EARTH'S DEFLECTIVE FORCE EXHIBITED IN TIDES AND CURRENTS

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Phases and characteristics of natural phenomena do not always exhibit close agreement with theories which have been advanced, many factors, difficult of evaluation, at times entering to disturb the agreement. It is therefore interesting and satisfactory to find the theory of the effect of the deflective force of the earth's rotation fairly well in accord with actual observations of tides and currents.

Geologists have noted the deflective force, due to the earth's rotation, in the evidence of erosion of one of the banks of nontidal streams, the results of which are shown in the bluff lines on one of their banks, the right bank in the Northern Hemisphere and the left bank in the Southern Hemisphere, facing in the direction of flow of the current. (*) In this paper examples will be taken in the Northern Hemisphere and the text illustrating the examples will have reference to such cases only, both as to tides and currents, and it is to be understood that, when the statement is made that the deflection is to the right, reference is made to the Northern Hemisphere.

In fresh water streams beyond the influence of tidal action, the direction of flow is always towards the sea and therefore the right bank is the one to the right facing down stream and the one showing the evidence of this erosion. In such streams the illustration of this deflective force in the eroding of the one bank is qualitative. In tidal streams, however, we have a quantitative evidence of this deflective force illustrated in the difference in ranges, or rise and fall of the tide, on the two shores of a tidal stream.

Facing upstream in the direction of flow of the flood current on a rising tide, the deflective force of the earth's rotation causes the tide to rise higher along the shore on the right. An increased range of tide therefore occurs due

(*) COLLIER COBB: "*Notes on the Deflective Effect of the Earth's Rotation as Shown in Streams*", Journal of the Elisha Mitchell Scientific Society, Vol. X, 1893, first part.

G. K. GILBERT: "*The Sufficiency of Terrestrial Rotation for the Deflection of Streams*", American Journal of Science, Third Series, Volume 27, 1884, Art. XLIX, pp. 427-432.

to the tides rising higher on that shore. Now facing downstream in the direction of flow of the ebb current on a falling tide, the water is likewise deflected toward the right, which is in this case the opposite shore, and the height of the water will register higher at low water than on the other shore. The tide, then, registers higher on the first-named shore on the rising tide and also registers lower on that shore on the falling tide. A double effect is therefore attained by the tide's rising and falling lower on the right-hand shore, facing upstream.

As an example, the tide entering Delaware Bay on the flood is deflected to the right, facing up the bay in the direction of the flow of the current, and the tide rises $\frac{1}{4}$ foot higher at Cape May on the Eastern shore than at Cape Henlopen on the Western shore. On the falling tide, facing down the bay in the direction of flow of the ebb current, the water is deflected toward the right or western shore and the low water at Cape Henlopen registers $\frac{1}{4}$ foot higher than the low water at Cape May. The high water then at Cape May is the higher by $\frac{1}{4}$ foot than at Cape Henlopen and the low water the lower by $\frac{1}{4}$ foot or a total of $\frac{1}{2}$ foot greater range of tide at Cape May than at Cape Henlopen.

The Tide Tables, Atlantic Coast, issued by the Coast and Geodetic Survey give on page 359 the mean ranges of the tide in Delaware Bay at points directly opposite on the western and eastern shores from the capes at the entrance to Bombay Hook as follows:—

Western Shore.	*Range in feet.*	*Eastern Shore.*	*Range in feet.*
Cape Henlopen	4.2	Cape May	4.7
Broadkill River (Entrance)	4.4	Marcey Landing	5.1
Mispillian River Light	5.1	Dennis Creek (Entrance)	5.6
Murderkill River (Entrance)	5.4	Egg Island Light	5.7
Mahon River Light	5.6	Fortescue Beach	5.9
Liepsic River (Entrance)	5.6	Ben Davis Point	6.0
Bombay Hook Point	5.7	Cohansey Light	6.0
Bombay Hook	5.8	Arnold Point	6.0
Average Mean Range	5.22	Average Mean Range	5.62

The average mean range of tide on the eastern (right) shore of Delaware Bay is found to be four-tenths of a foot greater than on the western (left) shore. In one case the differnce of the mean ranges at points directly opposite on the two shores is seen to be as much as seven-tenths of a foot, at Broadkill River Entrance on the western shore and at Marcey Landing on the eastern shore.

