


Figure 4: Salinity distribution through the Delaware Bay as a function of distance from the northern edge of the Bay.

Delaware estuary is very simplified, because the changes of river discharge, wind conditions and tides may displace the zones in different directions. However, in connection with the marine and fresh water micro-organisms we may draw some useful conclusions. Plankton organisms carried by the river water may not survive the salinity changes in the oligohaline zone, except some halophile forms. Marine forms entering the oligo- or meso-haline zone are decayed. Kühl and Mann (1968) showed for the Elbe, Weser and Ems that most marine organisms do not pass the 8% limit toward the fresh water.

Nutrients and Oxygen

The mortality and the change in populations due to changes in salinity control the concentration of inorganic oxides. This effect may be partly masked by sewage disposal, which has nutrient concentrations much higher than normally found in a natural water. This is shown in mean values for phosphate concentration in the Delaware estuary in Figure 5. The maximum concentration observed is a result of sewage disposed from a treatment plant located between Palmigra and Port Richmond. The maximum concentration reported for total phosphate is 145 mg PO_4^{3-}/1.

As a result of the high concentration of organic matter and oxygen uptake by micro-organisms, increased oxygen demand is observed in the river near Philadelphia (Figure 6). Anaerobic conditions (Figure 7) appear during the summer months and data about the oxygen deficiency are reported by O'Connor and Thomann (1967) and Beamer

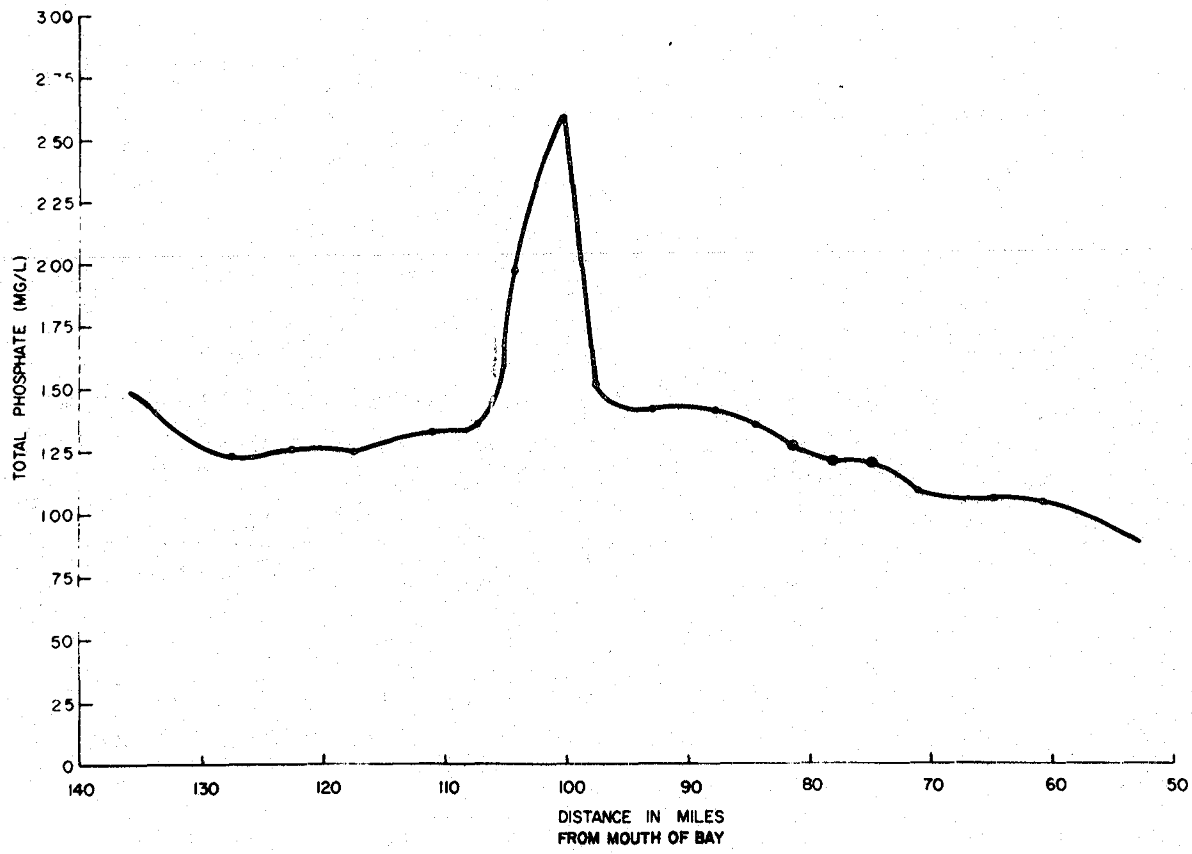


Figure 5: Distribution of total phosphate in the Delaware Estuary.

