igneous rocks only in the form of scattered dikes and finger-like plugs that at the time of intrusion failed to reach the surface, and have been made visible only by regional denudation.

Discussed by Messrs. KEITH, GILLULY, HEWETT, STOSE, BAKER, BASSLER, and SEARS.

ARTHUR KEITH: *Structure composite of North America.* (See Bull. Geol. Soc. Am. **39**: 321–385. 1928.)

Discussed by Messrs. G. R. MANSFIELD, BUCHER, REESIDE, and SCHUCHERT.

442D MEETING

The 442d meeting was held at the Cosmos Club, May 9, 1928, President HEWETT presiding.

Informal communication: W. C. ALDEN showed several photographs of the Sperry Glacier, Glacier National Park, Mont., taken in August, 1913, and 14 years later, in August, 1927. This small glacier, in the west side of the Continental Divide near Lake MacDonald, lies in a north-facing cirque above the great cliff at the head of Avalanche Basin. The foot of the glacier is 7,000–7,400 above sea level.

In 1913 the front of the glacier rested on top of the innermost ridge of the latest terminal moraine. This rock moraine is very fresh, with no soil nor vegetation upon it. By 1927 the front of the glacier had receded about 100 yards from the 1913 moraine, leaving exposed a bare rock surface with scattered pebbles and boulders upon it. A short distance outside the 1913 moraine is an older moraine somewhat smoothed down by erosion and with scrubby trees growing upon it. These relations are in accord with the opinion among geologists that the fronts of glaciers in the United States are, in general, receding.

Program: C. W. COOKE: *The stratigraphy and age of the Pleistocene deposits in Florida from which human bones have been reported.* (This JOURNAL **18**: 414–421. 1928.)

J. W. GIDLEY: *The contemporaneity of man and extinct animals in Florida.*

O. P. HAY: *Age of the "No. 2" bed at Vero and Melbourne.*

Joint discussion of the three papers by Messrs. W. C. ALDEN, PAUL BARTSCH, A. V. KIDDER, J. B. REESIDE, JR., H. G. FERGUSON, and W. T. SWINGLE.

W. W. RUBEY, A. A. BAKER, *Secretaries.*

SCIENTIFIC NOTES AND NEWS

N. ERNEST DORSEY, Associate Editor of the International Critical Tables of Numerical Data, has been appointed Principal Consulting Scientist (Physics) in the Bureau of Standards.

EDGAR W. WOOLARD, assistant meteorologist, U. S. Weather Bureau, has resigned to accept an appointment as instructor in the Department of Mathematics at George Washington University for the academic year 1928–29.

IMPORTANCE

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BROOKS

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METEOROLOGY and OCEANOGRAPHY.—*Scientific papers presented at the joint meeting of the sections of Meteorology and Oceanography, American Geophysical Union.*

The joint meeting of the sections of Meteorology and Oceanography during the ninth annual assembly of the American Geophysical Union was held in the building of the National Academy of Sciences on April 26, 1928. The joint meeting was devoted to a symposium and discussion on interrelations between the sea and the atmosphere, and the effect of these relations on weather and climate. The communications presented were on problems related to (*a*) solar radiation, (*b*) surface-water temperatures, and (*c*) atmospheric circulation. Reference to the papers under (*a*) will be found in Bulletin 68 of the National Research Council, and also to one by Sir Frederic Stupart, J. Patterson, and H. Grayson Smith under (*b*); the other three papers under (*b*) and those under (*c*) are printed below.

PROBLEMS RELATED TO SURFACE-WATER TEMPERATURE

Reliability of different methods of taking sea-surface temperatures.

CHARLES F. BROOKS, Clark University, Worcester, Mass.

This discussion is based chiefly on observations by the writer during 46 days at sea in middle and low latitudes of both Atlantic and Pacific, and on studies of the deck and engine-room logs of eight steamships. Altogether the conditions investigated cover practically the whole gamut of marine conditions from iceberg waters to calm tropical seas and from heavy storm to quiet weather.

Sea-surface temperatures, from a meteorological standpoint, involve more than the temperatures of the surface film. While it is the surface film alone that is in contact with the atmosphere, warming or cooling, humidifying or drying the air, the continuation of the influence of this sea surface at approximately the same level of temperature depends in considerable measure on the temperatures of the general surface layer of the sea, the layer that is commonly stirred by the wind to depths of 5 to 20 or more meters. Therefore, in this discussion of the reliability of different methods of taking sea surface temperatures, I shall include observations both at or near the actual surface and at a depth of 5 to 10 meters.

Two years ago an article of mine on "Observing water-surface temperatures at sea" appeared with a summary of the discussion that followed its presentation before the American Meteorological Society in Washington three years ago.[1] There was appended also a comment by Mr. F. G. Tingley, Chief of the Marine Division, U. S. Weather Bureau. Even in the low latitudes of the Caribbean Sea, I showed in this paper that in March, 1924, the sea was so well stirred by the wind that its temperature was within 0.1 degree the same at the surface near the bow, at the stern on the side or in the propeller wash and at intake depths, 6 or 7 meters. I indicated also that the usual canvas-bucket method was beset with numerous sources of error and that when air temperatures were appreciably lower than the sea temperature, errors of several degrees commonly arise, owing mainly to evaporational cooling of the bucket; and I found that the errors of condenser intake temperature records were appreciable, but less than those of the bucket. I concluded that the condenser intake temperature records were preferable to the canvas-bucket ones as indications of the surface temperatures under most conditions. I was convinced, however, that reliance would be placed better on a thermograph record than on those of uninterested observers. Mr. Tingley's studies of the canvas-bucket records made at Greenwich Mean Noon specially for the Weather Bureau indicated that they were sufficiently reliable, when used in fairly large numbers, for showing the changes in temperature occurring along the routes covered. But for well-founded marine meteorological studies we need to know the actual temperatures as well as the changes. With care, the errors of the canvas-bucket and condenser intake records can be reduced to insignificant proportions, but, unfortunately, that care cannot usually be commanded.

In the discussion of the paper there was no dissent from the general conclusion that seawater thermographs should come into widespread use. The experience of several present pointed to the bulb-capillary-and-Bourdon-tube type of thermograph as most rugged and generally satisfactory, and a condenser-intake pipe installation as best. Some question was raised, however, as to how far sea temperatures at 5 to 7 or 8 meters depth could be used as representing the surface temperature in calm weather, especially in summer or in the tropics. A study of this question, submitted a year later showed that even in summer an accurate record of temperature at intake depth would, with few exceptions, represent more closely the slightly higher surface temperature than the usual evaporationally cooled canvas-bucket observation of the actual surface temperature.

