Serial Observations of Drift Currents in the Central North Atlantic Ocean[1]

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(Manuscript received May 13, 1954)

1. Introduction

Between October 21, 1953 and February 9, 1954 a series of nearly continuous observations of wind-drift currents was made in the open ocean off Bermuda by means of drifting wireless-telemetering buoys. A rough plot of the position of each of these buoys relative to Bermuda was obtained by means of a mobile radio-direction-finding station. A composite plot of the tracks of all the buoys is exhibited in Figure 1. The island provides such a small base line for triangulation, especially for bearings to the northeast and southwest of the island, that reliable fixes of position could be obtained only during the time that the buoys were within about 20 miles of Bermuda. Because of the uncertainties in radio-direction-finding at 3 megacycles the information shown in Figure 1 cannot be used for measuring wind-drift of the buoys, but it does provide us with enough information to eliminate from the data those cases in which the buoys were within the 1000 fathom line. A total of 65 days of observations satisfying this criterion was obtained.

Figure 2 is a sketch of the buoy. A cylindrical steel can roughly 2 feet in diameter and 5 feet high surmounted by a 6 foot mast (which carried a 4 cup anemometer, wind vane, magnetic compass and whip type antenna) and carrying a 30 watt radio transmitter, telemetering equipment and batteries, is ballasted so as to float with about 5 inches of freeboard. To the lower portion of the can are attached two outrigger arms, from one of which is suspended a sheet metal drogue at depths from 120 to 530 feet. On the other arm a sheet metal rotor (Figure 3) is suspended as near to the surface as possible. Every three hours (in some cases every $1^1/_2$ hours) the buoy transmits by wireless the following data: (i) the number of revolutions of the rotor since the previous transmission; (ii) the number of revolutions of the anemometer since the previous transmission: (iii) the instantaneous magnetic heading of the buoy; (iv) the instantaneous bearing of the wind relative to the buoy. These wireless signals turn on the magnetic tape recording equipment in the land-based observatory so that the data is available for reduction in recorded form. The operation of the receiving station is entirely automatic except for occasional changing of reels of recording tape. The system in use at present works satisfactorily over distances up to 45 miles. Rough weather, even of moderate gale force, does not harm the buoys.

Calibration of the rotors was carried out in a tidal channel on the island. Because the buoys are free drifting they do not measure

[1] Contribution No. 713 from the Woods Hole Oceanographic Institution; under Contract with the Office of Naval Research. The work was done at the Bermuda Biological Station.

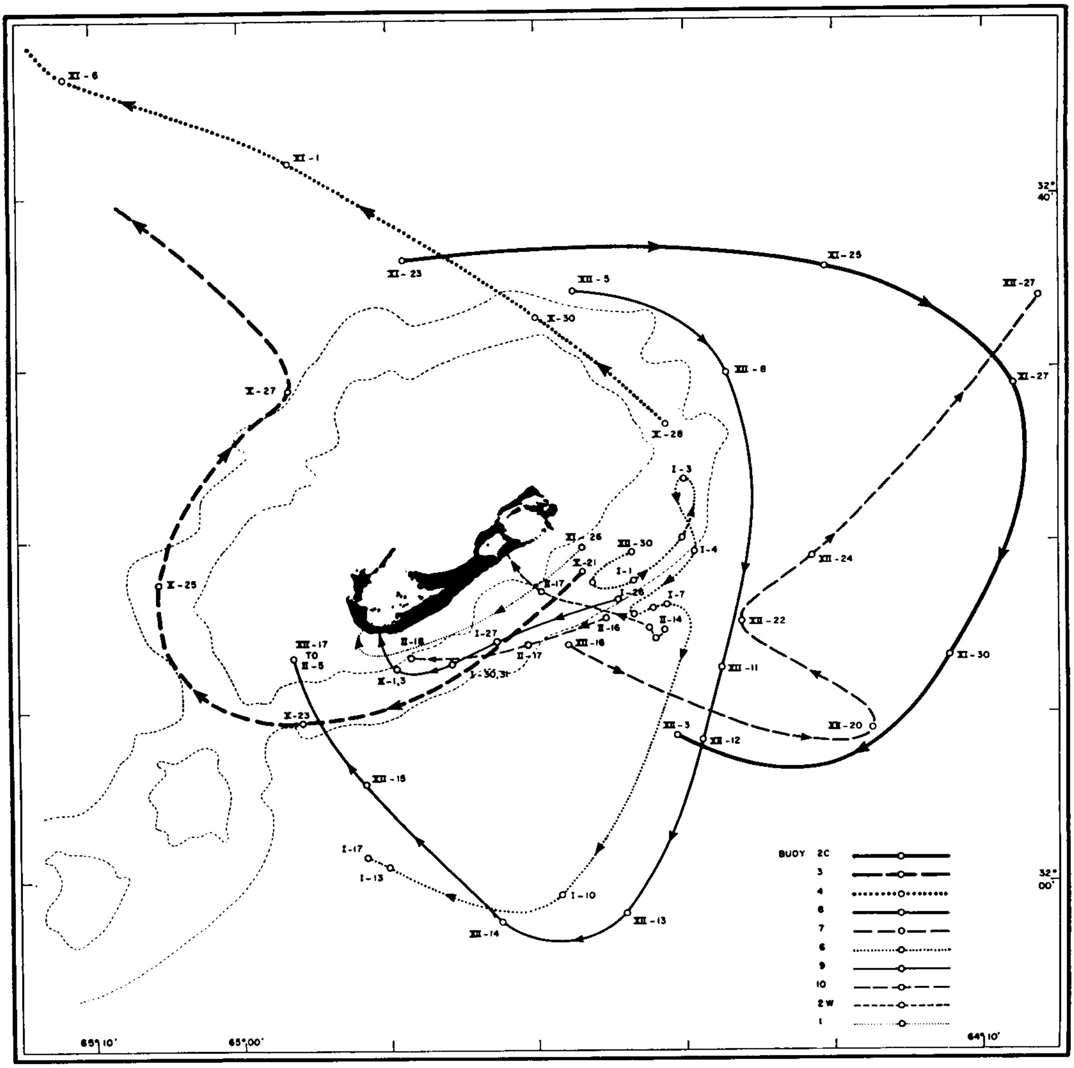

Fig. 1. Tracks of the various buoys around Bermuda. Contours of the 100 and 1000 fathom lines are drawn in about the island. The tracks of different buoys are shown by different qualities of line. The Roman numerals indicate the month and the numbers immediately following them the day. Tracks ending in shallow water show buoys that came ashore. Tracks pointing off the chart indicate buoys which drifted out of radio-direction-finding range but which were still able to telemeter data properly.

the velocity of the surface drift relative to the ocean bottom. They measure the vectorial difference of the surface velocity and the velocity at the depth of the drogue. The areas of the can and rotor together (in the surface water) and of the drogue (in the deep water) are nearly equal so that the actual speed of the vectorial difference is twice the speed past the surface rotor. The orientation of the buoy is determined by the direction of the vectorial difference. In this connection every effort has been made to reduce the area exposed to the wind. There is a small deflection (averaging 10°) of the orientation of the buoy from the direction of the vectorial difference of surface and deep velocities, due to Magnus effect of the rotor. A correction for this has been made on the basis of experiments made in a tidal

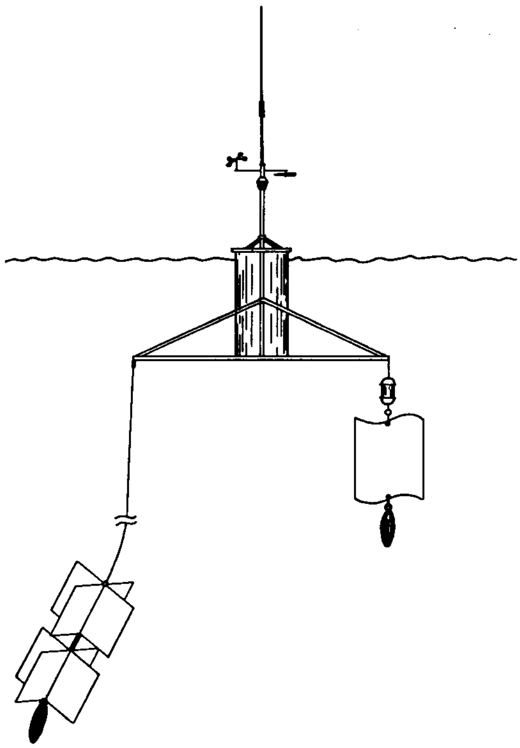

Fig. 2. Schematic sketch of the buoy showing the radio mast and meteorological instruments above water, the current and the deep drag each attached to ends of the outrigger arms.

channel; and the sense of rotation of the rotor was reversed in some of the later buoys in order to eliminate this possible source of error from the data.