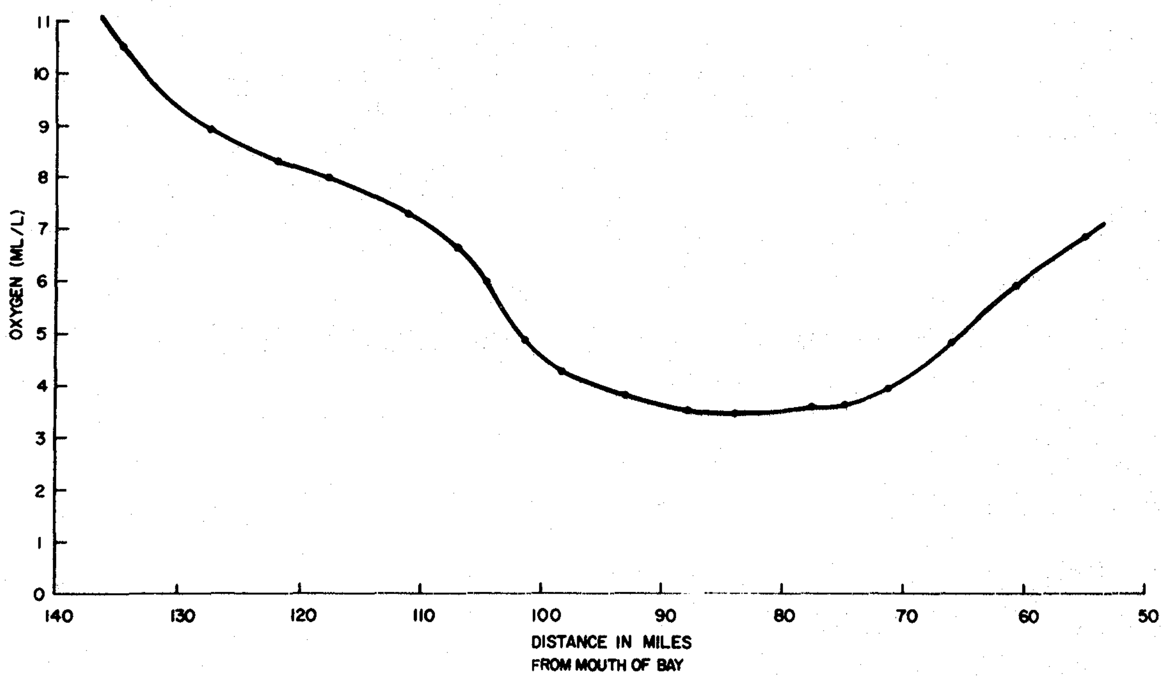


Figure 6: Distribution of oxygen in the Delaware Estuary.

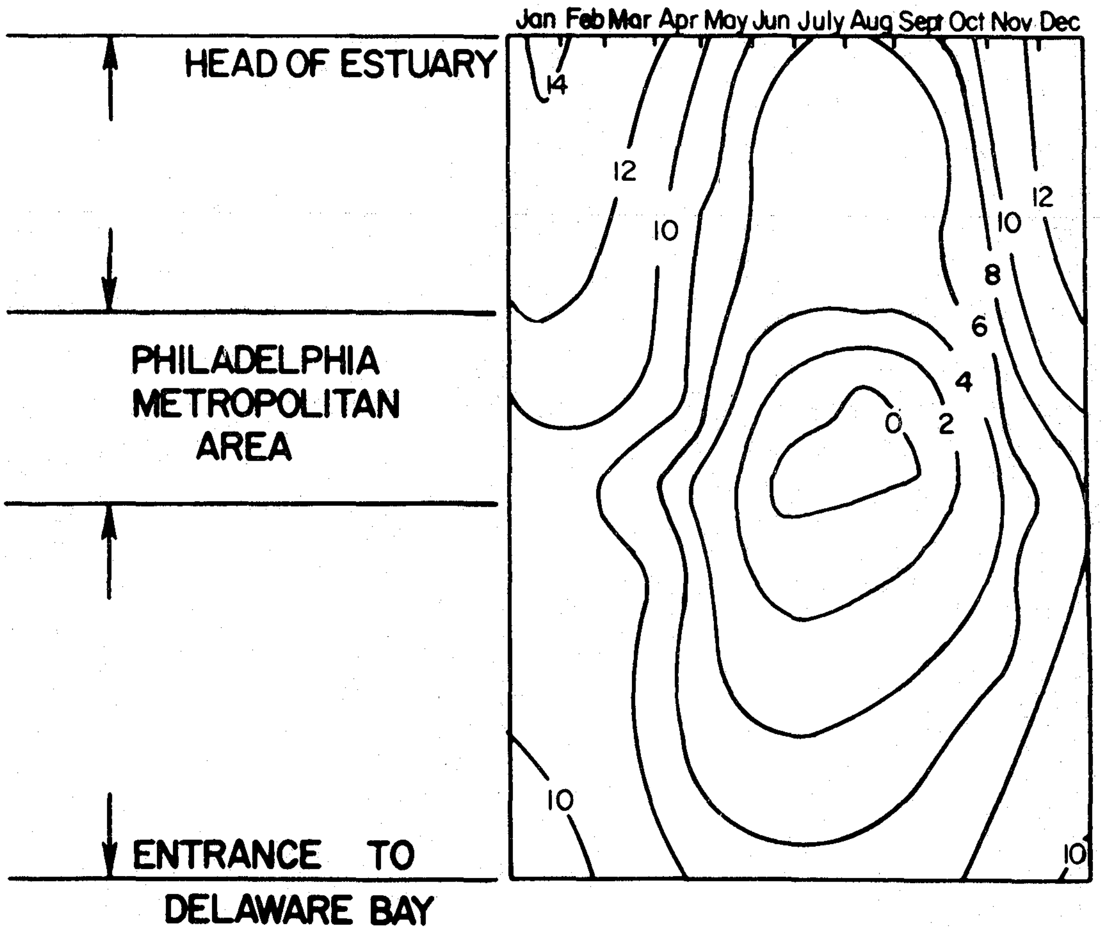


Figure 7: Oxygen distribution in the Delaware Estuary as a function of time and space.

(1970). Under this condition nitrate reduction may appear, since NO_3^- instead of oxygen is used as an electron donor.

An indication of this process is given by the significant increase of nitrite (Figure 8) in the river water. For comparison it should be mentioned that the polyhaline and euhaline zone show less than 0.01 mg NO_2^- per liter.

The oxygen concentrations near Philadelphia suggest that aerobic and anaerobic decomposition of sewage occurs. The high oxygen uptake