Since 1925 six seawater thermographs have been placed on American and three on Canadian ships—two others are about to be installed. These eleven installations, nine of which are in the Atlantic, at least in part, are under the auspices of the U. S. Weather Bureau,[2] Clark University, The Scripps Institution of Oceanography, The International Ice Patrol (2), The Carnegie Institution of Washington, the American Meteorological Society, the Furness-Bermuda Line, and the Canadian Meteorological Office (3). The Canadian Meteorological Office still operates its group of three seawater thermographs on the Canadian Pacific steamers crossing the Pacific. Thanks to a grant from Clark University, it was possible to purchase a Tycos seawater thermograph and to travel with it on the FINLAND, on which the Weather Bureau had installed it, from San Francisco to New York last May. On this voyage I had an excellent opportunity to check the conclusions, just summarized, reached after a cruise in the West Indies on the EMPRESS OF BRITAIN in February and March, 1924, and to make observations in calm weather under a vertical sun.

MAY 1928

The new set of observations made by me on the FINLAND were all by the same thermometer, calibrated by Mr. S. Chambers at the Scripps Institution of Oceanography. The necessary thermometric corrections, 0 to 0°.1C were applied throughout. For obtaining samples of sea water a rubber-covered tin bucket of broad cylindrical shape and having a capacity of 1.7 litres was dropped from the lowest open deck about 9 meters to the water. Experiments with the bucket before sailing showed that a full bucket cooled 0°.1C the first minute after leaving the water when it was exposed to a wet bulb temperature

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[1] Monthly Weather Rev. **54**: 241–254. June, 1926.

[2] The Weather Bureau owns 1, operates another and will soon be caring for 2 more.

6°C below the water and to a wind of 9 m/s.[3] The bucket observations I made on the ship usually took 30 to 40 seconds from the time the sample left the sea till the temperature was obtained. Every set of observations included the wet bulb temperature and the wind velocity. Under the most extreme conditions it is probable that the bucket cooled 0°.2 in a one minute observation, but the average conditions were only one-quarter as severe. The average negative error for all the tin bucket observations is estimated at 0°.03C. Therefore it has appeared reasonable to accept the tin bucket temperatures as correct without making any allowance for the insignificant cooling.

The standard observations for checking intake temperature records by the engineers and the Tycos seawater thermograph were obtained with the same calibrated thermometer and insulated pail as were used for the surface data. A large drain faucet was installed for the purpose at the base of the intake pump by Mr. Schiffmann, refrigerator engineer, and from this faucet the temperature of a rapidly filled second bucket was obtained. Experiments were made to discover whether the heat of the room affected the temperature of this bucket of water to an observable degree in the 10 seconds required for an observation. No effect was detected.

In windy weather, when the surface layer of the sea is well mixed, table 1 shows that on the FINLAND as well as on the EMPRESS OF BRITAIN the difference fore and aft did not exceed 0°.1C more than once in 23 comparisons, and averaged 0°.05C. In quiet weather, however, under a nearly vertical sun the contrast between the warmer surface water sampled near the bow and the deeply stirred water in the propeller wash becomes appreciable. The following notes made May 10, 1927 at latitude 15°N. in the Pacific, about 40 miles from the coast of Oaxaca, Mexico, may be of interest in showing how large the differences may become on quiet days and how readily they are erased by light winds.

> Today was a bright sunny day, with mostly light airs, and no land in sight. The sea temperature was from 84 to 88°F, and I found conditions unequalled for certain comparisons of surface and intake depth conditions. I had noticed that yesterday afternoon there was no opportunity of obtaining a constant temperature by any number of full dips, and suspected then that the farther from the ship the bucketful was obtained the higher would be the temperature. This afternoon at 2, after much bright sunshine and only a few ripples to disturb the surface, I found temperatures of 87.2–87.8 when my buckets dipped more than 2 feet from the ship, and 85.3 to 85.5 when actually or practically in contact with the side when the sample was obtained. At the same time (just after) the propeller upwell (caught square in the middle) was 84.0. At 4, after about an hour of wind of B.1 the warm surface layer had become mixed so that both near and far the temperatures were 87.0 to 87.2. The propeller upwell was 85.6. More wind B.1 to 2 for 2 hours put the ship-side temperature constant at 86.6–7, while the propeller upwell was 85.9. After two hours more perhaps deeper water was involved in the mixing, for the temperature fell to 85.8. A water sampling from the stateroom port-hole at 9 showed 85.7 three-quarter hour after the last 85.8 sample on the stern, suggesting that the mixing of the top 15 or 20 feet had been fully accomplished by 9 p.m., with a wind of 1–2 Beaufort.

TABLE 1.—CONTRASTS IN SEA TEMPERATURE ABOUT A LARGE SHIP IN MOTION

Ship	Wind velocities (Beaufort)	Time	No. of comparisons	No. of diff. days	Tot. no. of bucket obs.	Shipside near bow vs. prop. wash temps.					
						°C difference					Bow side the warmer, Mean °C
						0	0.05	0.1	0.15	Av.	
EMPRESS OF BRITAIN...	2–5	Any	10	8	42	3	5	2	0	0.04	−0.02
FINLAND..............	2–5	Any	13	9	78	5	3	4	1	0.06	−0.05
FINLAND..............	0–2[a]	Daytime exc. 12–4:30 p.	8	5	40						0.13
FINLAND..............	0–1[b]		5	3	43	Bow dips close in to ship's side.					0.9
			(3)			Bow dips away from ship's side					1.5

[a] When wind was B.2 the case was included here if the force 2 had been immediately preceded by light winds.

[b] Light winds since morning.

On the afternoons of three days which were quiet and fairly sunny, the forward hauls ranged from 0°.6 to 1°.4 and averaged 0°.9C warmer than those from the propeller wash, while dips made by flinging the bucket some distance out from the ship (1 to 3 meters) from the lowest open deck forward were 0°.6, 1°.9 and 2°.1, or a mean of 1°.5C the warmer. In quiet weather other than between noon and 4:30 p.m. the range of differences was from 0°.1C warmer forward than aft, and the mean of 8 cases 0°.13C warmer forward. Unfortunately,

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[3] Details are presented in the 1928 report of the Committee on Submarine Configuration and Oceanic Circulation of the National Research Council.

since no lights are permitted on the forward deck, it was impracticable to make more than a few comparisons (none of these in calm weather) between the ship-side forward and the propeller wash at night. So far as all these comparisons may indicate the extreme range of conditions, from sunny tropical calm to cold stormy weather, it appears that the temperatures of samples from the upwell from the propellers may be used interchangeably with those from ship-side hauls forward except between about 11 a.m. and 5 p.m. in calm sunny weather. Another limitation should also be noted. It is sometimes difficult to get clean up-well, and there is always a chance of getting a haul containing some of the hot out-take. In a series of hauls from the propeller wash I once obtained a temperature 0°.4C higher than the general run, and have at times hauled up an oily film. On the side of the stern I found the hauls 0°.2 to 0°.4C warmer than forward. Also, one fairly quiet sunny day, a range of 0°.5C was noted in a series of true propeller-wash hauls, owing apparently to the varying depth from which the water was pushed to the surface.