The telemetering itself is done in the following manner: the various sensing elements operate variable electric resistances, which produce variable audio frequencies which in turn are transmitted as a modulation of the radio frequencies. It is believed that adequate precautions were taken to prevent possible errors in the telemetering system. Messrs. Robert G. Walden and Donald Parson, Jr. collaborated with me in the design and construction of the buoys.

II. Discussion of data

The original data from the buoys, including all cases where the buoys were not near to the shore of the island, is collected in Table I. Perhaps the most striking feature of this data

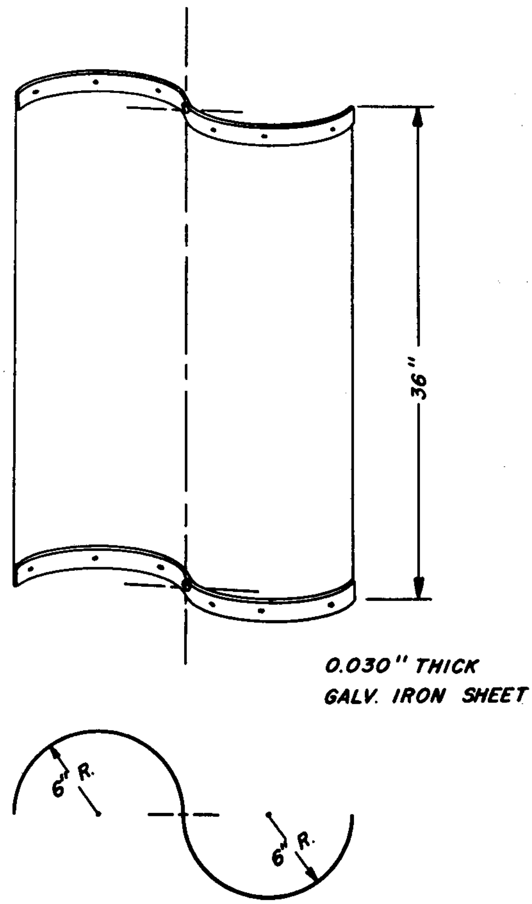

Fig. 3. Detailed sketch of the construction of the rotor.

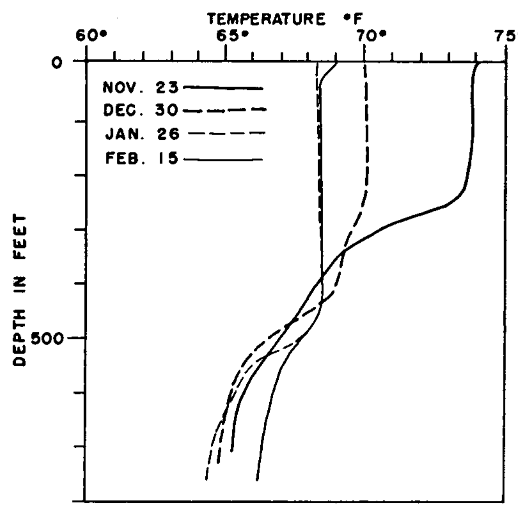

Fig. 4. Sample bathythermograph soundings showing the mixed water conditions prevailing through most of the period of measurements.