As another example the table following gives the mean ranges in Chesapeake Bay at points directly opposite on the western and eastern shores from the Capes at the entrance to the mouth of the Patapsco River:

Western Shore.	*Range in feet.*	*Fastern Shore.*	*Range in feet.*
Cape Henry	2.8	Cape Charles	3.0
Near Point Comfort	2.2	Cherry Stone Light	2.3
Stingray Point	1.4	Occohannock Creek	1.8
South Point Light	1.2	Tangier Light	1.6
Point Lookout	1.3	Holland Island Light	1.6
Cedar Point	1.2	Barren Island	1.5
Chesapeake Beach	0.9	Sharps Island	1.3
Herring Bay	0.9	Poplar Island	1.2
Sandy Point	0.8	Love Point	1.1
Seven Foot Knoll	0.9	Tolchester Beach	1.3
Average Mean Range	1.36	Average Mean Range	1.67

The average mean range on the eastern (right) shore of Chesapeake Bay is seen to be 0.31 foot greater than on the western (left) shore.

The Bay of Fundy, because of its larger range of tide, furnishes a more striking example of this interesting phenomenon. Below are shown the mean ranges of tide directly opposite on both shores of the bay from its mouth to its head:

Western Shore.	*Range in feet.*	*Eastern Shore.*	*Range in feet.*
Belfast, Maine	9.7	Jeboque Point, N. S.	14.0
Eastport, Maine	18.2	Annapolis, N. S.	25.1
St. Johns, N. B.	20.9	Port George, N. S.	27.8
Moncton, N. B.	41.2	Minas Basin, N. S.	44.2
Average Mean Range	22.6	Average Mean Range	27.8

The average mean range on the eastern shore of the Bay of Fundy is seen to be 5.3 feet greater than on the western shore.
(Figure 1) shows the mean range of tide on both shores of the Bay of Fundy. The upper curve is drawn through the plottings of the mean ranges at several points on the Nova Scotia shore as taken from the tide tables; the lower curve is for the Maine-New Brunswick Shore. These two curves of ranges differ at the mouth of the bay by about 4 feet, halfway up the bay about 6 feet, the difference decreasing to about 3 feet at the head where the bay becomes decidedly narrower.

In a body of water in which the tides are due primarily to a progressive wave the greatest velocity of the current occurs at the times of high and low