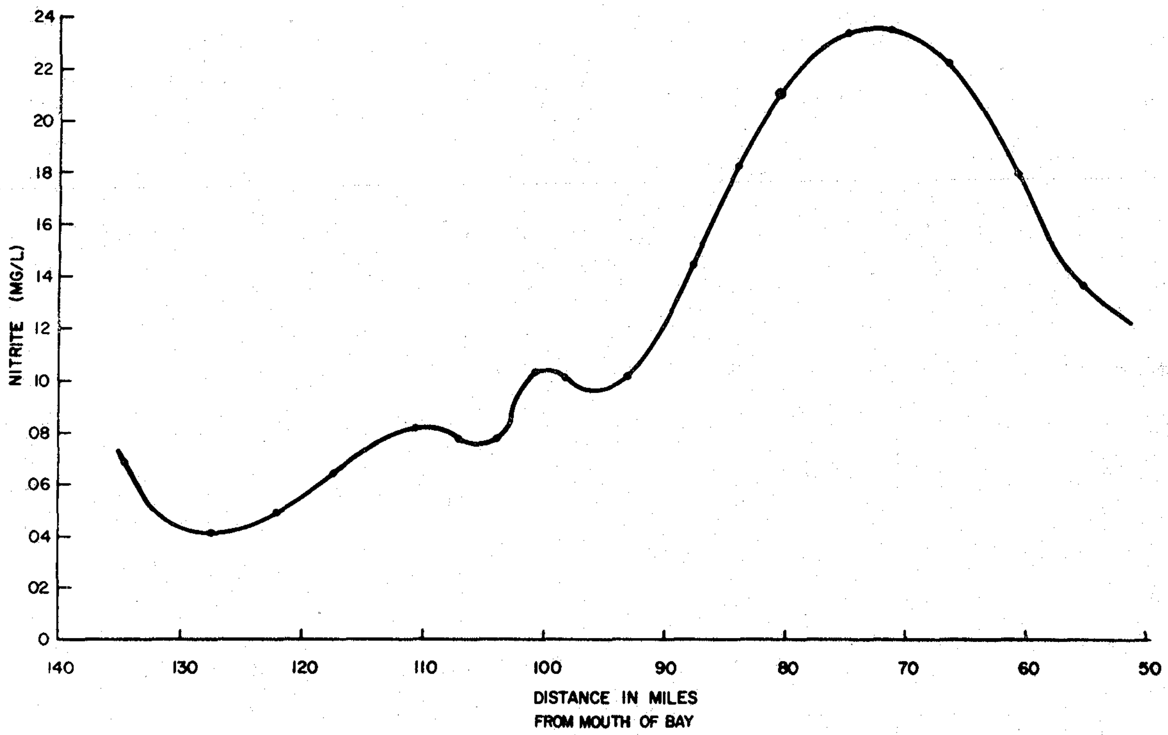


Figure 8: Nitrite concentration in the Delaware Estuary.

during the summer is a function of temperature rather than increased discharge of sewage: this can be shown with the mathematical formulation of the deoxygenation:

X_t	is O_2 used up in t days (biochemical oxygen demand for t days)
L	total first stage oxygen demand
L_t	first stage oxygen demand remaining after t days
$2.3k_1$	proportionality constant

$$\frac{dX_t}{dt} = \frac{d(L-L_t)}{dt} = \frac{dL_t}{dt} = 2.3k_1L_t$$

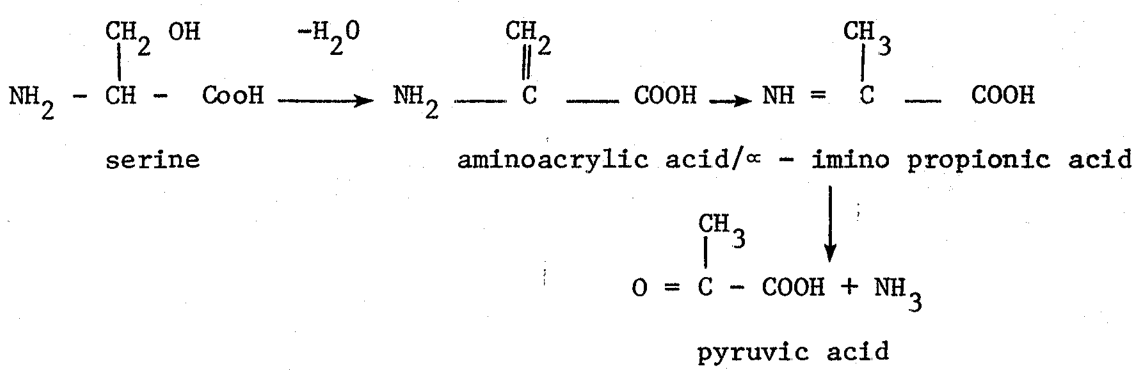
k_1 varies with temperature according to $\frac{k_1\ (T^1)}{k_1\ (T)} = \theta\ (T^1-T)$

$k_1(T^1)$ and $k_1(T)$ are the constants at temperatures T^1 and T respectively.

The thermal constant is Θ and has a value of approximately 1.05 between 10 and 37°C. This shows that the biochemical oxidation of organic compounds is similar to unimolecular chemical reactions. The rate of oxidation if thus proportional to the remaining concentration of unoxidized organic matter.

Many breakdown processes may produce lower molecular weight compounds including gases like methane, carbon dioxide, nitrogen, hydrogen and occasionally, under anaerobic conditions, hydrogen sulfide can be formed. Fair and Moore (cited in Camp, 1963) showed that during the course of anaerobic digestion of sewage sludge, 600 liters of gas per kilogram of sludge may be produced. About two thirds (by volume) is methane and the remainder CO_2, N_2, and H_2.

Sources for the breakdown products are mainly amino acids and carbohydrates which may be decomposed by micro-organisms and contribute to further increase of the nutrient concentrations (release of PO_4^{3-}, NH_4^+). Many bacteria, for instance, act on serine while building pyruvic acid and ammonia (Fruton and Simmonds, 1958).



Counts of coliforms in the Delaware River close to the sewage disposal sites showed 60,000/100 ml as a mean value on different media. Maximum value was 580,000. Koske, Krumm, Rheinheimer and Szekielda (1966) showed a maximum count for the Elbe of 4500/100 ml. The breakdown of sulfur containing amino acids contributes to the hydrogen sulfide concentration present under anaerobic conditions. For example, cysteine in aqueous solution may be converted to pyruvic acid and ammonia by yeast and bacteria:

$$NH_2 - \overset{CH_2SH}{\overset{|}{CH}} - COOH \longrightarrow O = \overset{CH_3}{\overset{|}{C}} - COOH + NH_3 + H_2S$$

Anaerobic conditions as observed in the Philadelphia metropolitan area are therefore a contributor to hydrogen sulfide concentrations and an important additional input to the nutrient pool.

Iron

The concentration of total iron varies between 0.64 mg Fe/l and 1.86 mg Fe/l, Sillen (1961) concludes that the major concentration of dissolved iron in seawater is present in the form of $Fe(OH)_3$. Most of it is in colloidal form and only 10^{-6}M iron appears in a true solution. The solid fraction of iron appears principally as oxide.