Table 1. Data for all cases where buoys were beyond island influence

	Local Time	Wind dir.	Wind mph	Buoy No.	Trans. Time	Current dir.	Current knots	Wind Vane
1953 Oct. 27	0000	200	1	3	0024	020	0.27	330
TM 0003	0300	200	1	3	0325	035	0.85	240
	0600	200	1	3	0625	060	0.74	225
	0900	160	6	3	0922	105	0.10	160
	1200	180	8	3	1222	305	0.69	000
	1500	180	5	3	1522	020	0.61	000
	1800	190	3	3	1823	100	0.72	240
	2100	200	5	3	2123	195	0.69	130
Oct. 28	0000	200	7	3	0023	250	0.46	070
TM 0058	0300	180	8	3	0323	310	0.61	030
	0600	170	8	3	0623	340	0.74	000
	0900	170	10	3	0923	340	0.54	320
	1200	180	15	3	1223	320	-	000
				4	1243	035	0.74	000
	1500	180	16	3	1522	000	0.50	350
	1800	180	15	4	1844	345	0.64	165
	2100	170	19	3	2122	000	0.51	310
				4	2145	080	0.34	340
Oct. 29	0000	180	23	3	0022	010	0.86	290
TM 0148	0300	200	25	3	0321	035	0.48	290
				4	0346	080	0.75	350
	0600	190	23	3	0621	100	0.98	250
				4	0646	080	0.30	350
	0900	200	23	3	0922	100	0.98	270
				4	0949	000	0.28	030
	1200	200	25	3	1222	050	0.69	290
				4	1249	055	0.70	330
	1500	200	26	3	1522	055	0.77	240
				4	1549	070	0.90	000
	1800	200	25	3	1822	030	2.00	285
				4	1849	090	0.93	340
	2100	200	23	3	2122	050	2.64	300
				4	2149	045	0.05	000
1953 Oct. 30	0000	200	27	3	0022	105	0.54	260
TM 0234				4	0050	055	0.58	000
	0300	200	26	3	0322	040	0.83	310
				4	0350	080	0.67	300
	0600	200	27	3	0622	070	0.90	300
				4	0650	060	1.01	355
	0900	200	26	3	0921	060	0.62	260
				4	0931	340	0.51	020
	1200	200	26	3	1221	035	0.83	330
				4	1252	010	0.21	020
	1500	200	26	3	1521	080	0.82	010
				4	1552	090	0.74	355
	1800	190	22	3	1821	200	1.01	340
				4	1854	070	0.88	340
	2100	270	5	3	2120	235	0.46	030
				4	2152	090	0.86	000
Oct. 31	0000	260	2	3	0020	290	0.80	270
TM 0317				4	0100	090	0.08	000
	0300	000	14	3	0320	150	0.80	000
				4	0400	105	0.64	010
	0600	000	13	3	0620	125	0.80	000
				4	0700	145	0.69	350
	0900	100	11	3	0920	220	0.37	000
				4	1005	-	1.12	335
	1200	320	9	3	1220	170	0.70	290
				4	1308	-	0.32	145
	1500	270	3	3	1520	010	0.75	000
				4	1610	-	0.26	010
	1800	220	7	3	1820	035	0.98	315
				4	1912	-	0.74	110
	2100	220	9	3	2120	105	0.34	000
				4	2212	-	0.70	000
Nov. 1	0000	320	9	3	0020	105	0.77	000
TM 0357				4	0114	-	0.92	215
	0300	320	7	3	0320	000	0.77	055
				4	0418	-	0.24	040
	0600	280	7	3	0620	070	0.67	020
				4	0718	-	0.30	245
	0900	270	11	3	0920	105	-	000
				4	1018	-	0.77	290
	1200	330	12	3	1220	070	0.48	350
				4	1317	-	0.90	000
	1500	320	12	3	1520	125	0.74	315
				4	1618	-	0.77	000
	1800	340	12	3	1819	150	0.75	270
				4	1918	-	0.03	000
	2100	350	7	3	2119	210	0.88	290
				4	2220	-	0.67	040
1953 Nov. 2	0000	340	3	3	0019	190	0.42	300
TM 0437				4	0120	-	2.08	035
	0300	340	5	3	0319	180	0.67	290
				4	0420	-	2.48	060
	0600	000	6	3	0619	250	0.77	045
				4	0720	-	0.30	270
	0900	070	2	3	0920	230	0.88	280
				4	1023	-	0.27	000
	1200	040	6	3	1220	215	0.26	000
				4	1322	-	0.64	180
	1500	000	7	3	1520	180	0.61	000
				4	1623	-	1.76	090
	1800	040	6	3	1820	205	0.64	000
				4	1923	-	-	000
	2100	-	-	3	2119	260	0.67	310
				4	2224	-	0.19	210
Nov. 3	0000	045	8	3	0019	245	0.74	290
TM 0517				4	0124	-	0.37	320
	0300	110	3	3	0319	210	0.51	300
				4	0424	-	0.74	280
	0600	060	5	3	0619	215	0.61	315
				4	0724	-	0.77	120
	0900	045	11	3	0920	210	0.67	000
				4	1024	-	0.88	350
	1200	045	10	3	1222	215	0.67	320
				4	1325	-	0.13	000
	1500	045	8	3	1522	215	0.30	340
				4	1626	-	0.32	340
	1800	-	-	3	1820	190	-	010
				4	1926	-	0.74	-
	2100	030	5	3	2123	220	0.54	310
				4	2226	-	0.62	210
Nov. 4	0000	045	3	3	0020	260	0.62	250
TM 0558				4	0126	-	0.88	110
	0300	050	2	3	0320	320	0.54	260
				4	0420	-	0.29	135
	0600	045	3	3	0626	330	0.53	180
				4	0726	-	0.03	325
	0900	023	5	3	0926	350	0.56	130
				4	1027	-	0.57	335
	1200	010	5	3	1228	105	0.56	060
				4	1327	-	0.54	325
	1500	000	3	3	1500	330	0.54	210
				4	1600	-	0.69	270
	1800	005	3	3	1831	330	0.61	210
				4	1927	-	0.77	225
	2100	005	4	3	2133	330	0.43	110
1953 Nov. 5	0000	-	calm	3	0035	025	0.42	090
TM 0640				4	0136	-	0.11	020
	0300	010	5	3	0300	050	0.58	060
				4	0436	-	0.56	305
	0600	015	3	3	0600	280	0.62	160
	0900	032	2	3	0941	270	0.69	215
	1200	055	3	3	1243	310	0.46	150
				4	1350	-	0.69	280
	1500	075	4	3	1545	310	0.69	085
				4	1654	-	0.10	000
	1800	075	5	3	1845	330	0.62	135
				4	1959	-	0.37	315
	2100	105	8	3	2146	010	0.61	280
				4	2303	-	0.54	000
Nov. 6	0000	110	7	3	0047	000	0.72	000
TM 0725				4	0205	-	0.64	000
	0300	122	11	3	0347	300	0.19	310
				4	0505	-	0.90	000
	0600	120	5	3	0647	340	0.77	330
				4	0805	-	0.34	000
	0900	120	12	3	0946	010	0.72	340
				4	1109	-	0.14	340
	1200	120	14	3	1246	020	0.75	260
				4	1409	-	0.70	340
	1500	135	15	3	1547	340	0.48	280
				4	1710	-	0.67	325
	1800	135	13	3	1846	320	0.77	350