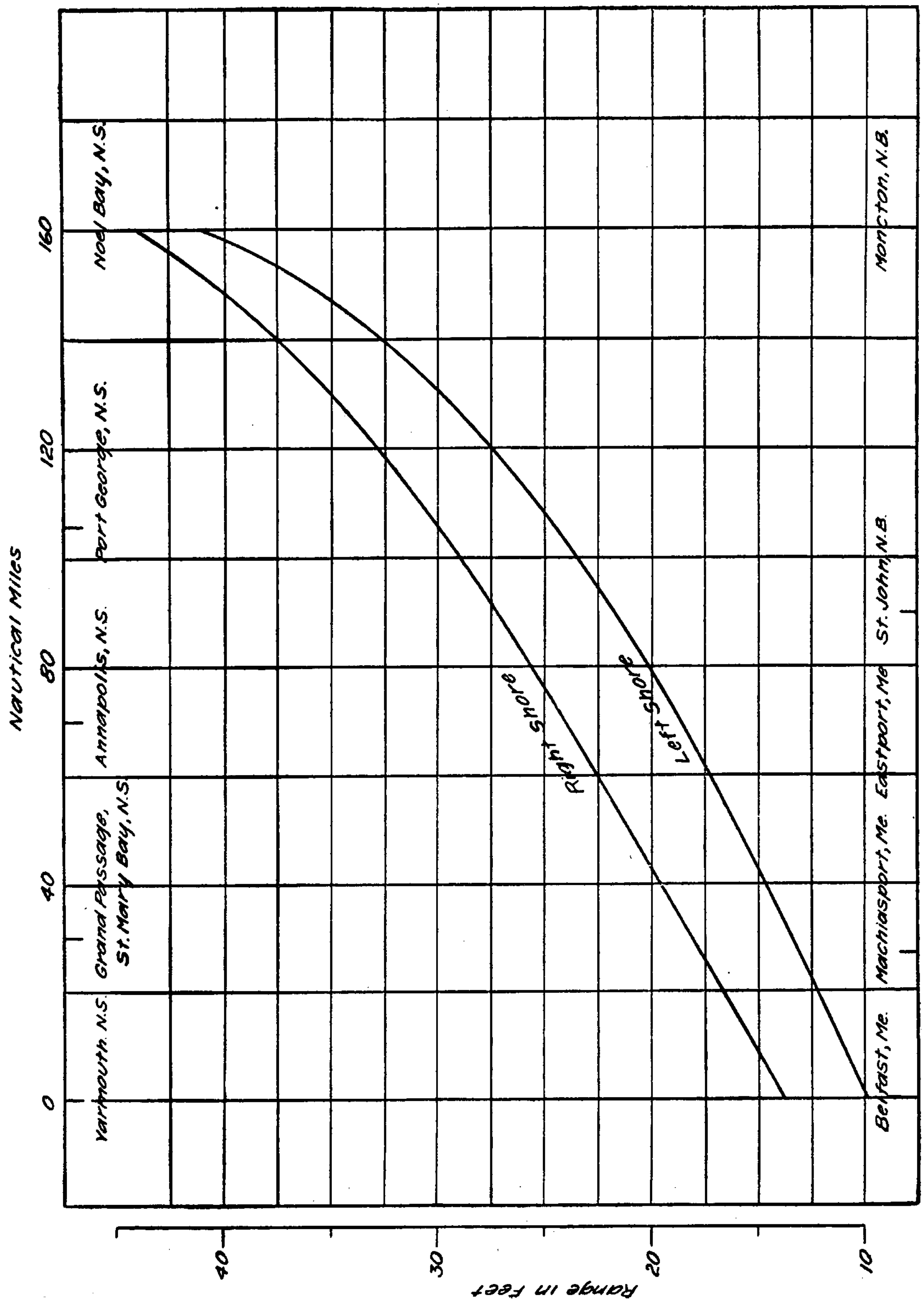

Fig. 1. — A comparison of the ranges of tide on the two shores of the Bay of Fundy.

water. Under such conditions, the theoretical value, in feet, by which the ranges on the two shores of such a tidal stream differ, is represented approximately by the formula (*)

$$\frac{3\ Vd \sin \varphi}{g}$$

in which V is the velocity of the water in knots; d is the width of the stream in nautical miles; φ the latitude; and g is the acceleration of gravity in feet per second (approximately 32.2).

Likewise the deflective force of the earth's rotation is evident in the currents occurring along the open coast. The tidal currents on the open coast are not of the rectilinear, or reversing, type with a period of slack water such as occurs in inland bodies of water. They are never slack — their direction changing constantly in a rotary movement. The velocities also vary throughout the tidal cycle, and when plotted to scale on polar-coordinate paper, approximate an elliptical figure illustrated in Figure 2. This figure shows plottings of the set and drift of the tidal current at Nantucket Shoals Light Vessel, Atlantic Coast of the United States, referred to the time of tide at Boston, Mass. For example, from the diagram at $H + 2$ that is, two hours after high water (H) at Boston, the current at Nantucket Shoals Light Vessel sets about south by east with a velocity of about 3/4 knot.

The deflective force of the earth's rotation causes the direction of the current to change constantly clockwise at a rate of about 30 degrees per hour from H (high water), Figure 2, through each hour to L (low water), and so on to H again.

At a current station well offshore like Nantucket Shoals Light Vessel, which is forty miles off, the elliptical current graph assumes very nearly a circular figure; as the coast is approached the ellipse becomes more elongated. A graph of the tidal current (Figure 3) at Brunswick Light Vessel, which is only a few miles offshore, illustrates that coastal tidal currents assume more nearly the character of the rectilinear or reversing type as the coast is approached, the ellipse becoming more elongated than the one for Nantucket Shoals Light Vessel.