Since $Fe_2(SO_4)_3$ is the most stable form of the different species of Fe III in aqueous solutions, we might expect that $Fe_2(SO_4)_3$ would be a dominant species in fresh water. This may change if salts and organic compounds are added. $FeCl_3$, for instance, coagulates in the presence of salts while building Fe_2O_3 sols.

$(Fe^{+++} \longrightarrow Fe_2O_3(sol) \longrightarrow Fe_2O_3)$

The coagulating effect depends on the valence of the ions and the temperature of the solution. The oligohaline and the mesohaline zones of the estuary indicate evidence for precipitation. Since the concentration of iron in the polyhaline zone of the Delaware estuary does not follow the mixing rules between water from the river and the euhaline zone, we might expect precipitation and/or coagulation. This conclusion was drawn from observations on the inner part of the Delaware Bay and the estuary. Along the shoreline the influence of freshwater containing high iron concentrations is still visible and reflects the discharge of the smaller creeks into the bay system (Figure 9), before a precipitation of iron compounds occurs.

A certain minimum concentration of the various electrolytes is in fact necessary to cause a precipitation of the positively charged ferric oxide. For instance, the amount of KCl to precipitate Fe_2O_3 is about 100 millimoles/l. Since the value does not significantly differ for NaCl solutions, we can conclude that iron precipitation occurs at a salinity of about 6.3%. However, the coagulating effect is amplified by the presence of bivalent ions. Therefore, the coagulation will be expected at salinities below 6%. This is in agreement with the observed deviation of the iron concentration in respect to the total solids of samples from the estuary.

Chromium

The world mining production of chromium is about 2 million tons per year, of which 0.04 million tons per year are discharged into the ocean (National Academy of Sciences, 1971). By their use in plant processes and by discharge into natural waters, Cr^{III} and Cr^{VI} can be

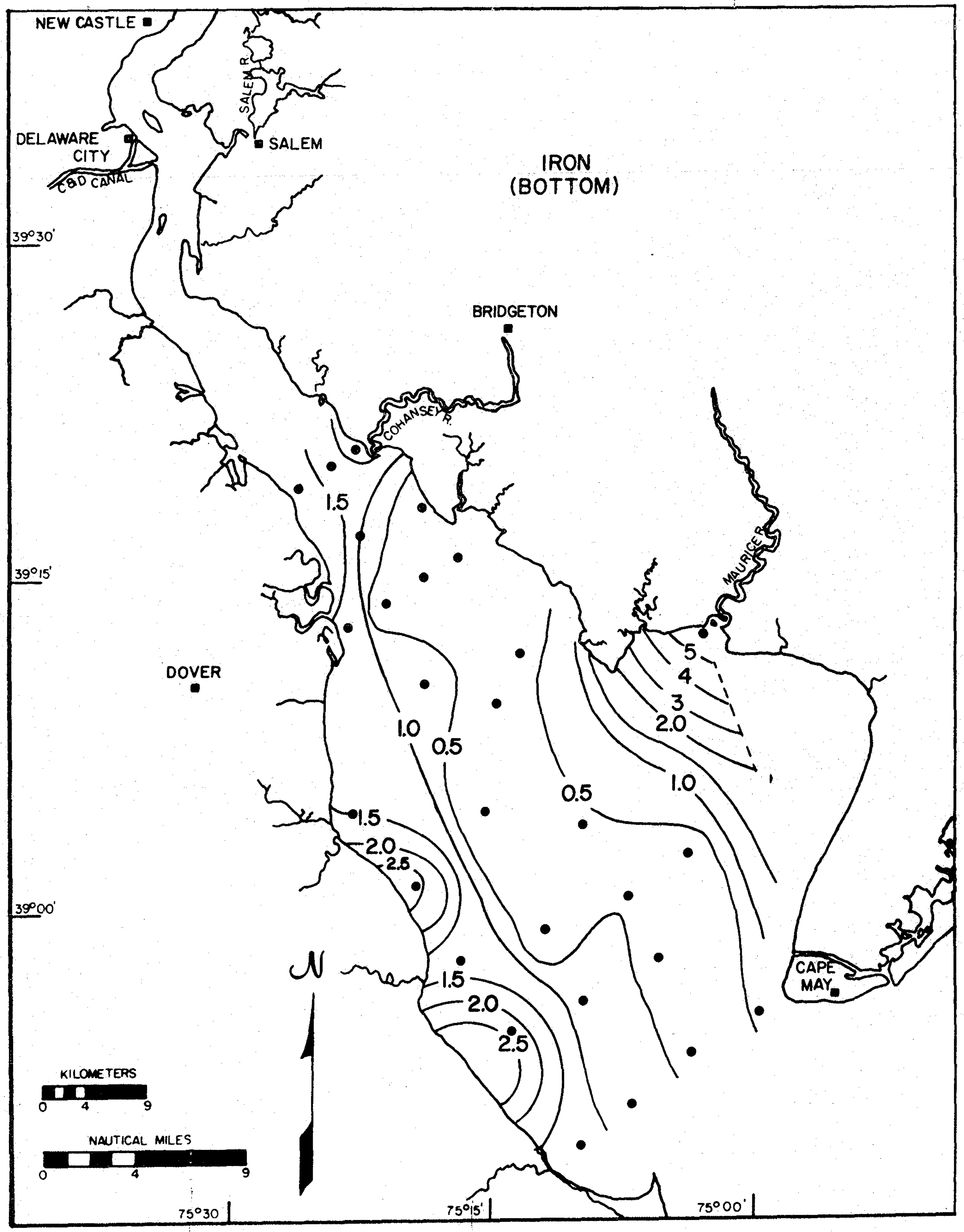


Figure 9: Iron distribution in the Delaware Bay.

regarded as the main species of chromium present in nearshore waters. In aqueous solution bichromate shows a deviation from Beer's Law which is an indication for the building of chromate.

$$H_2Cr_2O_7 + H_2O \rightleftharpoons 2H_2CrO_4$$

In very diluted solution the equilibrium is favored toward the right side of the equation. Due to the low chromium concentration in seawater of about 0.05 $\mu g \cdot l^{-1}$ (Goldberg, 1963) we may expect that H_2CrO_4 is the dominant species of the hexavalent chromium in a natural water system. H_2CrO_4 dissociates in two steps:

$$H_2CrO_4 \rightleftharpoons H^+ + HCrO_4^- \qquad K_1^{25} = 0.18 \pm 0.04$$

$$HCrO_4^- \rightleftharpoons H^+ + CrO_4^{--} \qquad K_1^{25} = 3.7 \times 10^{-7}$$

(Gmelin, 1962a)

The dissociation constant K_1 at 25°C evidently shows that approximately 95% of the chromate is dissociated to $HCrO_4^-$. The analysis of water sample from the Delaware estuary on hexavalent chromium indicated concentrations between 5 and 6 mg Cr^{VI}/l^{-1}. However the total dissolved chromium exceeds concentrations of 100 mg/l between Trenton and Trenton Marine Terminal (Figure 10). This is probably a result of direct discharge of chromium compounds in this area.