				4	2013	-	0.94	100
	2100	135	12	3	2146	340	0.72	300
				4	2317	-	0.18	355

(Cont.)

Date	Local Time	Wind dir.	Wind mph	Buoy No.	Trans. Time	Current dir.	Current knots	Wind Vane
Nov. 7 TM 0813	0000	140	-	3	0046	000	0.78	330
				4	0217	-	0.25	315
	0300	150	11	3	0346	020	0.51	290
				4	0519	-	0.69	350
	0600	180	-	3	0646	030	0.77	290
				4	0822	-	0.85	075
	0900	180	-	3	0946	010	0.83	315
				4	1123	-	0.80	005
	1200	220	-	3	1246	350	0.59	310
				4	1424	-	0.03	015
	1500	195	-	3	1545	035	0.43	340
				4	1727	-	0.51	010
	1800	123	7	3	1845	050	0.74	350
	2100	220	6	3	2145	290	-	000
				4	2333	-	0.83	025
1953 Nov. 8 TM 0905	0000	220	calm	3	0045	160	0.66	000
	0300	225	calm	3	0345	170	0.70	000
	0600	265	2	3	0645	215	0.48	340
	0900	050	4	3	0944	210	0.74	310
	1200	070	5	3	1244	230	0.82	280
	1500	050	6	-	-	-	-	-
	1800	050	5	3	1844	250	0.69	270
	2100	060	6	3	2144	240	0.75	270
Nov. 9 TM 0958	0000	015	6	3	0043	240	0.72	000
	0300	060	6	3	0343	225	0.64	290
	0600	080	3	3	0642	250	0.54	290
	0900	078	7	3	0942	230	0.67	320
	1200	120	7	-	-	-	-	-
	1500	070	3	3	1542	280	0.74	260
	1800	085	6	3	1841	305	0.43	240
	2100	080	6	3	2141	220	0.58	000
Nov. 10 TM 1053	0000	098	5	3	0041	220	0.59	010
	0300	098	3	-	-	-	-	-
	0600	090	3	3	0640	125	0.64	110
	0900	095	2	3	0940	000	0.27	270
	1200	090	3	3	1240	050	0.58	235
	1500	090	1	3	1539	060	0.64	240
	1800	-	calm	3	1839	035	0.58	270
	2100	-	calm	3	2138	000	0.69	340
Nov. 11 TM 1147	0000	-	calm	3	0037	030	0.18	350
	0300	240	3	3	0337	040	0.72	300
	0600	240	3	3	0637	105	0.64	260
	0900	220	7	-	-	-	-	-
	1200	190	10	3	1238	035	0.62	290
Nov. 25	0000	140	6	2	0048	010	0.72	280
	0300	140	7	2	0348	015	0.85	300
	0600	140	7	2	0648	010	0.37	310
	0900	150	8	2	0945	020	0.77	305
	1200	175	11	2	1236	055	0.67	295
	1500	175	11	2	1534	110	0.80	070
	1800	180	10	2	1830	090	0.37	290
	2100	180	8	2	2128	095	0.80	225
Nov. 26 TM 0027	0000	185	15	2	0025	315	0.70	030
	0300	185	11	-	-	-	-	-
	0600	190	14	2	0625	005	0.62	020
	0900	190	11	-	-	-	-	-
	1200	185	15	2	1216	060	0.59	350
	1500	185	18	2	1514	020	0.69	350
	1800	200	14	2	1812	035	0.80	330
	2100	195	23	2	2109	045	0.37	340
1953 Nov. 27 TM 0112	0000	210	12	2	0007	010	0.72	010
	0300	260	11	2	0305	080	0.70	350
	0600	295	14	2	0602	090	0.83	350
	0900	295	14	2	0900	145	0.37	305
	1200	295	10	2	1158	145	0.82	300
	1500	295	8	2	1456	190	0.70	235
	1800	285	3	2	1753	215	0.80	225
	2100	-	calm	2	2050	255	0.37	210
Nov. 28 TM 0154	0000	-	calm	-	-	-	-	-
	0300	280	-	2	0245	305	0.67	010
	0600	280	-	2	0540	055	0.77	320
	0900	280	-	2	0842	070	0.54	305
	1200	190	6	2	1140	070	0.48	305
	1500	270	5	2	1437	090	0.77	290
	1800	225	3	2	1735	090	0.78	320
	2100	255	2	2	2033	090	0.74	330
Nov. 29 TM 0234	0000	255	3	-	-	-	-	-
	0300	255	6	2	0230	095	0.67	340
	0600	260	8	2	0528	125	0.59	325
	0900	340	12	2	0824	110	0.75	335
	1200	350	10	2	1122	110	0.48	000
	1500	000	9	2	1420	135	0.69	000
	1800	015	7	2	1717	180	0.69	335
	2100	050	6	2	2016	165	0.69	020
Nov. 30 TM 0314	0000	040	5	-	-	-	-	-
	0300	050	5	-	-	-	-	-
	0600	040	3	2	0510	090	0.88	105
	0900	065	5	-	-	-	-	-
	1200	095	6	2	1105	075	0.37	165
	1500	080	7	2	1404	010	0.26	240
	1800	070	4	2	1701	030	0.72	260
	2100	-	calm	-	-	-	-	-
Dec. 1 TM 0354	0000	100	10	-	-	-	-	-
	0300	120	10	-	-	-	-	-
	0600	125	11	-	-	-	-	-
	0900	110	15	2	1050	010	-	350
	1200	150	6	2	1348	035	0.70	350
	1500	230	24	2	1646	090	0.37	295
	1800	225	22	2	1944	080	0.86	275
	2100	270	15	2	2242	100	0.85	310
1953 Dec. 2 TM 0436	0000	270	12	2	0140	105	0.80	330
	0300	275	14	2	0439	100	0.61	295
	0600	280	22	2	0737	070	0.91	350
	0900	285	20	2	1035	115	0.93	020
	1200	285	20	2	1333	055	0.48	350
	1500	290	18	2	1631	100	0.91	350
	1800	320	19	2	1929	115	0.80	350
	2100	330	18	2	2228	120	0.90	325
Dec. 3 TM 0520	0000	330	15	2	0126	095	0.45	005
	0300	330	14	2	0424	145	0.85	335
	0600	330	15	2	0722	180	0.86	340
	0900	330	16	2	1022	215	0.59	345
	1200	335	15	2	1322	175	0.72	350
	1500	340	16	2	1620	140	0.82	350
	1800	000	12	2	1919	205	0.91	340
	2100	000	11	2	2118	260	0.40	335
Dec. 4 TM 0607	0000	015	7	2	0110	130	0.83	350
	0300	015	8	2	0410	350	0.75	210
	0600	025	6	-	-	-	-	-
	0900	030	7	-	-	-	-	-
	1200	055	7	-	-	-	-	-
	1500	075	8	-	-	-	-	-
	1800	070	6	-	-	-	-	-
	2100	095	9	-	-	-	-	-
Dec. 5 TM 0658	0000	095	6	-	-	-	-	-
	0300	095	5	-	-	-	-	-
	0600	100	4	-	-	-	-	-
	0900	120	4	-	-	-	-	-
	1200	020	2	8	1228	055	-	210
	1500	080	4	8	1528	025	0.06	220
	1800	080	4	8	1828	320	0.49	305
	2100	080	2	8	2128	195	0.34	040
Dec. 6 TM 0752	0000	075	3	8	0028	185	0.39	015
	0300	085	2	8	0328	230	0.43	325
	0600	080	4	8	0628	330	0.69	280
	0900	080	5	8	0929	010	0.36	250
	1200	060	4	8	1359	030	0.56	240
	1500	075	6	8	1659	080	0.60	230
	1800	080	5	8	1959	290	0.42	010
	2100	100	6	8	2127	305	0.34	000