The set of non-tidal currents on the open coast, due to local winds, is also affected by the deflective force of the earth's rotation. In an ocean of infinite depth it may be shown from theoretical considerations that a current produced by local winds should be deflected on the surface 45 degrees to the right of the wind direction due to this cause (**)

Naturally near the coast this degree of deflection is considerably modified by the configuration of the shore. Comparatively long series of current observations made during the past few years on light vessels stationed along the coast of the United States verifiy this theory and bring out the fact that,

(*) Special Publication N° 111, "*United States Coast and Geodetic Survey*", p. 68.

** "*On the influence of the Earth's Rotation on Ocean Currents*", Arkiv for Mathematik Astronomie, och Fysik, vol. 2, N° 11, 1895.

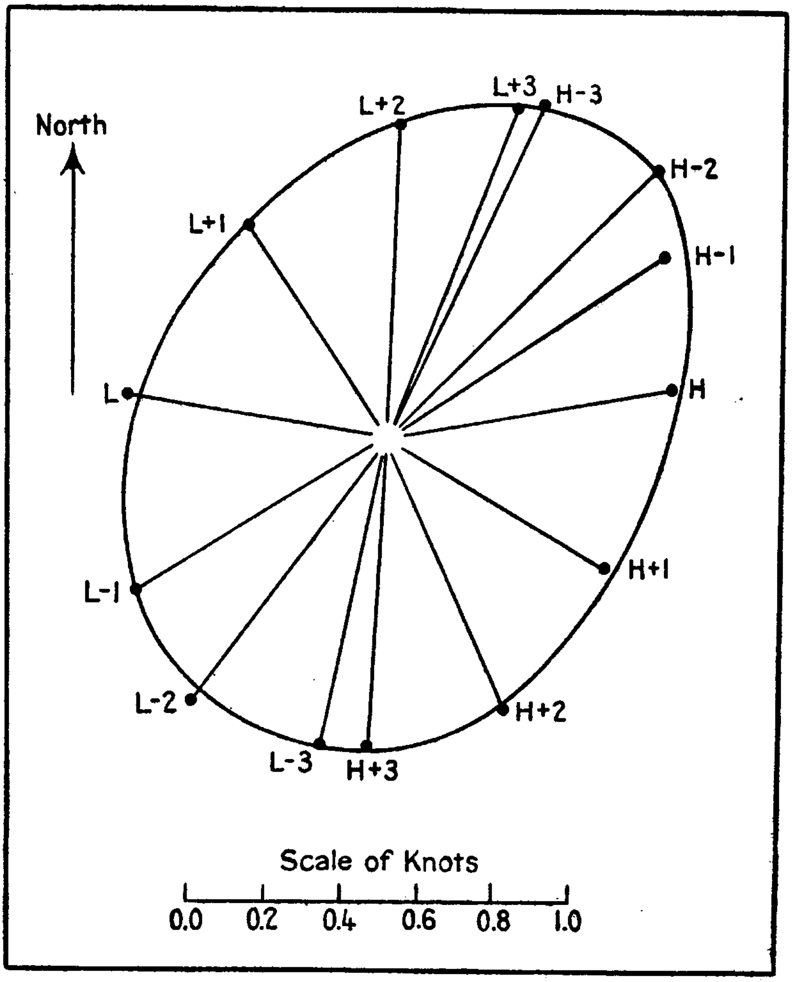

Fig. 2. — Mean current curve, Nantucket Shoals Light Vessel. July 1920.