Among other species of dissolved chromium, we can expect that Cr^{III} will be important as a contributor. Since Cr^{VI} may be reduced easily in aqueous solutions by the presence of ions like Fe^{2+} and S^{2-} and organic compounds, it is most likely that during anaerobic conditions in the water near Philadelphia, Cr^{VI} is reduced to Cr^{III}.

The concentration of 100 mg Cr/l is obviously much higher than

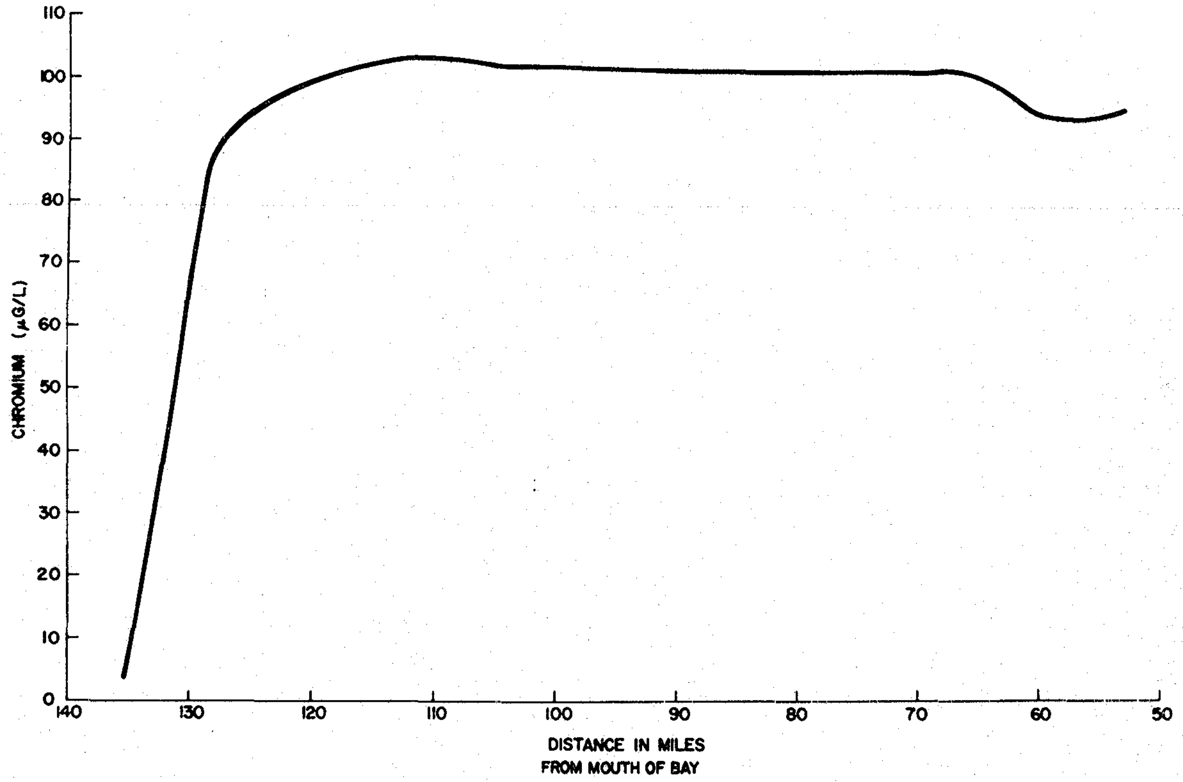


Figure 10: Chromium distribution in the Delaware Bay.

the expected natural background in an unpolluted water system (Table 2).

TABLE 2: Chromium Concentrations in Natural Water

	Cr Mg·l^{-1}	
Baltic Sea	<0.2	Gmelin (1962)
Open Ocean	0.05	Goldberg (1963)
Angara (Russia)	1.1	Gmelin (1962)
Usakovka (Russia)	1.5	Gmelin (1962)
Irkut (Russia)	1.7	Gmelin (1962)
Ground water	0-40	Gmelin (1962)

During a survey in July, 1971, the Delaware Bay system showed concentrations below 50 mg Cr/1. If one considers only two main sources for the bay water, namely open ocean water and the water from the Delaware River, the theoretical concentration can be estimated from the fractions of seawater and freshwater composing the bay water from

$$F = (1 - S/\sigma)$$

where F is the fraction of freshwater; s, salinity of mixture; and σ, salinity of the source of seawater. Using a reference water mass with $\sigma = 36^{o}/oo$ and 0.05 mg Cr/1, and the river water with a mean concentration of 100 mg Cr/L, the concentration of chromium should be higher than that actually found in the bay. Although this has to be regarded only as an estimate, we may speculate that part of the chromium is adsorbed on particles and taken up by organisms during its transport through the estuary. For instance, it is a known fact that $Cr^{2}(SO_4)_3$ may be adsorbed on silica gel, even from very diluted solutions. Further, <u>in situ</u> precipitation during the mixing of sea water with fresh water has to be considered a possible mechanism to adsorb chromium on particles. The precipitation of iron as discussed before may be a contributor for active sites to sorb other metals.

Laboratory experiments with water from the Rhone River and water from the Mediterranean Sea showed a significant increase of particulate carbon (organic and inorganic together) after both water masses are mixed. The data is presented in Figure 11.