(Cont.)

Date	Local Time	Wind dir.	Wind mph	Buoy No.	Trans. Time	Current dir.	Current knots	Wind Vane
1953 Dec. 7 TM 0847	0000	150	5	8	0027	000	0.00	315
	0300	180	10	8	0327	005	0.49	000
	0600	180	6	8	0627	350	0.59	350
	0900	220	8	8	0926	015	0.49	335
	1200	225	12	8	1224	080	0.43	315
	1500	230	12	8	1526	130	0.43	230
	1800	245	3	8	1825	210	0.00	210
	2100	260	2	8	2125	230	0.42	190
Dec. 8 TM 0943	0000	260	2	8	0025	230	0.56	185
	0300	260	2	8	0325	215	0.46	225
	0600	-	calm	8	0625	240	0.56	140
	0900	010	4	8	0925	215	0.13	295
	1200	035	5	8	1225	200	0.36	020
	1500	080	6	8	1525	260	0.56	350
	1800	125	3	8	1825	280	0.42	015
	2100	125	4	8	2125	285	0.46	245
Dec. 9 TM 1037	0000	125	4	8	0025	350	0.60	300
	0300	130	6	8	0325	330	0.07	320
	0600	130	7	8	0625	335	0.52	315
	0900	120	6	8	0925	305	0.49	330
	1200	100	8	8	1225	035	0.46	315
	1500	135	11	8	1525	030	0.52	300
	1800	120	11	8	1825	080	0.56	215
	2100	130	7	8	2125	200	0.13	080
Dec. 10 TM 1129	0000	120	7	8	0157	090	0.63	225
	0300	150	11	8	0325	080	0.49	245
	0600	180	14	8	0625	080	0.63	275
	0900	180	15	8	0923	080	0.39	280
	1200	200	18	8	1223	080	0.29	305
	1500	225	17	8	1521	080	0.83	285
	1800	225	15	8	1821	085	0.95	295
	2100	255	14	8	2121	095	0.53	260
Dec. 11 TM 1219	0000	-	calm	8	0021	130	0.70	260
	0300	240	4	8	0321	110	0.90	260
	0600	240	4	8	0621	150	0.63	300
	0900	230	6	8	0921	150	0.13	290
	1200	060	3	8	1221	195	0.83	115
	1500	080	10	8	1521	195	0.85	000
	1800	065	10	8	1821	200	0.70	010
	2100	090	11	8	2121	195	0.00	020
1953 Dec. 12 TM 1308	0000	090	12	8	0021	230	0.49	010
	0300	100	10	8	0321	190	0.62	030
	0600	110	10	8	0621	195	0.49	030
	0900	120	11	8	0921	190	0.34	100
	1200	150	11	8	1221	215	0.42	055
	1500	180	12	8	1521	205	0.17	080
	1800	200	14	8	1821	120	0.32	190
	2100	220	12	8	2121	100	0.40	225
Dec. 13 TM 1356	0000	220	15	8	0021	090	0.46	215
	0300	225	15	8	0321	180	0.46	185
	0600	225	14	8	0621	170	0.56	200
	0900	230	13	8	0921	120	0.07	235
	1200	240	17	8	1221	125	0.40	240
	1500	240	14	8	1521	120	0.60	235
	1800	220	11	8	1821	180	0.84	180
	2100	210	11	8	2121	185	0.07	135
Dec. 14 TM 1445	0000	220	13	8	0021	195	0.76	145
	0300	220	12	8	0321	120	0.73	215
	0600	210	13	8	0621	170	0.77	160
	0900	220	13	8	0918	160	0.39	160
	1200	220	15	8	1218	160	0.98	135
	1500	210	14	8	1521	195	0.70	140
	1800	210	14	8	1818	160	0.29	160
	2100	210	18	8	2117	185	0.87	130
Dec. 15 TM 1536	0000	210	15	8	0017	250	0.60	095
	0300	210	17	8	0317	280	0.49	035
	0600	210	16	8	0617	155	0.07	170
	0900	220	20	8	0917	150	-	220
	1200	210	23	-	-	-	-	-
	1500	270	10	-	-	-	-	-
	1800	330	12	-	-	-	-	-
	2100	350	16	-	-	-	-	-
Dec. 16 TM 1630	0000	350	12	-	-	-	-	-
	0300	345	9	-	-	-	-	-
	0600	015	7	-	-	-	-	-
	0900	045	3	-	-	-	-	-
	1200	030	3	-	-	-	-	-
	1500	350	4	7	1538	340	-	-
	1800	000	6	7	1838	310	0.53	-
	2100	000	5	7	2138	240	0.62	-
1953 Dec. 17 TM 1727	0000	330	3	7	0038	075	0.43	-
	0300	300	5	7	0338	175	0.07	-
	0600	280	10	7	0638	125	0.62	-
	0900	300	12	7	0938	170	0.52	-
	1200	320	14	7	1238	185	0.60	-
	1500	330	15	7	1537	270	0.55	-
	1800	330	19	7	1837	295	0.17	-
	2100	320	17	7	2137	150	0.60	-
Dec. 18 TM 1827	0000	320	14	7	0037	250	0.60	-
	0300	320	17	7	0337	215	0.45	-
	0600	320	14	7	0637	265	0.77	-
	0900	310	14	7	0937	220	0.00	-
	1200	310	9	7	1237	185	0.78	-
	1500	320	10	7	1537	190	0.81	-
	1800	320	18	7	1837	225	0.69	-
	2100	320	21	7	2137	235	0.00	-
Dec. 19 TM 1928	0000	320	23	7	0037	210	0.64	-
	0300	325	12	7	0337	255	0.70	-
	0600	325	18	7	0637	220	0.78	-
	0900	325	17	7	0937	225	0.31	-
	1200	320	18	7	1237	195	0.76	-
	1500	320	18	7	1537	235	0.70	-
	1800	320	18	7	1837	220	0.80	-
	2100	350	15	7	2137	190	0.18	-
Dec. 20 TM 2028	0000	350	11	7	0037	225	0.70	-
	0300	345	9	7	0337	190	0.70	-
	0600	340	6	7	0637	180	0.60	-
	0900	340	6	7	0936	250	0.45	-
	1200	340	6	7	1236	225	0.31	-
	1500	270	2	7	1536	210	0.62	-
	1800	270	2	7	1836	210	0.53	-
	2100	270	3	7	2136	240	0.55	-
Dec. 21 TM 2124	0000	270	7	7	0036	120	0.42	-
	0300	270	6	7	0336	145	0.07	-
	0600	-	calm	7	0636	115	0.62	-
	0900	270	2	7	0936	095	0.59	-
	1200	200	15	7	1236	095	0.46	-
	1500	195	18	7	1536	065	0.50	-
	1800	210	15	7	1836	065	0.28	-
	2100	210	16	7	2136	065	0.38	-
1953 Dec. 22 TM 2216	0000	210	22	7	0036	065	0.64	-
	0300	210	22	7	0336	065	0.70	-
	0600	210	22	7	0636	065	0.67	-
	0900	210	19	7	0935	095	0.15	-
	1200	210	22	7	1235	085	0.69	-
	1500	210	19	7	1535	075	0.64	-
	1800	210	16	7	1835	095	0.69	-
	2100	210	15	7	2135	110	0.25	-
Dec. 23 TM 2303	0000	230	9	7	0035	090	0.36	-
	0300	215	6	7	0335	110	0.73	-
	0600	-	-	7	0635	125	0.60	-
	0900	250	4	7	0935	135	0.52	-
	1200	260	6	7	1235	165	0.21	-
	1500	260	6	7	1534	105	0.13	-
	1800	250	6	-	-	-	-	-
	2100	250	9	7	2134	105	0.52	-
Dec. 24 TM 2348	0000	260	17	7	0034	230	0.52	-
	0300	260	20	7	0334	110	0.60	-
	0600	260	21	7	0634	120	0.13	-
	0900	260	23	7	0934	095	0.70	-
	1200	270	12	7	1234	130	0.70	-
	1500	030	8	7	1534	195	0.70	-
	1800	020	11	7	1834	345	0.34	-
	2100	000	10	7	2134	275	0.18	-

(Cont.)

	Local Time	Wind dir.	Wind mph	Buoy No.	Trans. Time	Current dir.	Current knots	Wind Vane
Dec. 25	0000	000	13	7	0034	250	0.73	-
	0300	020	10	7	0334	285	0.70	-
	0600	030	9	7	0634	270	0.66	-
	0900	045	5	7	0934	300	0.17	-
	1200	045	3	7	1234	315	0.43	-
	1500	120	3	7	1534	065	0.57	-
	1800	180	7	7	1834	065	0.53	-
	2100	210	12	7	2134	065	0.49	-
Dec. 26	0000	210	22	7	0034	065	0.41	-
TM 0029	0300	210	20	7	0334	130	0.20	-
	0600	210	32	7	0634	075	0.74	-
	0900	250	18	7	0932	105	0.71	-
	1200	320	12	7	1232	175	0.73	-
	1500	320	11	7	1532	190	0.07	-
1953 Dec. 30	0000	250	14	-	-	-	-	-
TM 0313	0300	270	9	-	-	-	-	-
	0600	270	8	-	-	-	-	-
	0900	260	7	-	-	-	-	-
	1200	270	9	6	1346	115	0.66	280
	1500	270	7	6	1527	130	0.46	280
				6	1646	150	0.07	225
	1800	250	6	6	1827	145	0.85	225
				6	1946	275	0.71	180
	2100	250	6	6	2127	255	0.59	175
				6	2246	255	0.71	175
Dec. 31	0000	250	12	6	0027	130	0.67	230
TM 0359				6	0146	090	0.57	230
	0300	250	8	6	0327	355	0.50	080
				6	0446	090	0.20	355
	0600	250	12	6	0627	090	0.27	355
				6	0746	065	0.77	000
	0900	250	18	6	0948	095	0.66	240
				6	1048	105	0.66	240
	1200	250	22	6	1228	115	0.70	240
				6	1348	105	0.90	255
	1500	250	22	6	1529	085	0.77	240
				6	1649	095	0.17	225
	1800	250	21	6	1828	105	0.69	145
				6	1949	095	0.78	025
	2100	330	27	6	2128	115	0.74	005
				6	2249	130	0.87	355
1954 Jan. 1	0000	330	25	6	0028	130	0.97	005
TM 0448				6	0149	150	0.80	015
	0300	330	24	6	0328	120	0.43	015
				6	0449	115	0.69	355
	0600	330	21	6	0628	120	0.87	035
				6	0749	160	0.71	335
	0900	330	18	6	0928	140	0.80	030
				6	1049	125	0.74	015
	1200	330	16	6	1228	130	0.71	025
				6	1351	120	0.08	025
	1500	310	13	6	1651	120	0.71	120
	1800	310	11	6	1830	115	0.59	030
				6	1951	105	0.55	355
	2100	310	10	6	2130	055	0.74	060
				6	2251	110	0.74	000
1954 Jan. 2	0000	326	13	6	0030	105	0.63	295
TM 0540				6	0151	120	0.11	355
	0300	330	13	6	0330	095	0.48	045
				6	0451	120	0.00	355
	0600	330	13	6	0630	120	0.59	025
				6	0751	120	0.63	355
	0900	340	11	6	0932	125	0.67	295
				6	1053	130	0.71	355
	1200	340	9	6	1232	160	0.70	030
				6	1353	140	0.21	295
	1500	030	7	6	1532	165	0.24	040
				6	1653	175	1.06	025
	1800	050	3	6	1832	205	0.70	000
				6	1953	185	0.63	040
	2100	-	calm	6	2132	195	0.70	045
				6	2253	145	0.77	125