Table 2 shows that by eye observations the intake drain averages 0°.05C warmer than temperatures obtained by bucket at the surface in stirred water, but that there is no such close correspondence in quiet weather, the intake for the mean of three instances being 0°.3 colder than the surface at the side of the bow.

TABLE 2.—SEA TEMPERATURES AT SURFACE VS. INTAKE DEPTH, BY EYE OBSERVATIONS

Ship	Wind velocity (Beaufort)	No. of comparisons	No. of diff. days	Sea temps. °C	Shipside near bow or prop. wash. temps. vs. refrigerator intake pump drain faucet									
					Intake the warmer °C				0	Intake the colder °C		Mean diff.	Intake the	
					0.3	0.2	0.1	0.05		0.1	0.8		Warmer °C	Colder °C
EMPRESS OF BRITAIN.	2–8	11	8	3–26	0	0	4	2	0	1		0.07	0.06	
FINLAND.............	1[a]–4	16	12	10–30	1	0	3	1	7	1		0.09	0.04	
FINLAND.............	0–1	3	3		1	0	0	0	0	1	1[b]	0.4[b]		0.3

[a] When light winds, propellor wash temperature taken instead of bow side temperature.

[b] Cf. the larger differences, found earlier in the afternoon, between shipside and propellor-wash temperatures, discussed above.

Table 3 gives *in extenso* the same facts as the first part of Table 2, the intake thermograph data being used for comparison with propeller-wash temperatures. Here the intake is a mean of 0°.03C, a negligible amount, warmer than the surface data.

TABLE 3.—SEA TEMPERATURES AT SURFACE VS. INTAKE DEPTH, BY EYE OBSERVATIONS AT SURFACE (IN PROPELLOR WASH) AND CORRECTED[a] THERMOGRAPH INDICATIONS ("TRUE INTAKE") BELOW. S. S. FINLAND.

Hour	°C	8 a.m.	10	12	2 p.m.	4	6	8	10	Total
		Number of cases								
True intake the colder by..	1.1	0	0	0	0	0	0	0	1	1
	0.6	2	5	6	2	2	2	1	1	21
No difference................	0	7	0	7	8	6	3	6	4	41
True intake the warmer by ..	0.6	4	3	3	2	3	3	3	1	22
	1.1	1	0	0	0	0	0	1	1	3
Total cases..................		14	8	16	12	11	8	11	8	88
Mean diffs. °C...............		0.2	−0.2	−0.2	0	0.1	0.1	0.4	0	0.03

[a] Corrected to pump drain faucet temperatures daily.

Combining the observations made by myself on the EMPRESS OF BRITAIN and on the FINLAND with those by Lieut. Commander Edward H. Smith on the MODOC and TAMPA[4] we find that except in calm or nearly calm weather the temperatures at 5 to 7 meters depth were the same, within 0°.2C, as those at the surface 49 times out of 50. Since quiet weather is uncommonly met at sea, this fact makes observations at either surface or 5–8 meters depth generally sufficient for both. In quiet weather, however, surface temperatures may be much higher than at 5 meters, the differences exceeding 1°.5C at times.[5] Near shore these surface excesses of temperature may be greater than any met with in the open sea. Observations by the Scripps Institution of Oceanography at 5 and 10 miles west of the Institution's pier at La Jolla, Calif., show such surface warming to be the normal condition in the warmer months there. According to a summary kindly furnished by Dr. G. F. McEwen[6] the mean surface temperature during 35 fortnights was 0°.66C ± 0.1 warmer than the water at a depth of 5

[4] Monthly Weather Rev. **54**: 252–253. June, 1926.

[5] Ibid. p. 252–253; also by surmise from the difference between ship-side and propeller-wash temperatures, of which I observed an extreme of 2.7°C.

[6] Details in the 1928 report of the Committee on Submarine Configuration and Oceanic Circulation of the National Research Council.

meters at the station 10 miles out, and for 29 fortnights was 1°.34C ± 0.11 warmer than at 5 meters at the station 5 miles from shore. The largest fortnightly mean difference was 2°.31C at the 10-mile station and 3°.96C at the 5-mile one. Half the fortnights averaged more than 0°.6 the warmer at the surface at the 10-mile station and more than 1°.1 the warmer at the surface at the 5-mile station. The data are for the months March, May, June, July, August, September and October during the period 1921–1926. June had the largest average difference, 0.92, at the station 10-miles out, while August had the largest, 1.95, at the 5-mile station. Owing to the upwelling of cold water and the relative lack of storminess here coupled with brilliant sunshine, the differences between surface and subsurface temperatures should approach the maxima to be found anywhere at sea.

We may conclude that in calm tropical regions and in periods of calm in summer elsewhere actual surface observations are indispensable.

Though many methods of taking sea surface temperatures have been tried, only two are in widespread use: (1) the reading of the fixed mercurial thermometer projecting into the condenser intake of a steamship, and (2) putting a mercurial thermometer into a sample of water obtained with a bucket heaved over the side of the ship. Electrical resistance thermometers (a) in condenser intake, (b) touching the inside of the shell of the ship, and (c) trailing behind, have been used but found impracticable except when closely supervised.[7] Outside exposures of thermograph bulbs (bulb and capillary type) have been tried on the sides of some battleships, I believe, and there is a new keel exposure of this type on the CARNEGIE. The bucket method has numerous variations, some involving lowering the thermometer in the bucket.

Condenser intake temperatures are observed once or twice each watch by an officer in the engine room. Table 4A provides various checks against these temperatures as recorded by the engineer. The difference between the two sets on the FINLAND, and especially the poor showing of the main engine-room observations need further details. (Table 4B).

One of the engineers told me that temperatures read within 5° would be close enough. His watch probably centered on 10 o'clock, the errors for which are about twice those for the other watches. However, he came well within a five-degree error. The location or errors of the

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[7] Discussion by Dr. H. C. DICKINSON. Mo. Weather Rev. **54:** 251. June, 1926.