Precipitation and coagulation may be the sources for <u>in situ</u>

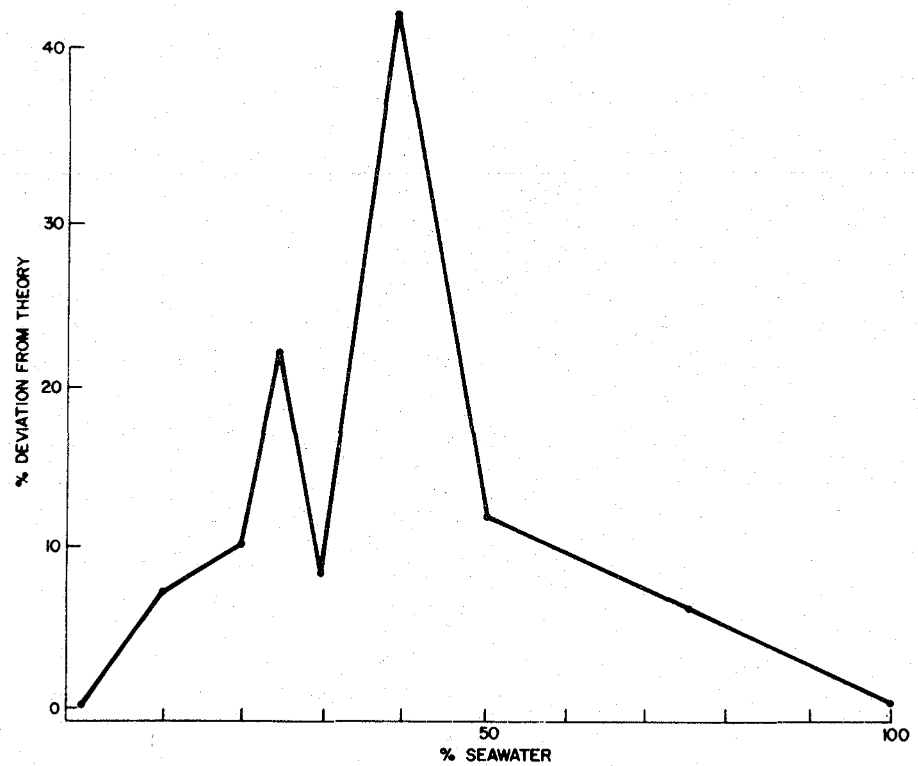
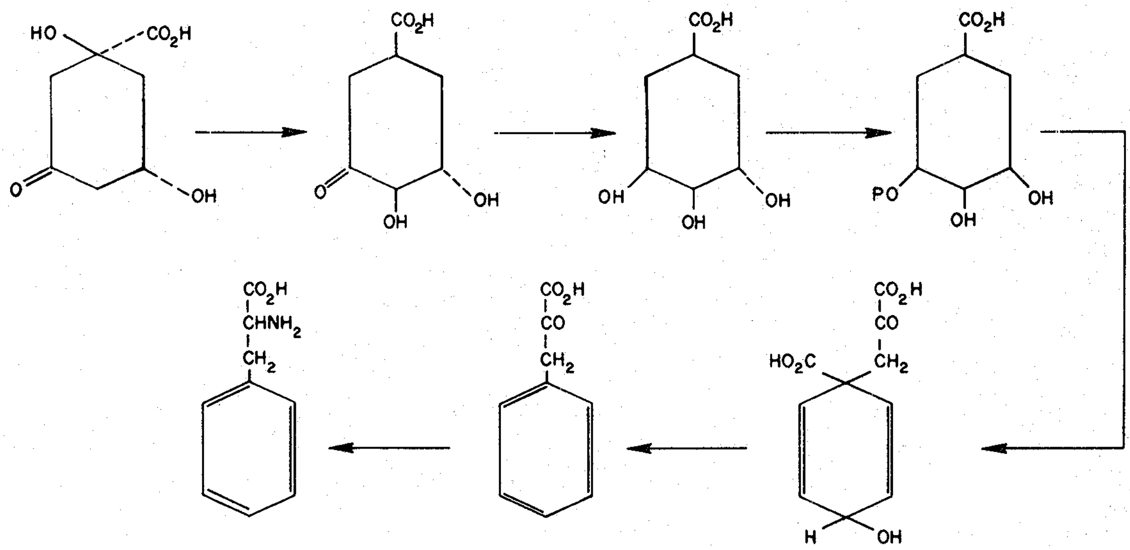


Figure 11: Mixing experiment with Rhone water and water from the Mediterranean Sea.

building of new particles. Also the adsorption of dissolved and colloidal substances on particles may play a role in increasing the concentration of particulate matter. Thus, the deviation of Cr-concentrations from the theoretical physics can be explained by biological uptake processes and physicochemical reactions.

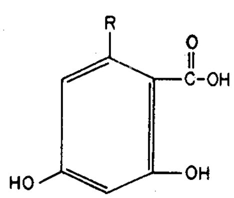
Phenols

The origin of phenols in natural waters can be traced back to two different processes: 1) direct discharge into the environment and 2) the biosynthesis by micro-organisms. Two basic routes are known to build phenolic compounds by natural processes (cited in Rickards, 1961). The first one includes shikimic acid and the second one acetic acid as the key compounds during the synthesis. The first phenol compound in the biosynthesis is 5-Dehydro-quinic acid which is converted in different reaction steps to phenylalanine.

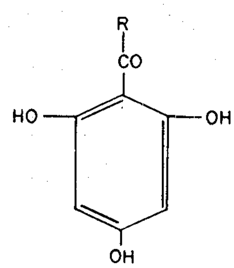


The generation of the phenolic compounds from acetic acid units is principally based on a condensation of three moles of acetic acid with carboxylic acids. The end products are phenols of the orcinol (1) or acylphloroglucinol (2) type:

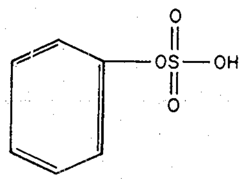
1



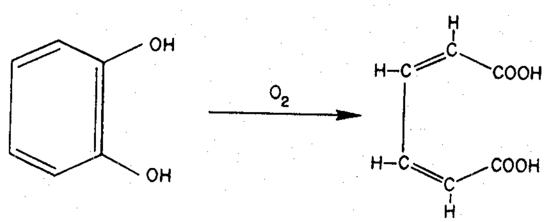
2



A further source of phenols in the aquatic environment are excretion of man and animals. Part of the urinary sulfur is in the form of phenolsulfuric acid:



This summary of biologically-chemically produced phenolic compounds, illustrates the problems in interpreting the data for the Delaware estuary shown in Figure 12. High concentrations of phenols may be a result of biological activity but also may reflect sewage disposal in the natural water. Furthermore, the oxidation of certain phenols by micro-organisms may vary in time and space. Catechol, for instance, may easily be converted to cis, cis-muconic acid:



Chlorophyll

As with total Kjeldahl nitrogen, high concentrations of chlorophyll are found as a result of the sewage disposal near Philadelphia. The maximum value for the averaged data is 40 μg/l (Figure 13). This high concentration may effect the water quality seriously, since mass mortality of organisms may occur if the plankton bloom passes the mesohaline, polyhaline and/or euhaline zone.