	Local Time	Wind dir.	Wind mph	Buoy No.	Trans. Time	Current dir.	Current knots	Wind Vane
Jan. 3	0000	-	calm	6	0032	205	0.63	125
TM 0636				6	0153	165	0.15	170
	0300	-	calm	6	0332	285	0.35	115
				6	0453	220	0.60	100
	0600	060	1	6	0632	210	0.81	140
	0900	120	3	6	0934	270	0.71	055
				6	1054	310	0.85	020
	1200	180	12	6	1234	285	0.67	025
				6	1356	295	0.11	035
	1500	300	4	6	1534	285	0.67	060
				6	1656	305	0.66	025
	1800	210	20	6	1834	045	0.59	355
				6	1956	340	0.63	355
	2100	200	19	6	2134	320	0.70	015
				6	2256	025	0.85	185
Jan. 4	0000	210	19	6	0034	025	0.59	355
TM 0732				6	0156	030	0.14	355
	0300	210	22	6	0334	350	0.35	355
				6	0456	005	0.77	010
	0600	210	19	6	0634	340	0.67	025
				6	0756	055	0.77	060
	0900	210	20	6	0936	031	-	001
				6	1056	015	0.63	358
	1200	210	23	6	1236	022	0.77	356
				6	1356	030	0.08	-
	1500	210	19	6	1556	005	1.68	002
	1800	240	7	6	1836	-	0.13	-
				6	1956	102	1.67	356
	2100	000	9	6	2136	110	0.08	-
				6	2256	212	-	097
1954 Jan. 5	0000	020	8	6	0036	301	0.35	-
TM 0828				6	0156	212	0.20	-
	0300	035	4	6	0336	147	1.40	059
				6	0456	175	0.35	000
	0600	060	5	6	0636	298	0.85	041
				6	0756	297	0.77	042
	0900	038	4	6	0940	295	0.67	105
				6	1056	270	0.53	356
	1200	085	5	6	1240	212	0.63	048
				6	1356	212	0.00	059
	1500	063	5	6	1540	339	0.66	012
				6	1700	264	0.69	012
	1800	090	10	6	1842	264	0.13	042
	2100	120	14	6	2142	270	0.41	026
Jan. 6	0000	170	17	6	0042	270	0.11	031
TM 0923				6	0200	297	0.27	-
	0300	180	19	6	0342	311	-	000
				6	0500	330	0.62	356
	0600	185	19	6	0642	321	0.62	358
				6	0800	330	0.59	018
	0900	220	14	6	0942	005	0.74	352
				6	1100	201	0.83	000
	1200	225	9	6	1242	032	0.56	000
				6	1400	076	0.27	020
	1500	260	6	6	1542	076	0.66	338
				6	1700	060	0.62	-
	1800	260	8	6	1842	100	0.87	338
				6	2000	041	0.60	-
	2100	225	14	-	-	-	-	-
Jan. 7	0000	220	24	-	-	-	-	-
TM 1015	0300	215	26	-	-	-	-	-
	0600	210	20	-	-	-	-	-
	0900	200	16	6	0942	153	-	000
				6	1100	121	0.63	338
	1200	305	15	6	1242	119	0.21	000
				6	1400	152	-	338
	1500	305	15	6	1542	130	-	338
	1800	315	16	-	-	-	-	-
	2100	315	20	6	2142	092	-	000
				6	2300	066	0.27	-
1954 Jan. 8	0000	315	20	6	0042	085	0.88	338
TM 1105				6	0200	100	0.11	000
	0300	320	19	6	0342	110	0.43	000
				6	0500	169	0.88	301
	0600	330	20	6	0800	154	0.56	283
	0900	330	22	6	0944	160	-	275
				6	1100	122	0.10	000
	1200	330	20	6	1244	131	0.74	000
	1500	330	20	6	1545	103	0.77	000
				6	1700	155	0.90	000
	1800	335	22	6	1845	158	0.07	338
				6	2000	160	0.27	000
	2100	335	20	-	-	-	-	-

(Cont.)

	Local Time	Wind dir.	Wind mph	Buoy No.	Trans. Time	Current dir.	Current knots	Wind Vane
Jan. 9	0000	330	19	-	-	-	-	-
TM 1154	0300	330	13	6	0500	270	-	000
	0600	345	15	6	0642	192	0.43	000
	0900	000	10	6	1100	168	0.56	357
	1200	000	13	6	1242	211	0.83	338
				6	1400	202	0.85	000
	1500	000	7	6	1548	230	0.56	000
				6	1700	168	0.27	-
	1800	010	5	6	1848	239	0.64	224
	2100	-	calm	6	2128	097	0.56	085
Jan. 10	0000	-	calm	-	-	-	-	-
TM 1243	0300	-	calm	-	-	-	-	-
	0600	225	6	-	-	-	-	-
	0900	225	7	-	-	-	-	-
	1200	220	10	6	1249	330	-	356
				6	1400	329	0.55	356
	1500	190	12	6	1548	350	0.69	000
				6	1700	358	0.55	000
	1800	190	14	-	-	-	-	-
	2100	185	17	-	-	-	-	-
Jan. 11	0000	185	14	-	-	-	-	-
TM 1333	0300	195	20	-	-	-	-	-
	0600	220	21	-	-	-	-	-
	0900	225	17	6	0951	349	-	356
				6	1100	005	1.62	000
	1200	220	20	6	1413	357	0.15	000
	1500	210	21	6	1552	008	0.80	301
				6	1700	008	0.83	000
	1800	200	16	-	-	-	-	-
	2100	200	16	-	-	-	-	-
1954 Jan. 12	0000	190	21	-	-	-	-	-
TM 1425	0300	190	21	6	0342	026	-	000
				6	0500	006	0.77	000
	0600	240	26	6	0642	027	0.76	139
				6	0800	008	0.88	003
	0900	245	26	6	0953	041	0.11	352
				6	1141	103	0.83	008
	1200	270	8	6	1253	028	0.46	358
				6	1414	060	0.66	301
	1500	250	10	6	1553	078	0.88	150
	1800	245	8	6	2015	103	-	-
	2100	270	8	6	2153	121	0.21	353
				6	2315	-	1.16	007
Jan. 13	0000	300	11	6	0053	060	0.49	042
TM 1519	0300	300	12	6	0353	152	0.49	264
				6	0515	152	1.10	264
	0600	310	14	6	0653	121	0.84	000
				6	0815	010	0.15	000
	0900	335	21	6	0953	264	0.70	098
				6	1015	264	0.76	221
Jan. 26	0000	355	13	-	-	-	-	-
TM 0107	0300	030	11	-	-	-	-	-
	0600	030	7	-	-	-	-	-
	0900	040	6	-	-	-	-	-
	1200	065	7	9	1245	293	0.35	026
	1500	070	6	9	1545	-	0.56	332
	1800	095	4	9	1845	011	0.66	350
	2100	090	4	9	2145	031	0.71	305
Jan. 27	0000	090	5	9	0047	328	0.20	312
TM 0151	0300	090	4	9	0347	063	0.52	286
	0600	100	4	9	0647	048	0.57	287
	0900	105	5	9	0946	045	0.66	311
	1200	100	6	9	1246	005	0.49	260
	1500	090	3	9	1545	334	0.34	328
	1800	-	calm	9	1845	350	0.59	338
	2100	-	calm	9	2145	034	1.54	348
1954 Feb. 8	0000	280	10	-	-	-	-	-
TM 1221	0300	-	-	-	-	-	-	-
	0600	-	-	-	-	-	-	-
	0900	-	-	-	-	-	-	-
	1200	150	7	-	-	-	-	-
	1500	140	14	14	1637	307	-	000
	1800	180	17	14	1937	001	0.72	000
				14	2043	359	0.45	312
	2100	225	24	-	-	-	-	-
Feb. 9	0000	265	26	-	-	-	-	-
TM 1315	0300	270	50	-	-	-	-	-
	0600	260	43	-	-	-	-	-
	0900	265	30	14	1040	100	-	000
				14	1145	095	0.96	270
	1200	270	18	14	1340	096	1.08	280
	1500	280	18	14	1445	140	1.08	336
	1800	280	20	-	-	-	-	-
	2100	280	23	-	-	-	-	-

Notes on Table I.