TABLE 4.—CONDENSER INTAKE TEMPERATURES AS RECORDED BY ENGINEER OBSERVERS

A. Comparison with quick surface observations in stirred water by C. F. B.

Intake minus tin bucket °C	−3	−1.0	−0.5	0	0.5	1.0	1.5	2	3	Total	Mean °C
				Number of cases							
EMPRESS OF BRITAIN (once each watch).....	1	1	5	20	21	6	1	0	1	56	0.3
FINLAND (Main eng.) (once each watch)....	0	2	3	7	8	6	3	5	1	35	0.8
FINLAND (Refrig.) (twice each watch).......	0	1	10	39	34	6	1	0	0	91	0.2

B. Main engine-room intake minus probable true intake (corrected thermograph)

Error °C	−3	−2	−1.5	−1	−0.5	0	0.5	1	1.5	2	3	5	Totals	Mean °C	Mean error °C
						Number of cases									
2 a. or 2 p..........	(1)[a]	0	0	2	6	2	11	6	1	2	0	0	30+(1)	0.4	±0.8
6 a. or 6 p..........	0	1	0	0	4	5	10	5	2	0	1	(1)	28+(1)	0.4	0.8
10 a. or 10 p..........	0	0	1	1	1	2	9	6	6	0	4	1	31	1.1	1.3
Totals..............	(1)	1	1	3	11	9	30	17	9	2	5	1(1)	89+(2)	0.7	1.0

C. Refrigerator intake minus probable true intake temperature

°C	Hours—a.m. and p.m. together									Totals
	12	12 & 2	2	4	4 & 6	6	8	8 & 10	10	
−0.6	3		1	4		2	4		2	16
0	9		21	18		14	13		7	82
0.6	18		12	11		14	14		20	89
1.1	3		0	1		3	2		5	14
Totals....................	33		34	34		33	33		34	201
Means°C..................	0.3		0.2	0.2		0.3	0.2		0.4	0.3
		0.3			0.2			0.3		
Mean diff. °C..............	0.4		0.2	0.3		0.4	0.4		0.5	0.4
		±0.3			0.3			0.4		

D. Corrected fixed refrigerator intake temperature minus pump drain temperature

°C	−0.1	−0.05	0	0.05	0.1	0.2	0.3	Total	Mean °C
No. of cases..............	1	4	8	4	4	1	1	23	0.03

[a] Figures in () were for observations during periods of rapid changes in sea temperature. They are not included in the means.

main intake thermometer are unknown to me. Two of the officers told me that for the log the refrigerator room intake was read instead of the main engine-room intake. This may have been true much of the time, but the fact that the departure of the mean for the two best watches was twice as large as for the regular refrigerator intake record suggests that the engine-room intake thermometer was read somewhat higher than the refrigerator-room thermometer, owing probably to a combination of (a) greater heating of the water in the much hotter room, (b) larger thermometric error, and (c) greater parallax. (Table 4C.)

Subtracting from the means the thermometric error of 0°.3C, the mean indication of the refrigerator intake is 0 to 0.1°C below the pump drain temperature. (Table 4D.) A warming averaging 0°.03C seems to occur while the water passes from the pump to the intake thermometer. In connection with the foregoing, this means that the observers' parallax in reading is of the order of 0°.1C. This surprisingly small parallax for a thermometer graduated by 2°F is due to the very favorable location of the thermometer, about 1 meter above the floor in an accessible and well lighted position. The top of the scale is up. These observations, consistently good by all the observers, were made for checking the thermograph.

The usual condenser intake record is subject to (a) thermometric error, (b) error of parallax in reading, (c) time error (any time within a stretch of four hours), (d) personal errors of uninterested observers. (a) and (b) are readily determinable, (c) is unimportant except where the sea temperatures are changing rapidly, (d) is serious only infrequently. Observations on the EMPRESS OF BRITAIN and FINLAND (except for 10 o'clock watch) show 70 to 80 per cent of the intake records to be no more than 0°.6C off from the probable true intake temperature at the mid-watch hours, 2, 6 and 10.

The refrigerator intake record is likely to be better than the main engine condenser intake, for the refrigerator engineer in charge has to keep a closer watch of the temperature. The bihourly record kept on the FINLAND was 93 per cent within 0°.6C of the probable true intake.

The intake thermograph has the great advantages (1) of showing when important changes occur, (2) giving a continuous record from which any number of observations can be taken, and (3) in being free from erratic indications. But it has the disadvantages of being expensive and requiring careful attention and needing temperature and time checks. Experience on the FINLAND has shown, however, that engineers are capable and very willing to operate a thermograph and to make accurate observations for checking it.

It is evident from the foregoing discussion of intake observations by the engineers that any seawater thermograph that is to obtain reliable data must itself be of such quality that it may be considered a standard instrument. The thermograph should have a permanent adjustment and it should have pen arm attached directly to the coil and hinged so that the pressure of the pen on the paper will not be heavy. Joints to transmit the movement of the coil to the pen arm are very undesirable, for it is difficult to keep these free from corrosion and consequent "freezing."

The point of installation should be the intake pipe between the intake value and the pump. If there is a choice the hole should be drilled in the side or bottom of the intake pipe so that heated water cannot collect about the upper part of the bulb. The capillary should run directly from the bulb to the recorder, and any extra length should be coiled near the recorder, where it will have approximately the same temperature as the recorder.[8] Unusually hot locations for the recorder are to be avoided. According to the experience of the Canadian Meteorological Office, the recorder is best placed by bolting it to a shelf by the shell of the ship. Here it is relatively cool and free from excessive vibration. In any other location a spring suspension and guying has been found necessary to dampen the vibrations.

No matter how accurate the instrument itself may be it should be carefully checked at least once each month or two against a thermometer of known accuracy. Furthermore, since the recorder paper may not always be placed tight against the basal flange, and since this paper suffers some change in size with changing humidities, accuracy demands concurrent observations by engineers once daily or more often. From what has been said above, however, it is evident that the engineers' thermometer must be calibrated and the engineers must be trained and induced to make careful observations with it. The reliability of the bihourly checking observations on the FINLAND has already been mentioned. On the CALAWAII[9] the engineer in charge makes a particularly careful observation to the minute and fraction of a degree once a day and taps the recorder at this time to make a vertical mark on the trace. Without such a time mark it is difficult

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[8] Detailed comment on the performance of the Tycos thermograph is presented in the 1928 report of the Committee on Submarine Configuration and Oceanic Circulation, National Research Council.

[9] Los Angeles to Honolulu. Instrument owned and operated by the Scripps Institution of Oceanography.

to take due account of the combined effect of clock error and change of time with change of longitude.