Chlorophyll measurements in the Delaware Bay from a multi-ship cruise during one day showed that high concentrations of chlorophyll

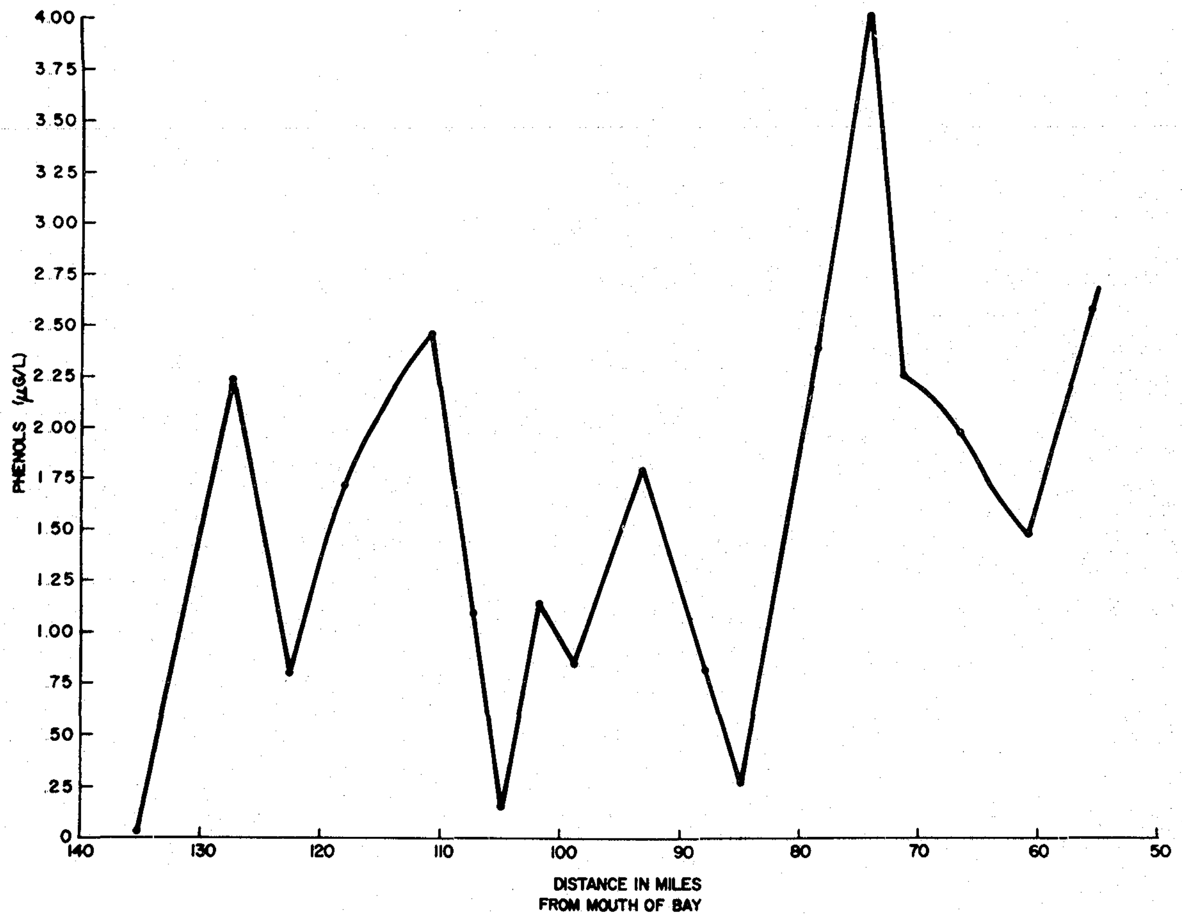


Figure 12: Distribution of phenolic compounds in the Delaware estuary.

are transported with the outflowing water along the Delaware side which is in agreement with the water movements under the influence of the Corioliss effect (Figure 14). Maximum values reported were above 100 μg/l. The eutrophication of the Delaware estuary including the Delaware Bay is also reflected in the concentrations of organic carbon. The concentration for organic carbon in the Delaware Bay is ten times higher than in the open ocean.