Buoys 8, 9, and 14 were all rigged as shown in Figure 2; buoys 6 and 7 were rigged with the deep drag on a bridle directly beneath the can; buoys 2, 3 and 4 were rigged the same as Figure 2, but the deep drag was replaced by another rotor similar to that at the surface. The depth of the deep drag, of the surface rotor, and the Magnus correction applied in determining current direction from the rough data, were as follows:

Buoy No.	Depth of deep drag (or rotor) (feet)	Depth of surface rotor (feet)	Current direction correction
2	150	8	− 10°
3	200	8	− 10°
4	150	8	− 10°
6	170	8	unknown
7	120	8	− 25°
8	530	13	− 10°
9	150	8	+ 10°
14	300	10	+ 10°

It is probable that there is a systematic error in all angles measured by buoy 6.

The notation "TM" means the Bermuda Time (GMT − 4 hours) of Greenwich upper transit of the moon. The anemometers on the buoys were so unreliable (due to circuit troubles) that all of their data are omitted. Winds tabulated are those on a 50 foot mast at the observatory at Bermuda. The exposure was not ideal, there being several hills, and a large building in the neighborhood. Particularly, the anemometer is partly sheltered from west winds.

The notation 'Trans. Time" means the Bermuda time at which the buoy wireless transmission was received. The current direction is the instantaneous magnetic direction of the surface current (vectorial difference of surface and deep) with the above corrections applied. The current speed is an average for the previous three hours (in the case of buoy 6, 90 minutes).

The figures under "Wind Vane" are angle between the geographical orientation of the buoy and the wind direction measured by the vane on the buoy. Thus an angle of 000° means that the instantaneous wind and uncorrected current vector point in the same direction; an angle of 030° means the uncorrected current is 30° to the left of the wind; an angle of 320° means the uncorrected current is 40° to the right of the wind.

is the considerable irregularity of the currents even during days while the wind is fairly steady. In his discussion of the current measurements which he made on board the "Armauer Hansen" in 1930, EKMAN (1953) has called this irregular motion a kind of "macro-turbulence". As a result it is difficult to extract from the data definite statements about such things as: (i) the deviation of the surface current from the direction of the surface wind; and (ii) the ratio of current speed to the speed of the wind producing it. EKMAN (1953) attempted to analyze his data for "Armauer Hansen" anchor station D in order to find the answer to these questions and to delineate the drift current spiral as a function of depth. Because of the macro-turbulence the results of his analysis were disappointingly indefinite. The purpose of such an analysis, of course, was to verify in the deep ocean the results of his theory (EKMAN 1905).

Table 2. Total number of vane readings (cumulative) for each 10° angle of deviation of current from wind

Buoys 2, 3, 4, and 8

170 R	4	010 L	274
160 R	6	020 L	288
150 R	7	030 L	297
140 R	18	040 L	307
130 R	25	050 L	309
120 R	30	060 L	311
110 R	32	070 L	314
100 R	46	080 L	318
090 R	56	090 L	320
080 R	68	100 L	322
070 R	79	110 L	325
060 R	103	120 L	331
050 R	121	130 L	333
040 R	141	140 L	338
030 R	154	150 L	340
020 R	172*	160 L	341
010 R	192	170 L	345
000	223		

*Half the readings are on either side of this point.

The present buoy measurements are confined to the surface. They cover a longer period than those made on the "Armauer Hansen". It is therefore hopeful that certain features of drift currents may emerge more clearly from the confusion of the macro-turbulence.

In order to appreciate how serious an obstacle the macro-turbulence is to a simple analysis of the data, an analysis can be made of all the wind vane readings obtained from buoys 2, 3, 4, and 8 (Table II). The current direction correction due to the Magnus effect on the rotor has been applied. As can be seen, there is a very large scatter of the angle of deviation of the current from the wind; at one time or another every possible angle has occurred. On the average, however, there is a greater frequency of small angles of deviation showing that usually a current does not run against the wind. Moreover, there is a rather definite indication that currents to the right of the wind are more frequent than currents to the left of the wind. The mode of this frequency distribution lies at about 20° to the right of the wind, but it is obvious that this type of analysis of the data, including as it does all cases where the winds were rapidly varying, and all cases with pronounced irregular motions or possible inertial oscillations, gives at best a very diffuse and indefinite kind of answer to question (i). Similar objections can be raised to an attempt to make a gross average determining the ratio of current to wind velocity. A more rational approach is to study individual cases where the wind was observed to be steady. Of course the currents are not exactly steady during the same time. The question arises as to how long a time interval to employ for the study of individual cases. EKMAN (1905) indicated that after the onset of a wind the average of the current for the first 24 hours (at 30° N) is a very close approximation to the theoretical current produced by a wind of infinite duration. Thus, in attempting to find answers to questions such as (i) and (ii) (above), 24-hour vectorial averages of wind and current are formed for days of steady wind. The concept of a steady wind is subjective.

The data obtained from October 28—31 is a good sample of the relation between wind and current as it actually appears in nature (Figure 5). During October 28 the wind began to blow toward the north and by midnight was blowing about 23 knots; the currents, which were at first weak and variable, gradually veered to the right of the wind and grew stronger. Early on October 29 the wind itself veered until it blew toward NNE. The current veered, too, and executed a rotatory motion about a mean velocity about 42° to the right of the wind. During the afternoon of October 30, the wind dropped rapidly, and the current began to execute a rotatory (inertial) motion about a zero mean velocity. By October 31,