Tabulating the thermograph traces is complicated by four variables: (1) local time, (2) clock error, (3) departure of check observations from the stated hour, and, (4) for the Tycos thermograph at least, varying temperature-error rising vs. falling and at different temperatures. For the May voyage of the FINLAND I checked the thermograph against pump drain faucet temperatures and against time once or twice daily—always about 4:30 p.m., sometimes at 7:30 a.m. in addition. Usually every twelve hours, at a recorded time and temperature, the engineer in charge, Mr. Schiffmann, tapped the recorder, thus providing a ready check against all variables. The thermograph traces were tabulated in black by hours and directly above each bihourly reading was placed in red the refrigerator intake observation. Finally, the more exact corrections that I obtained personally once or twice daily were entered in their appropriate places. The hours at which the exact correction from one day would give way to those for the next were determined by sudden changes of temperature, if any, about 6 hours before or after the check point, otherwise by the refrigerator intake value, or simply exactly halfway to the next correction. Without the pump drain-cock checks it is necessary to average the bihourly intake observations approximately by 12-hour periods or by intervals having even temperatures on the thermogram, apply the calibration correction and heating correction, if any (on FINLAND refrigerator intake this was only 0°.03C. See Table 4D), compare this corrected temperature with the indicated one for the central hour, and apply the difference throughout the period.

The corrections for the U. S. Weather Bureau's thermograph on the COAMO (New York to Porto Rico) are obtained by comparison with eye-observations of condenser intake temperatures on that portion of the voyage where the sea temperatures are uniform. These corrections are then applied throughout the smooth and rough parts of the thermograms.

The common bucket used on commercial ships is a heavy canvas one of approximately 2 to 4 litres capacity. The base is heavy wood, to make it sink, and the top rim is stiff, to favor a good catch. Full catches are not the rule, and the evaporational cooling of the sample during the haul and while the thermometer is becoming adjusted may be considerable. The evaporational cooling and other errors are aggravated at night when the observer must carry the thermometer to a light. Other materials are sometimes used, e.g. leather and lead.

The bucket on the FINLAND was particularly good, as buckets go, having a double wall of canvas and a good diameter. It was 26 centimeters high by 15 centimeters in diameter. Of its height, 2.5 centimeters was the block of wood forming the bottom. Its capacity was 4 litres.

Table 5A shows that the mean error of all the canvas bucket observations on the FINLAND was less than that on the EMPRESS OF BRITAIN, probably because chiefly the FINLAND did not encounter so many days with air temperature considerably under the sea temperature. The FINLAND error exceeds that of the EMPRESS OF BRITAIN south of latitude 35. The low deck haul of the FINLAND vs. the high bridge of the EMPRESS OF BRITAIN and the double walls of the FINLAND's bucket should have put its observations to some advantage over those of the EMPRESS OF BRITAIN, but the lesser carefulness of the FINLAND's observers, coupled with some guess-work, seems to have offset these advantages. Tables 5B and 5C give further details on evaporational cooling and the personal element.

It is striking that for like conditions, the error of the canvas bucket observations on the EMPRESS OF BRITAIN (58 cases) and on the FINLAND (69 cases) should be identical. Note, for both ships, the increasing evaporational cooling at lower temperatures of the wet bulb relative to the sea. The greater cooling effects of stronger winds are of secondary importance.

Nighttime observations are nearly twice as much cooled as the daytime ones. The errors of the noontime "observation" (often not made, but guessed) are with one exception the greatest of the daytime errors. Significant of the admitted and observed guesswork of the quartermasters on duty at 10 and 12 is the fact that the mean departure for the daytime pairs is for this watch the greatest of all.

There is no reason for believing that these observations on the FINLAND are not a fair sample of those bucket series made more or less listlessly, without the urge of official scrutiny or iceberg menace. The crew of the EMPRESS OF BRITAIN, normally crossing the iceberg region, did better, considering the poorer bucket and higher haul. On both ships the mean error by day was a cooling of about 0°.5C, on the FINLAND the mean error by night was a cooling of about 1°C, with no seawater thermograph on the EMPRESS OF BRITAIN, no numerous comparisons at night were practicable on that ship. 70 per cent of the canvas bucket observations on the EMPRESS OF BRITAIN were within 0°.6C of the probable true surface temperature. After correc-

TABLE 5

A. Depression of canvas bucket below quickly-hauled tin-bucket temperatures

°C	−1.1	−0.6	0	0.6	1.1	1.7	2.7	2.8	3.3	3.9	Total cases	Mean °C
EMPRESS OF BRITAIN (all)	2	8	23	24	10	5	4	1	1	1	79	0.6
(South of lat. 35° only)	2	8	22	23	9	0	1	0	0	0	65	0.3
FINLAND	2	7	15	31	11	5	0	0	0	0	81	0.4

B. Cooling "error" of canvas bucket at different depressions of wet bulb temperature below sea temperature and at different wind velocities

Depression of sling wet bulb below tin bucket temperature °C		0–2		2.5–5		5.5–8		8.5		0–8.5+	
		Mean °C	No. of cases	Mean °C	No. of cases	Mean °C	No. of cases	Mean °C	No. of cases	Mean °C	No. of cases
Wind velocity (Beaufort) relative to ship	7–9 E[a]	−0.3	6	—	0	1.0	10	1.8	5	1.0	21
	F[a]	—	0	—	0	—	0	—	0	—	0
	4–6 E	−0.2	10	0.4	17	0.7	9	0.8	2	0.4	38
	F	+0.3	6	0.6	12	0.6	6	—	0	0.5	24
	0–3 E	0.0	4	0.1	5	1.0	9	1.7	2	0.7	20
	F	0.0	14	0.4	26	0.7	5	—	0	0.3	45
Means (0–6 E)		−0.2		0.3		0.8		1.2		0.4	
Cases			14		22		18		4		58
Means (0–6 F)		−0.2		0.5		0.7		—		0.4	
Cases			20		38		11		0		69

[a] E — EMPRESS OF BRITAIN; F — FINLAND.

1°C

C. Canvas-bucket "errors" through the 24 hours. Probable true intake (night and occasional daytime hours—and tin bucket—daytime and a few 8 and 10 p.m. observations) minus canvas bucket

	Night		Daytime							Night			Night	Day	All
	2A	4	6	8	10	12	2P	4	6	8	10	12			
Mean "error" corrected (0°.8F) for thermometer error.......°C	−1.3	−1.0	−0.7	−0.3	−0.3	−0.6	−0.4	−0.1	−0.3	−0.7	−0.9	−1.3	−1.1	−0.4	−0.7
Mean departure ±. Corrected to nearest whole degree F (1) for thermometer error...........°C	1.5	1.1	0.8	0.6	0.8	1.0	0.6	0.8	0.7	0.9	1.1	1.3	1.2	0.7	0.9
No. of cases	16	15	14	14	14	13	14	14	14	14	16	15	97	76	173

tion for thermometer error, 65 per cent of the FINLAND canvas-bucket observations were equally close.

The bucket method provides the only generally practicable means for obtaining the temperature of the actual surface of the sea, but under present usage it has unsatisfactory inaccuracies. Therefore, how to improve method and practice require consideration. In my previous paper[10] I listed 9 sources of error in the bucket method. I shall now add the tenth: guesswork. A brief review of these, with means for improvement in each case, may serve as a satisfactory concluding section of this paper.

