(Errors of uninsulated buckets)

OBSERVING WATER-SURFACE TEMPERATURES AT SEA[1]

By CHARLES F. BROOKS

[Clark University, Worcester, Mass.]

(Based mainly on observations made aboard the R. M. S. *Empress of Britain* during a four weeks' West Indies cruise, February to March, 1924.[2])

OUTLINE

SYNOPSIS

This paper is largely a summary of water-surface temperature comparisons by the author on a winter-time West Indies cruise of the R. M. S. *Empress of Britain*. An attempt was made to determine the accuracy of observational methods under a great variety of conditions, including the most trying ones likely to be experienced. Temperatures obtained nearly simultaneously (1) from a low deck with a 2 or 4 quart tin bucket by quick dips forward of the ship's main outtakes and (2) aft in the propellor wash, and (3) in the discharge from faucets attached to the condenser intake pumps, were consistent always within 0.25° F., and differed, on the average, but 0.1° F. Reliable results are evidently procurable from the stern, where "surface" observations may, perhaps, most accurately and readily be made in cold windy weather. A record from the condenser intake pipe appears truly representative of the surface temperatures under virtually all conditions.

The condenser intake temperatures recorded by engineers in the engine-room log of the *Empress of Britain* were found to average 0.5° F. above the temperatures accurately obtained in other ways. This difference appears to arise from some heating of the water about the fixed thermometers in the pumps but mostly from errors of parallax in reading. The most serious deficiency in these observations is the absence of a record of the exact time when they were made. Hourly observations on the international ice patrol ships, *Tampa* and *Modoc* are apparently of the same order of accuracy as those on the *Empress of Britain*.

In comparison with the surface water temperature obtained with a tin bucket from a lower deck at about the same time, water surface temperatures procured by the author with a canvas bucket dropped from the bridge averaged 0.5° F. too low, and those by quartermasters with the same bucket averaged 1° F. too low. These errors were the combined result of the predip temperature of the canvas bucket, evaporative cooling of the partially filled canvas bucket after leaving the sea, temperature change of the thermometer if withdrawn for reading, and several unsystematic errors, such as occasional 5 or 10 degrees misreadings. On some other ships the average depression of the recorded canvas bucket temperatures below the condenser intake values was found to be 3° F. or more. In the Gulf Stream region north and northeast of Hatteras, winter observations from four ships gave canvas bucket temperatures averaging about 5° F. lower than the condenser intake. In cold gales over the Gulf Stream, departures in a group of 24 observations from 4 ships were so large as to have a median at 7 and upper extremes of 20 to 24° F.

An analysis of some observations made on the ice patrol ships show the same tendencies when the air was much colder than the sea. Thus, Lieut. Commander E. H. Smith's observations of surface temperature stood higher than the usual canvas bucket determination from the bridge by an average of 0.7° F. for cold water (10 cases) and 1.8° F. for warm (13 cases) on and about the Grand Banks.

Errors are closely related to the depression of wet bulb or air temperature below the water temperature. With air temperatures no more than 3° F. below the observed water temperatures the temperatures obtained with the canvas bucket are likely to be more than 1° F. in error in but 15 to 30 per cent of the cases. Water temperatures obtained under lower air temperatures, and especially when wind velocities are high, are likely to be too low by one-third to one-half the depression of the air temperature below the observed water temperature.

With due care, involving the use of dry, stiffened canvas or wooden or fiber buckets dropped from a low deck, heaved up rapidly and as quickly observed, accurate temperatures are obtainable. The use of a thermograph, the thermal element of which projects into the condenser intake pipe, is recommended, however, as much the easiest method for procuring temperatures of the general surface layer accurately under all conditions of weather. Even in late spring and summer, when surface layers are warmed more than those at intake depths, the average difference between the surface and 5 meters depth (16.3 feet) has been found to average but 0.2° C. (0.36° F.). In the 66 observations on which this average was based the surface was 0.5° C. (0.9° F.) or more warmer than water at 5 meters but 12 times, and 1° C. (1.8° F.) or more warmer but three times. The greatest difference observed was 1.52° C. (2.7° F.).