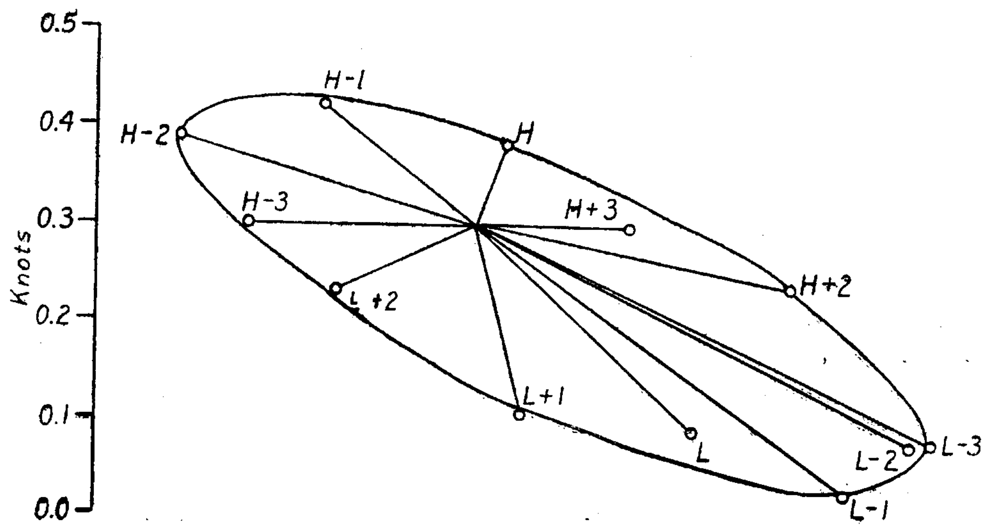

Fig. 3. — Graph of the Rotary Tidal Current at Brunswick Light Nessel, Atlantic Coast of the United States.

contrary to the general belief of the mariner, a local wind near the coast creates a current setting in a direction about 20 degrees to the right of the winds' direction instead of directly with that direction.

These current observations are analyzed so as to separate the tidal current and the prevailing set from the currents of a temporary nature due to local winds. A considerable number of observations are necessary for obtaining averages of any degree of accuracy for these wind-produced currents, since they are non-periodic, and also for the purpose of eliminating the periodic tidal current from the resulting data; for example, observations have to