(1) The bucket is not likely to have the same initial temperature as the sea surface. This would be of no consequence if the thermal capacity of the bucket were low. This suggests (a) hanging the bucket bottom-side up after every observation; or (b) at least making a pointed base so the bucket will have to empty; and, (c) where practicable, the use of water-shedding fiber, metal, rubber, or paraffined canvas, instead of water-holding canvas for buckets. Double dips, the first to warm the bucket closer to sea temperature, were found to raise the temperature by a mean of less than 0°.1C.[11]

(2) The water sample being hauled up is usually cooled by evaporation and conduction. This cooling takes place at the free water surface in the bucket and by conduction through the walls of the bucket. The problem, then, is to reduce the cooling at both places. Experiments with a bare and rubber-covered wide tin bucket indicated that for a bucket openly exposing a large free surface the cooling directly from the surface accounted for one-third the total cooling. This probably represents the maximum proportionate cooling from the water surface that is likely to be found, for the buckets used on ships are deeper relative to diameter. Furthermore, they rarely come up full. A cover or smaller top than body is the logical solution for the cooling of the surface. The rate of cooling through the walls of the bucket may be reduced by having the outside of the bucket paraffined to shed water, or insulated from the inside. A paraffined exterior, providing a dry surface, cannot be so helpful as might at first appear, for at sea the wet bulb temperatures rarely get many degrees below the dry. For insulation, a rubber covering 2–4 mm. thick on a tin bucket was found to hold up the cooling wave for 1½ minutes, or enough time for observation. An outer cone of sheet iron insulated by air from the inner water-holding cone, both cones being covered, was found by Mr. Benjamin Parry to be twice as efficiently insulated as was the coverless, rubber-jacketed tin bucket just mentioned. Under a 9°C depression of wet-bulb temperature below the water temperature, a condition was rarely experienced at sea, Parry's first bucket cooled but 0°.6C in 4 minutes in a brisk wind.[12] A full canvas bucket, exposed to a 12°C depression of wet bulb temperature cooled 0°.6C in 3 minutes in a moderate wind. For an ordinary partial haul at such temperatures this amount of cooling is found after only one minute. At sea this bucket gave temperatures ½°C higher than the canvas bucket on 12 out of 15 simultaneous hauls. The other three hauls with the iron bucket gave ¼° (2) and ¾° warmer. Parry's improved bucket, put into experimental use after the first was lost at sea, has an inner water vessel with a rubber ball stopper. Its readings were ½°C higher than the canvas bucket's for 8 of 19 observations made, ¼° higher once, ¼° lower once, and the same 9 times, suggesting that it too was well insulated, and that its rate of cooling may be only half that for a full canvas bucket. The average of the 34 comparisons from January to mid-April, under diverse wind and sea conditions and in both middle and low latitudes, comes out insulated bucket 0°.4C the warmer—the same as the average error of the canvas bucket on the FINLAND. If the typical leisurely bucket haul could be speeded from two minutes down to one, and an insulated covered bucket used, the evaporational cooling could be reduced to but a quarter its present average, or to about 0°.1C.

bucket
⅓ swell?

Dr. G. F. McEwen's new metal water bucket, with valves top and bottom and lined with hard rubber, cooled but 0°.2C in 12 minutes in the shade, with wet bulb depression (below water temperature) of 6°.4C and a wind of 6 m/s. There was no cooling observed in the first four minutes.[13] In four other tests, made by Dr. McEwen, there was no cooling in the first four minutes in two and but 0°.04 and 0°.01C in the other two.

(3) The thermometer inserted is seldom at the same temperature as the water in the bucket. The typical thermometer used is a rather large mercurial one in a heavy metal case, the lower part of which is closed into a cistern. After an observation, this cistern may not be wholly dumped and the water may not evaporate before the next

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[10] Ibid., p. 245

[11] Ibid., p. 246.

[12] Further details are presented in the 1928 report of the Comm. on Submar. Config., etc., loc. cit.

[13] Personal communication.

observation. Since the bulb is in the cistern, the original temperature of the cistern and its water may have an appreciable effect on the indicated temperature. The essential part of a cure is to remove the cistern.

(4) While the thermometer is resting in the bucket further cooling, or perhaps heating, of the water sample may take place. For insulated and covered and, to a less extent, for buckets with water-shedding exteriors, this further cooling is reduced, but speeding up the process of determining the temperature of the sample is the easiest cure for this difficulty. The thermometer should have the quicker responding cylindrical instead of the usual spherical bulb. The observer should have the thermometer ready to immerse in the bucket at once. He should hold the bulb near the middle of the bucket and near the top and refrain from stirring the water, thereby mixing the usually cooler bottom and side water through the mass, and he should read it within a few seconds of the time of immersion. On the FINLAND readings were usually made in 45–60 seconds. It is possible to obtain the temperature only 20 seconds after the sample leaves the water. At night the *entire bucket* should be carried at once to the nearest light and the thermometer read there while its bulb is still in the water.

(5) When the thermometer is read it may not have reached the temperature of the water in which it is immersed. This is unlikely, but can be obviated by a quickly responding thermometer.

(6) If the thermometer is withdrawn, to be read more easily, the temperature of the very small sample in the reservoir may change before it is observed. Omitting reservoirs from sea-water deck thermometers should help, for only the least thoughtful observer would carry a bare thermometer from bucket to light, and expect it to show the water temperature. Anyway, a 3°[14] error is better than a 1°[15] one, for it is more easily spotted and discarded. On the FINLAND I saw an observer shake the water from the reservoir before reading.

(7) After the markings and numbers have become indistinct, errors of reading may creep in, and it is easy to see the same temperature as at the last reading. A bottle of thermometer-marking ink should be part of the ship's equipment.

(8) The thermometer should be calibrated, and its errors noted in each log. A spare thermometer with known errors should be carried. On the FINLAND the thermometer in use during the first few days was 0°.9F too high at the temperatures than prevailing. Before comparisons were made at higher temperatures this thermometer first suffered a 4°F separation of the mercury column—much to the elevation of a few observations, and then was broken when an observer tried to cure the trouble by heating. A galley thermometer brought into use for the remainder of the voyage was $\frac{3}{4}$°F too high in the eighties and $\frac{1}{2}$°F too low in the fifties, with intermediate errors between.

(9) There is a slight chance that the quartermaster may forget what the reading was by the time he gets to the log-book, and simply repeat the preceding figure. A hand pad for the observations would fix this.