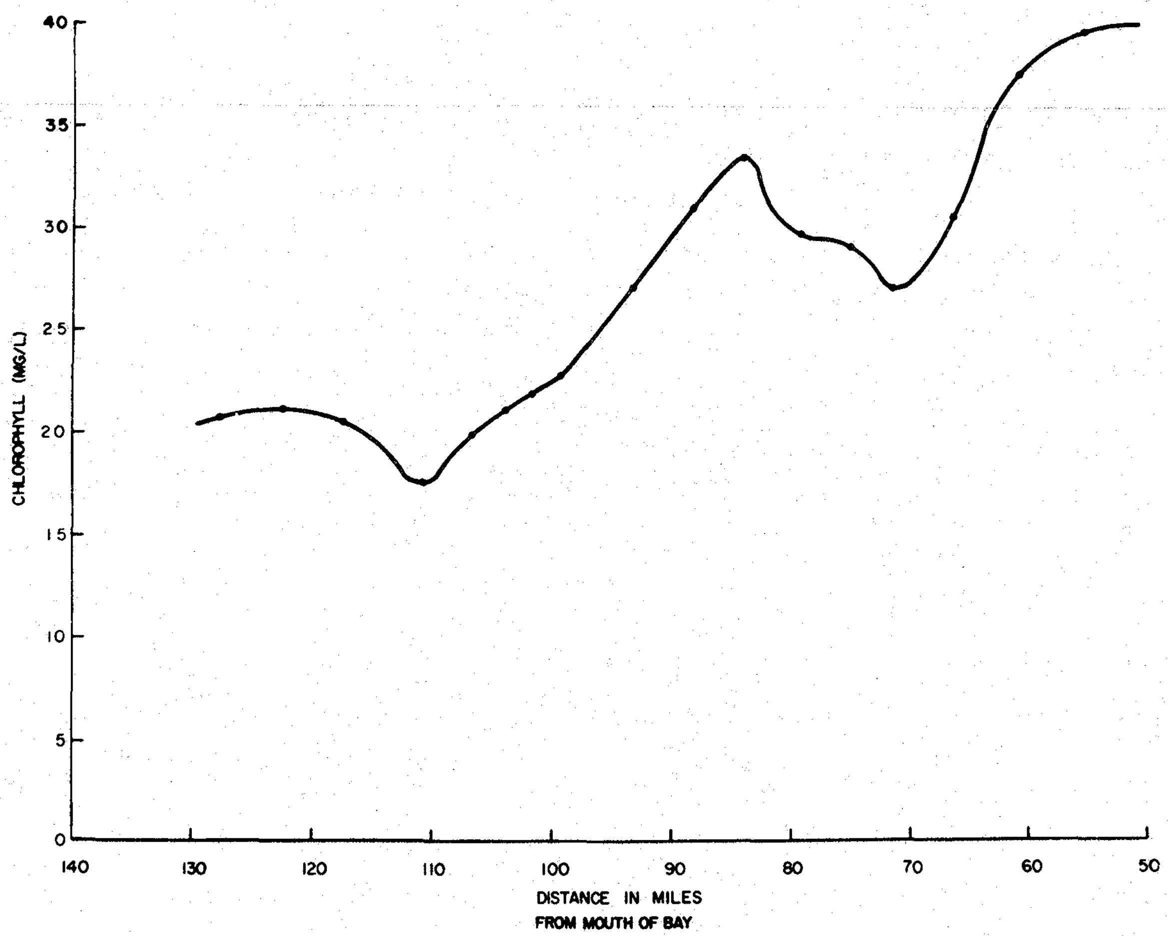


Figure 13: Chlorophyll distribution in the Delaware estuary.

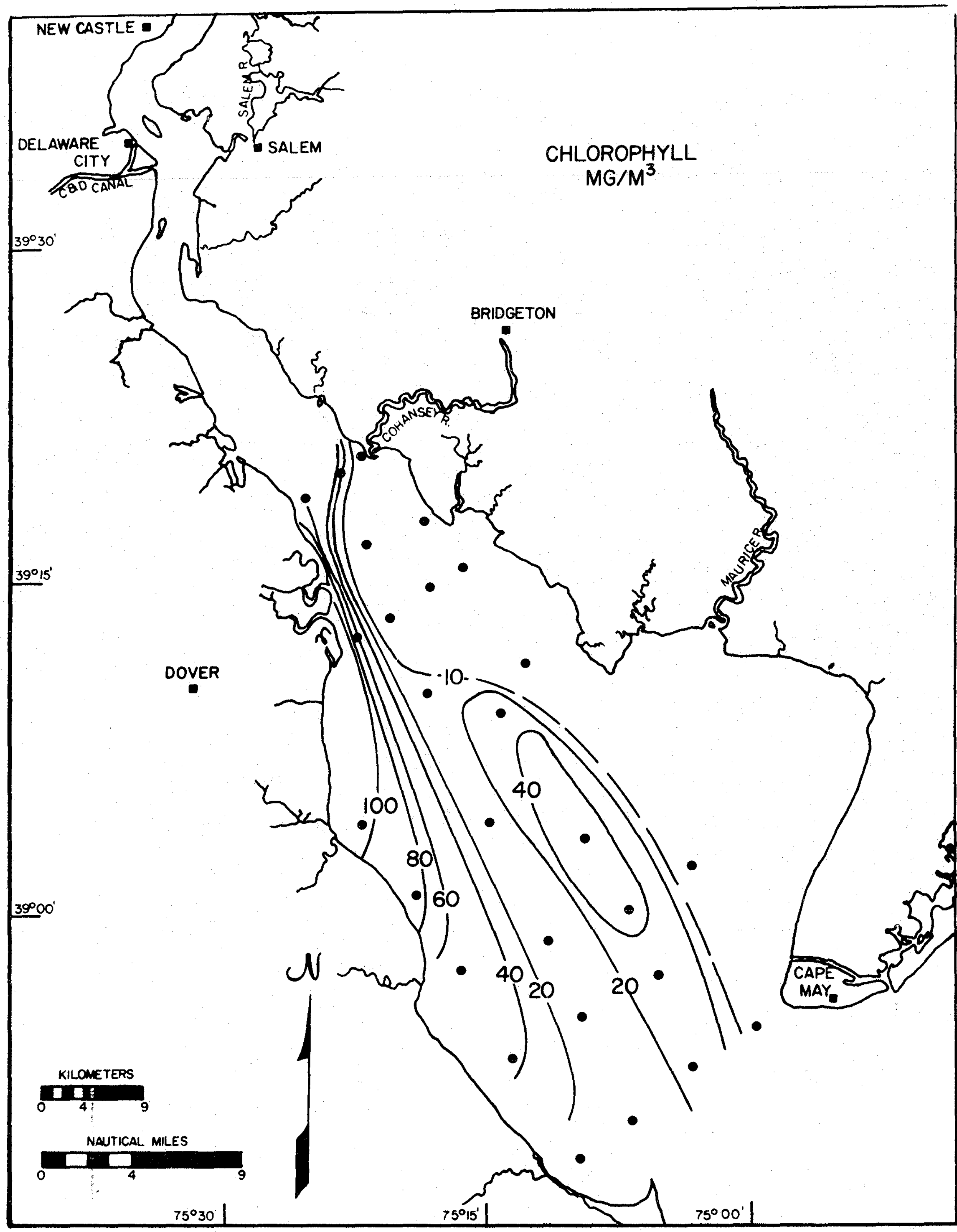


Figure 14: Chlorophyll distribution in the Delaware Bay.

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