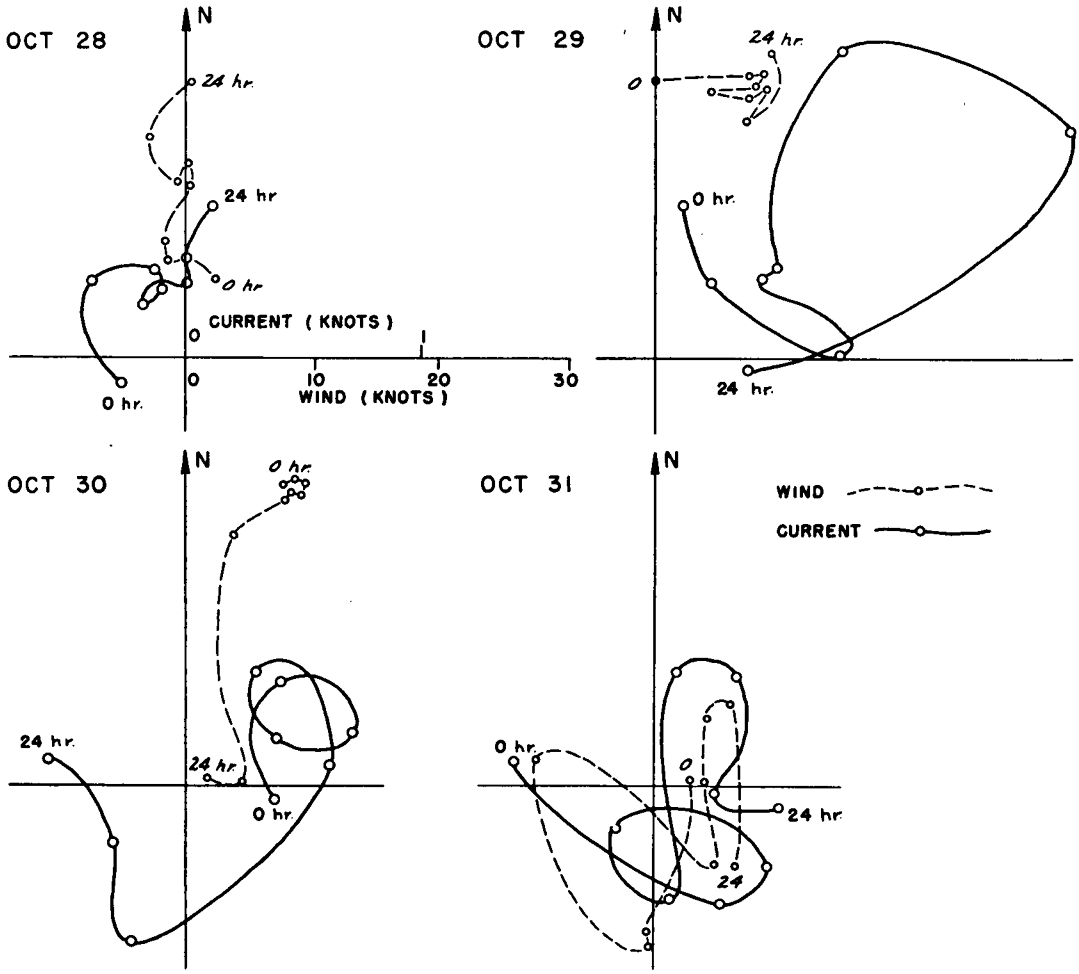

Fig. 5. Sample daily records of wind and current showing the response of the current to a strong wind and the after-effects following it.

the winds were light variable and the motions of the current were very irregular and confused. All evidence of a simple 24-hour inertial period was gone. During the winter of 1953—1954 the currents in the Northwestern Sargasso Sea are most often in a confused state such as depicted on October 31. It is only during days of steady strong winds, and immediately following them, that the theoretical features deduced by EKMAN (1905) are clearly defined. Table III contains means of wind and current for all days during which the wind was steady. It was prepared for the purpose of examining the data from the 24-hour mean "case history" point of view.

III. The angle between the wind and current

Two independent ways of measuring the angle between wind and current are possible. The angle may be determined by comparing the mean wind direction at the observatory with direction of the current given by the magnetic compass on the buoy (Method 1). The angle may also be determined directly from the wind vane on the buoy, which

Table 3. 24-hour vectorial means of current and winds for days with steady winds.

Day	Buoy	Wind blows toward	Wind speed (knots)	Current Direction	Current Speed (knots)	Angle of current relative to wind Method (1)	Angle of current relative to wind Method (2)
Oct. 29	3	018	20.0	060	1.09	042 R	070 R
29	4	018	20.0	070	0.70	052 R	000
Nov. 3	3	225	6.1	230	0.51	005 R	025 R
6	3	305	11.2	345	0.64	040 R	045 R
8	3	230	4.4	235	0.72	005 R	040 R
9	3	270	4.5	270	0.57	000	055 R
23(1)	2	285	11.2	315	0.45	030 R	010 R
24	2	335	6.0	335	0.56	000	005 L
26	2	015	13.0	030	0.57	015 R	005 R
Dec. 2-3	2	150	13.0	170	0.50	020 R	020 R
5	8	270	3.0	(2)	0.08	(2)	(2)
6	8	260	4.0	(2)	0.18	(2)	(2)
18	7	140	13.0	220	0.61	080 R	(5)
19	7	145	16.0	225	0.67	080 R	(5)
22	7	030	17.0	075	0.62	045 R	(5)
23	7	060	6.0	115	0.48	055 R	(5)
Jan. 1	6	150	18.0	(3)	0.70	(3)	(3)
3-4	6	030	17.0	(3)	0.50	(3)	(3)
8	6	150	18.0	(3)	0.68	(3)	(3)
11(4)	6	025	18.0	(3)	0.72	(3)	(3)
26-27	9	270	4.0	010	0.48	100 R	055 R
Feb. 9	14	270	23.0	(4)	1.45	(4)	045 R

(1) Current data not available for entire 24 hours, but winds blew steady for previous four days.

(2) Mean direction meaningless because of large oscillatory motions.

(3) Angles have unknown systematic errors due to faulty bridling of Buoy 6.

(4) Current data not available for entire 24 hours.

(5) Wind vane broken.

measures the instantaneous angle between wind and buoy orientation (Method 2). Although this latter method is direct, it is likely to be more erratic due to gustiness of the wind—the sampling of wind direction from wind vane measurements on the buoy is naturally much poorer than the continuous records available at the observatory.

By both methods it is seen that (in agreement with EKMAN, 1905) the current is to the right of the wind, by an angle varying between 30° and 60°. During weak winds there is a greater spread of angles, and on the average the angle appears to be less than for strong winds.

IV. The Ratio of current speed to wind speed

The ratios of current speed to wind speed cited in Table III are about twice what would be expected from Ekman's study. When plotted on a logarithmic scale (Figure 6) these data give some indication that the ratio is not independent of wind speed. There is enough scatter in the data to prevent certainty concerning this point. EKMAN (1905) discussed the case of a "quadratic" law of friction in the sea, and showed that in this case the current speed would be proportional to the three-halves power of the wind speed (rather than linearly proportional). The very limited data at hand suggests the reality of this law of friction, but of course does not prove it. The solid line in Figure 6 depicts the linear law; the dashed line, the three-halves law.

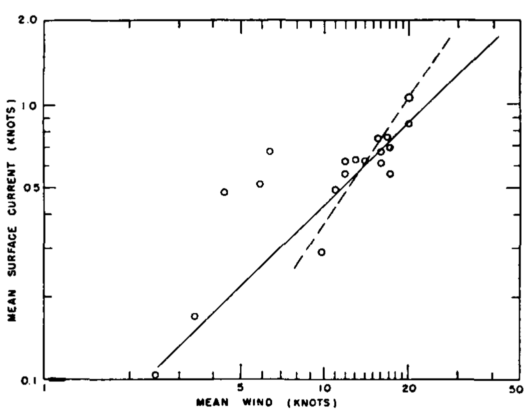

Fig. 6. Logarithmic graph of mean wind against mean surface current for days with steady wind. The solid line has slope of 1.0; the dashed line, slope of 1.5.

Table 4. Inertial amplitudes and phase for days showing 24-hour rotatory currents. All cases are cum sole.

Day	Buoy	Amplitude (knots)	Time of Maximum Northerly Flow: Local Mean Solar Time	Time of Maximum Northerly Flow: Greenwich Lunar Time
Oct. 29	3	0.20	1500	1310
30	3	0.25	0800	0530
Nov. 1	3	0.13	0430	0030
5	3	0.10	2030	1400
9	3	0.10	1330	0330
25	2	0.06	0000	0030
27	2	0.25	0000	2230
Dec. 6	8	0.25	0730	2330
7	8	0.20	0630	2145
23	7	0.10	0900	1000
24	7	0.25	1300	1330
26	7	0.06	1100	1200
Jan. 4	6	0.20	0730	0000
6	6	0.20	0900	2330

V. The Presence of inertial oscillations

The design of the rig used on these buoys is not ideal for detecting or studying inertial oscillations because, as Fredholm (EKMAN, 1905) showed, the inertial motions penetrate quickly to layers below the depth of frictional influence, and hence the inertial, or quasi-periodic, term in the vectorial difference of velocity is likely to diminish quickly if the deep drag is not much below the depth of frictional influence. Very clear and distinct rotatory currents with 24-hour period were observed on 14 separate days (Table IV); they were quickly damped out (whether by vertical diffusion of momentum, or horizontal dispersion of energy in the form of gravity waves is uncertain). The sense of rotation in every case was *cum sole*. Comparison of phase, to time of transit of the moon results in a complete scatter, thus ruling out the likelihood that these 24-hour periods are lunar tidal currents. There is also no relation to time of day, thus ruling out solar tides.

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