(10) Observers may prefer guessing to observing. On the FINLAND two quarter-masters openly admitted guessing the sea temperature, usually 1°F above or below the air temperature. They had the 8 to 12 watch (see Table 5C). In justification they said such observations were of no consequence in waters not infested with icebergs and that towards noon, especially, they had too much to do to bother with the unimportant bucket observation. I was told by others, that some ship captains wouldn't have bucket observations—they were so far off in cold weather, and that some deck logs were filled in for bucket temperatures from the condenser intake temperatures of the engine-room log. Other quartermasters are faithful to the last degree. If the officers and observers could all be shown the value of the observations to investigators when accurately made, and how they were worse than worthless when guessed, this difficulty would be reduced.

The canvas bucket now in common use could be measurably improved by simply soaking it in melted paraffine and adding a cone of lead to its base. The paraffine would keep its heat capacity low, provide a water-shedding exterior, and increase the stiffness. The lead would make it sink better on striking the water and would prevent leaving the bucket in a standing position with residual water after an observation.

The bucket observation can be made reasonably accurate chiefly (1) by getting the observers more interested; (2) by having dry or insulated, non-collapsing buckets; and (3) by doubling the speed of the observation, both by quicker handwork and by using quicker thermometers.

Sea-surface temperatures both at the actual surface and at a depth of say, 5 to 8 meters (15 to 25 feet) are needed by the meteorologist

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[14] Case reported for P. E. James, in loc. cit., p. 247.

[15] See Table 4C above.

who wishes to know the immediate temperature and vapor effects of the sea surface on the air and the general storage of readily available heat in the stirred surface layer. Observations on four ships showed that except in calm or nearly calm weather the temperatures at 5 to 7 meters depth were the same, within 0°.2C, as those at the surface 49 times out of 50. Since quiet weather is uncommonly met at sea, this fact makes observations at either surface or 5 to 8 meters depth generally sufficient for both. In quiet weather, however, surface temperatures are much higher than those at 5 meters, the differences amounting to as much as 1°.5C at times. Therefore, in calm tropical regions and in periods of calm in summer elsewhere actual surface observations are indispensable.

The methods most commonly employed for obtaining these sea temperatures are the bucket and the condenser-intake. A thermometer fixed in the condenser-intake pipe is read by an engineer at any time once during each watch. These readings are commonly subject to a mean error of 0°.2 to 0°.5C or more due to parallax and other coarseness in reading by an observer interested only in the general temperature of the water that is chilling the exhaust steam. Since the actual hour of his observation is not recorded, the best that can be done is to assign the record for each watch to the middle of it. The temperatures so assigned come within 0°.6C of the actual in about $\frac{2}{3}$ of the cases. Refrigerator intake observers on the Finland under favorable conditions averaged 93 per cent within 0°.6C of the actual temperature, during a 17-day voyage. A thermograph attached to the intake provides the most satisfactory service for continuity and accuracy, though not without due care and checking.

Bucket observations are usually made with a cylindrical canvas bucket of about 4 litres (1 gal.) capacity. The bucket is dropped from an open deck forward, hauled up and a thermometer used to obtain the temperature of the water. Cooling of the sample in the air is the chief source of error. The average error by day is about 0°.3C (too low) in weather when the wet bulb temperature is not much below the sea temperature (the average of observations equatorward of latitude 35), and up to several times this in severe weather. The average error at night on the Finland was 1°.1C (too cool) (vs. 0°.4C day) for a voyage from San Francisco to New York in May. The larger cooling at night is owing chiefly to the observer withdrawing the thermometer from the bucket to take the instrument to a light where he could read it. Some observers when pressed record a fictitious temperature instead of using the bucket. Like the engineers' observations, about $\frac{2}{3}$ of the daytime bucket observations were found correct within 0°.6C. The bucket observation can be improved chiefly by more interest, an insulated bucket, and more speed.

Accurate observations of surface temperatures and of those at 5 to 8 meters depth are both needed wherever and whenever the weather is calm and sunny. Bucket observations show surface temperatures to within 0°.5 and intake observations show the deeper temperatures with the same accuracy about two-thirds to three-fourths of the time and can be made to do better. General reliance on intake thermographs for sea "surface" temperatures is indicated by this study, provided that in quiet weather, carefully made bucket or other actual surface observations be used to supplement.

Significance of water-temperature measurements not made exactly at the surface. G. F. McEwen, Scripps Institution of Oceanography, La Jolla, California.

The difference between the surface temperature and that at a depth of five meters is least in mid-winter and greatest in mid-summer. In general it decreases with an increase of latitude and is negligible when the wind velocity exceeds about fifteen miles per hour. In the Pacific at distances ten to twenty miles off the Southern California Coast the temperature at five meters averages 0°.3 or 0°.4C less than that at the surface. During summer the difference is about twice this value, and during a calm clear day it may be as much as 1°.5C but this is very rare. The prevailing ocean winds are stronger farther from shore, and their maximum velocity occurs in summer, thus tending to reduce the temperature difference between the surface and five meter level below that found near shore.

Owing to the seasonal and regional change in this temperature difference, and its relation to meteorological conditions an extensive tabulation of data on surface temperatures and corresponding temperatures at depths of a few meters (those from condenser intakes, for example) should provide a means of estimating surface temperatures from subsurface temperatures.

An estimate of the accuracy with which the average surface temperature of a quadrangle thirty minutes on a side could be determined was based upon hourly observations made by the U. S. Destroyer Fleet of about thirty ships during a ten day period of maneuvers south west of San Diego, California. These temperatures were read from condenser intake thermometers and were divided into two equal groups, in one of which the thermometers were calibrated and the readings corrected. It did not prove practicable to calibrate those of the other group. Average temperatures of each of 141 quadrangles were computed from each group. The difference averaged about 0°.1C.

There were on the average 17 observations per quadrangle, from each group. The average difference in temperature of a quadrangle found from calibrated thermometers minus that found from uncalibrated thermometers was 0°.1C. The probable error of a single observation regarded as an estimate of the temperature of one quadrangle was 0°.8C. This estimate of error based upon about 5000 observations includes errors of reading, differences of position in the quadrangle and differences of time. The range of a group of readings corresponding to a single quadrangle was from 4 to 10°F. No appreciable difference was noted between means and medians. In order to obtain an estimate of the temperature of a single quadrangle with a probable error of 0°.2 about sixteen observations are required.

The time required for temperature-departures to cross from the western to the eastern side of the Pacific, and changes in departures during the crossing. G. F. McEwen.

Surface temperatures observed from Japanese ships and averaged by months and five-degree quadrangles have been published by the Imperial Marine Observatory at Kobe, Japan. Preliminary computations of surface drift have been made at the Scripps Institution from these data for the period 1916 to 1920.