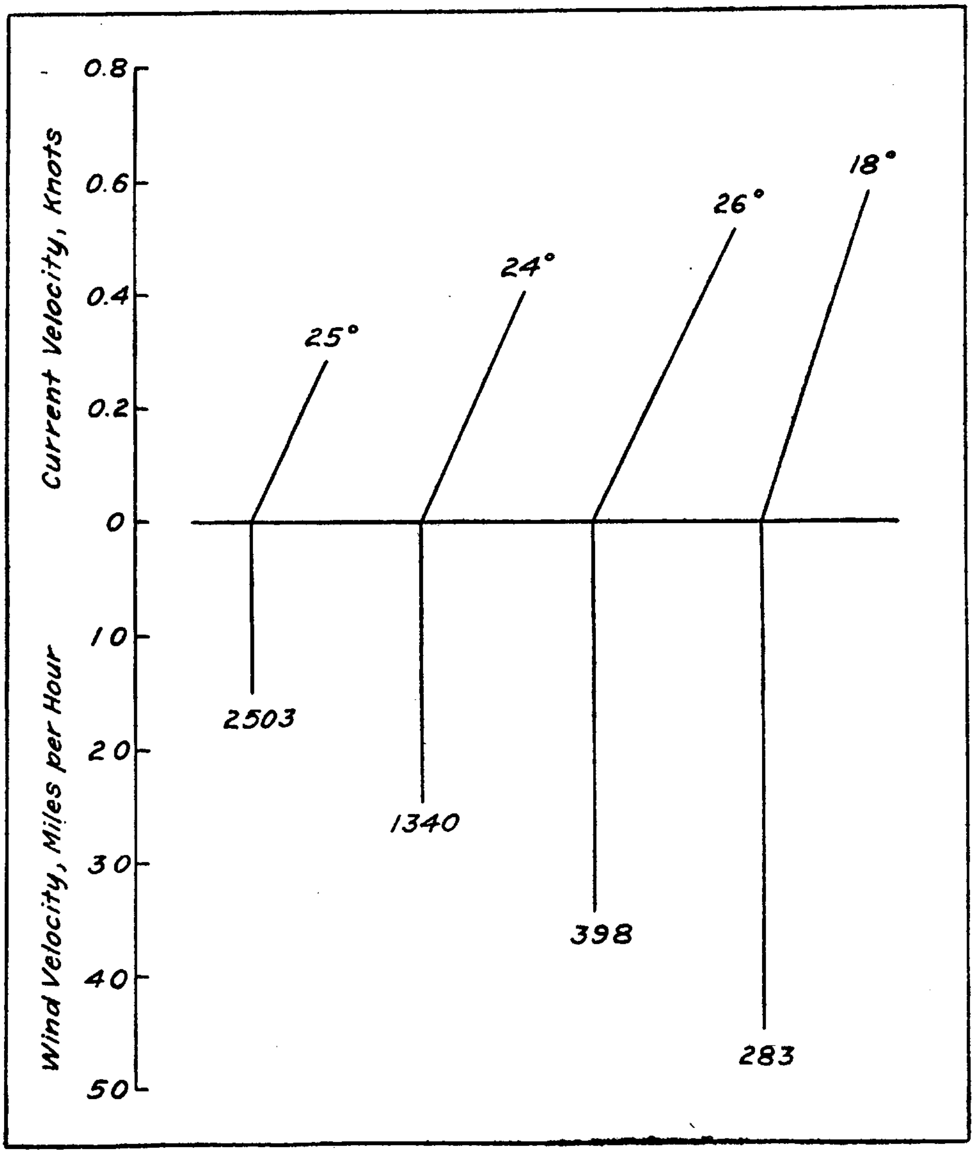

Fig. 4. — Results of observations of wind-produced currents, due to southeast winds, at Swifture Bank Light Vessel, Pacific Coast, United States.

cover a considerable period of time to include a number of winds from various directions at different velocities. A diagrammatic representation is furnished by Figure 4 of the mean results of current observations made during periods of southeast winds with velocities of from 10 to 50 miles an hour at Swiftsure Bank Light Vessel station on the Pacific Coast of the United States.

The wind velocities are represented by the lengths of the vertical lines below the horizontal line, and the number of current observations obtained with the wind at that velocity is indicated by the number at the lower extremity of each line; for example, 2503 current observations were made when a southeast wind was blowing at velocities of from 10 to 20 miles an hour, 1340 observations with a southeast wind of 20 to 30 miles an hour velocity and so on.

The drift of the wind-produced current due to each respective wind velocity is represented by the length of the slanting line above the horizontal line, and the deflection in the set of the resulting wind-produced current to the right of the wind direction, due to the deflective force of the earth's rotation, is shown by the degree of deflection of each line from the vertical; for example, at Swiftsure Bank Light Vessel a southeast wind with a velocity of from 10 to 20 miles an hour creates an average current of 0.28 knot velocity, setting 25 degrees to the right of the wind direction, or the average of 283 current observations, made during the time 40 to 50 mile southeast winds were blowing, shows a current of 0.58 knot velocity deflected 18 degrees to the right of the wind direction and so on.

The following tables(*) give the average velocities and the average deflections from the wind directions of the wind-produced surface current for the various wind velocities (Beaufort Scale) as observed on the five light vessels stationed along the Pacific Coast of the United States. The observations were made with a current line and current pole, and adaptation of the old chip log; a 15-foot pole, weighted at one end with sheet lead so as to float upright with a draft of 14 feet, being substituted for the chip.

AVERAGE VELOCITY OF WIND-PRODUCED CURRENT.

Wind Velocity	10-19	20-29	30-39	40-49	50 59
Number of Observations	47,821	25,788	6,084	3,789	594
Average current Velocity in knots	0.29	0.47	0.64	0.76	0.87

(*) Special Publication N° 121, "*U. S. Coast and Geodetic Survey*", pp. 74 and 77.

DEFLECTION OF WIND-PRODUCED CURRENT FROM DIRECTION OF WIND.

Light-Vessel	*Wind from quadrant*	Wind 10-19 Current		Wind 20-29 Current		Wind 30-39 Current		Wind 40-49 Current		Wind 50-59 Current	
		N° of Obs.	*Deflection*	*N° of Obs.*	*Deflection*	*N° of Obs.*	*Deflection*	*N° of Obs.*	*Deflection*	*N° of Obs.*	*Deflection*
			Deg.		Deg.		Deg.		Deg.		Deg.
San Francisco......	N. E.	1,059	28	377	5	....	....	....	....	....	....
	S. E.	1,904	16	666	22	205	14	138	15	24	0
	S. W.	2,075	—43	339	0	76	— 4	43	27	6	—12
	N. W.	8,429	34	4,866	30	874	23	323	9	36	—16
Blunts Reef..	N. E.	4,560	16	2,863	0	435	8	150	8	22	14
	S. E.	1,825	6	1,480	3	733	11	595	10	255	9
	S. W.	677	—11	384	—23	96	—13	66	—19	16	—12
	N. W.	2,724	28	1,744	2	391	11	158	— 4	22	14
Columbia River......	N. E.	2,363	8	1,371	13	225	62	96	62	....	....
	S. E.	2,606	50	2,271	37	578	28	434	42	49	25
	S. W.	2,370	— 6	1,984	— 7	630	— 9	435	—23	50	2
	N. W.	3,832	56	2,056	56	327	53	155	29	15	14
Umatilla Reef........	N. E.	691	13	174	26	20	31	19	42	....	....
	S. E.	2,384	19	1,288	26	424	18	518	14	42	5
	S. W.	1,380	— 37	540	—38	211	—39	136	—40	15	—10
	N. W.	2,442	21	550	—25	143	—43	109	7	....	....
Swiftsure Bank	N. E.	862	2	272	—20	57	—16	19	12	....	....
	S. E.	2,503	25	1,340	24	398	26	283	18	20	34
	S. W.	1,134	28	390	11	104	— 3	66	26	....	....
	N. W.	2,000	33	834	33	146	20	54	28	22	25

While deflections to the right of the wind directions are expected from theoretical considerations, the set of the current along a coast is modified by configuration of the bottom, by friction, by the form of the coast line and by the angle of impingement of the current against the coast line. For these reasons observations are necessary at intervals along the coast, particularly well inshore, to determine the actual velocities and degree of deflections which may be expected for that particular locality, although a general law may be deduced of the average current produced by any given wind velocity.

It has been found that the velocity of a wind-produced current varies fairly proportionately with the wind velocity. On the Pacific Coast the average current velocity is about 2 per cent of the velocity of the wind and on the Atlantic Coast about $1\frac{1}{2}$ per cent. The average deflection to the right is about 20 degrees, except where modified by the angle of impingement against the coast line which at certain angles may modify this direction to the left of the wind.

In the lower table above the deflection of the wind-produced current from the direction of the wind is given for each of the light vessels arranged for the four quadrants. In the "Deflection" columns the unmarked figures indicate a deflection to the right of the wind direction and a minus sign, a deflection to the left of the wind direction.

From the deflection table it will be seen that at San Francisco, Blunts Reef, Columbia River and Umatilla Reef Light Vessels the deflection is to the right for winds from the northeast, southeast and northwest quadrants. Due to the angle of impingement against the coast line, currents at these four light vessels produced by winds from the southwest quadrant are deflected to the left of the wind direction. At Swiftsure Light Vessel, however, currents produced by southwest winds are deflected to the right as usual. The other four light vessels have the coastline to the eastward while Swiftsure Light Vessel has the coastline to the northward.

The foregoing statements regarding ocean currents have particular reference to coastwise currents. Little of a quantitative nature has been done in the study of oceanic circulation by direct observation of currents. The set and drift of ocean currents have been mapped in a general way; but the principal information on which these results are based is of a qualitative nature obtained from a record of the drift of bottles and of wrecks, and from a difference between the true and the dead reckoning positions of vessels, the determination of which does not permit of a high degree of accuracy.

An investigation of the relation of surface currents to wind directions has been made for a part of the North Atlantic Ocean (Latitude 47° to 53° *N.* Longitude 10° to 36° W.) (*) and the results, shown in the form of a rose, tend to verify the theory, the greatest number of observed currents having a direction exactly 45° to the right of the wind direction.

In the general oceanic circulation we have further evidence of the effect of the deflective force of the earth's rotation on the direction of the flow of currents. The deep-seated ocean currents of both the Atlantic and Pacific Oceans comprise two distinct and clearly defined major systems. In each ocean the circulation in the Northern Hemisphere is in a clockwise direction and in the Southern Hemisphere in a counter-clockwise direction. (**) For example, the circulation of the Atlantic Ocean in the Northern Hemisphere is comprised on the south of the North Equatorial current flowing westward, on the west and north is the Gulf Stream flowing northward and then eastward and on the east is the Canary current flowing southward to complete the circuit. And in the centre of this mighty clockwise swirl is the comparatively stagnant Sargasso Sea.

(*) The *Marine Observer*, vol. IV., page 153.
(**) *Deutsche Seewarte Atlas, Atlantic Ocean,* plate 3.
Deutsche Seewarte Atlas, Pacific Ocean, plate 3.