One method was to plot as ordinates the departures from this five-year mean for each month using the distance along the direction of flow from a selected point, off Japan for example. Find by trial that horizontal displacement of one such curve with reference to that corresponding to the curve for one, two, or three months earlier which results in the best agreement of peaks and depressions. Thus the distance through which the water flows along this stream line in the corresponding time interval may be estimated. Sufficiently accurate data treated in this way should serve to determine seasonal and regional variations of velocity. The departures actually found rarely exceeded 3°.0C, and were usually less than 2°.0, while not infrequently greater differences were found between adjacent quadrangles. Temperature variations with respect to distance were especially marked near the boundaries of the Japan stream. Accordingly data from a large number of quadrangles could not be used in computations of currents.

The most satisfactory pair of curves tested in this way was for October and November, 1920, in latitude $32\frac{1}{2}$° beginning near Japan. Comparing peaks and depressions, assuming no lag, there were 7 agreements and 11 disagreements. Assuming one month to be required for a flow equal to the breadth of one quadrangle, or displacing the curve corresponding to November one unit to the left, there were 15 agreements and 4 disagreements. The length of one unit at this latitude is 250 miles, therefore the estimated velocity is about 8 miles per day. Other pairs of curves gave approximately the same velocity, but the uncertainty did not seem to justify attempting to distinguish accurately between different regions or seasons.

Another method is to select a month and quadrangle in which the departure from the five-year mean is reasonably large. Find by trial that quadrangle in the general direction of drift having a somewhat smaller departure. Then find another farther along the stream-line having a still smaller departure, and so on. Make readjustments, if necessary to obtain a series of consistently decreasing departures as far along the stream-line as possible. Then assume the difference in distance between these successive quadrangles was traversed in the corresponding difference in time, and estimate the velocity in each interval. Actually it was found that the reduction of variability obtained by using a three month interval (January, February, March for the winter season, etc.) resulted in much more consistent results. For example in the quadrangle 27°.5 N and 142°.5 E the departure was + 1°.4 in the summer of 1916. In the fall it was 0°.8 C at a distance of 540 miles. Nine hundred miles from here it was 0°.6 C in the winter of 1917, and could not be detected by spring at an additional distance of 900 miles. The estimated velocities are respectively, 6, 10, and 10 miles per day, which agree with velocities estimated by the first method. The "Kobe" data when treated in this way frequently failed to give sufficiently consistent departures to warrant computing the velocities.

Using the stream lines assumed in either of the above methods, independent computations of velocity can be made from the difference between observed and "normal" surface temperatures, by the method explained on pages 230 to 235 of the publication of the Section of Oceanography, American Geophysical Union, April, 1927. These velocities were consistent with those estimated by the above methods.

These preliminary results indicate that oceanic circulation can be computed from temperatures by either of the above three methods.

However, care must be used in selecting appropriate intervals of time and space in order to reduce the effect of accidental variation. Also, the magnitude of the accidental variation in the "Kobe" data is rather large in comparison to the departures dealt with and thus tends to complicate the problem. Such data should be carefully examined in order to decide whether they are of sufficient accuracy to justify the particular use it is intended to make of them.

Problems Related to Atmospheric Circulation

The effect of surface-winds upon ocean-drift. G. W. Littlehales, Hydrographic Office.

The theatre of pure wind-driven currents is in the open ocean where the water is deep as compared with the depth to which the effect of the wind penetrates and where land masses are remote. When wind blows over a tract of the ocean, all the air does not pass over the water. The lowest parts of the air in the boundary between the atmosphere and the ocean remain in fixed contact with the water, giving rise to shearing stresses in overlying parts and generating eddies and turbulence whose effect is to produce a tangential pressure upon the surface of the sea in the direction of the force of the wind. This effect is augmented by the direct pressure of the wind upon the waves of the sea. The rate of drift thus communicated to the surface-waters varies directly with the velocity of the wind, relative to the sea and inversely as the square root of the sine of the latitude of the place, being approximately two percent of the velocity of the wind in high latitudes and four percent in low latitudes.

The deflective force arising from the rotation of the globe, which was passive before the motion of the water began, now comes into play, so that the direction of the drift does not follow the direction toward which the wind blows; but deviates 45° to the right-hand in the northern hemisphere and 45° to the left-hand in the southern hemisphere. And this deviation increases proportionately with the depth.

Descending from the surface into the depths, the vectors representing the velocity and direction of the movement are related to one another like the edges of the successive treads of a helical staircase whose steps decrease in radial extent in geometrical progression toward the bottom, in such a manner that the horizontal projection of the outer contour of the stair assumes the form of the logarithmic or equiangular spiral. That is to say, when the velocity of the current at any depth is denoted by V, and the angle between the direction of the current at the same depth and the direction of the surface current by a, there exists the relation $V = Ce^{-a}$, in which C is a constant and e is the base of the Naperian system of logarithms. When the tangential pressure exercised by the wind upon the surface of the sea decreases or increases in a certain proportion, the velocity of the current in the depths as well as on the surface will decrease or increase in the same proportion, while the direction of the motion relative to the direction of the wind will remain unchanged.

At a depth where the current has turned 180°, the velocity has decreased in the proportion $e^{-\pi} = 0.043$, or to about one twenty-third of the surface-velocity.

As one twenty-third of the surface-velocity may generally be disregarded on account of its smallness, it is usual to call the depth, D, at which the direction of the current has completed its first half revolution, the *drift-current depth.* In order to compute the drift-current depth, it is formulated that the resultant of the frictional forces acting upon the upper and lower surfaces of a layer must balance the deflecting force acting upon the same layer. The deflecting force acting upon the layer is for square centimeter $2\,\Delta\cdot d\cdot V\omega\cdot\sin\varphi$, where Δ is the thickness of the layer, d the density of the water, V the velocity, ω the angular velocity of the earth, and φ the latitude.

Likewise, the tangential force acting upon the surface of the water, due to the wind, is $u\cdot V\cdot 2\pi^2\Delta/D^2$ in which u is the virtual coefficient of friction.

Whence

$$D = \pi\,(u/d\cdot\omega\cdot\sin\varphi)^{1/2}$$

The drift-current depth thus depends not only upon the coefficient of friction but also upon the latitude of the place. If D is 100 meters at the Pole, assuming equal coefficients of friction it would be 108 meters in 60° of latitude, 141 meters in 30°, and 240 meters in 10°.

It appears from the above equation that D and u are mutually dependent, and, therefore, as Eckman has pointed out, that D may be used in place of u as a measure of the internal friction. This has the advantage of simplification, since it has been found, that for practical purposes, the drift-current depth may be expressed in feet by the equation

$$D = 4.5\ W/(\sin\varphi)^{1/2}$$

in which W represents the velocity of the wind in knots, and φ the latitude.

At a depth of one-fifth of D below the surface, the direction of the