INTRODUCTION

Purpose of observations on merchant ships.—Observations of sea-water temperatures are made every four hours or oftener by the great majority of ocean-going steamships. The objectives are: (1) to obtain indications of currents or the general proximity of ice, (2) to determine the volume of water required for the condenser, and (3) to cooperate in the collection of observations for forecast purposes and for later study. A degree of accuracy giving temperatures within a few degrees Fahrenheit may be satisfactory for immediate purposes of navigation but not for scientific study. This paper attempts to show to what extent water temperatures observed by the usual methods differ from the actual surface temperatures, and by what means the most accurate surface temperature observations may be obtained.

Sea surface temperatures needed for meteorology.—For a study of ocean temperatures in relation to the weather, those of the surface waters are most important. It would seem to be a simple matter to obtain such temperatures, but there are a number of difficulties, beginning

---

[1] Amplified from papers presented before the American Meteorological Society, Jan. 3, 1925, and the U. S. Weather Bureau Staff, Mar. 10, 1926, at Washington, D. C.

[2] Appreciative acknowledgment is due President W. W. Atwood and the Board of Trustees of Clark University for encouraging the expedition and providing the funds necessary for travel and clerical assistance.

The observations and comprisons would not have been possible without the hearty cooperation of Mr. E. T. Stebbing of the Canadian Pacific Co., Capt. R. G. Latta, Chief Engineer J. F. Cumming, and other officers and members of the crew of the R. M. S. *Empress of Britain*. Special acknowledgment is due Fourth Officer R. W. Jones, and Quartermasters A. Evans, G. Seed, W. Keig, and W. Jones, for their unflagging assistance, day and night.

The well-directed criticisms of Mr. F. G. Tingley, Chief of the Marine Division, U. S. Weather Bureau have been a valued contribution to this paper.

with that of getting a thermometer into truly surface water. From a small boat or canoe at rest in quiet water the temperature may be found simply by inserting the thermometer into the water. On a large boat under such conditions a pail or pipe is required to bring water to the thermometer unless a closed reservoir thermometer or registering thermometer can be used. As soon as water is dipped up, however, its temperature begins to change. In calm weather, if the ship is in motion, surface temperatures can be obtained only from the bow, by some device to test the undisturbed surface.

WATER TEMPERATURE OBSERVATIONS FROM LARGE SHIPS UNDER ORDINARY CONDITIONS

In windy weather, the usual condition at sea, the disturbance created by the boat is little, if any, greater than that made by the waves themselves. So the temperature of water dipped from any position on the ship, or even sucked in from several feet below the surface, is likely to represent the true surface temperature, provided the water so transported does not cool or warm appreciably before its temperature is taken. Under the conditions of turbulence and rapid mixture going on in windy weather, the discharges from a ship rarely have a noticeable effect on the temperature of water forward of the main outlets or in the churned wake of the vessel. Ten sets of nearly simultaneous observations fore and aft were made with a 2 or a 4 quart tin bucket heaved up rapidly after practically a full catch. Of 42 observations on 10 occasions on 8 days, with wind velocities from Beaufort 2 to 5, 3 showed no difference in temperature fore versus aft; 5 differences of 0.1° F. or less; and 2, differences of 0.2° F.[3] The average difference of but 0.08° F. is only a third greater than the average of the differences between similar successive observations made each time from the same place on the ship. The temperatures aft averaged only 0.04° F. warmer than those forward. This difference can readily be attributed to the cooling of the bucket while it was being heaved up, this cooling being greater on the windswept side of the ship than under the stern. On the only occasion when the wet bulb temperature was the same as the water temperature, five dips, three aft and two forward, were of identically the same temperature.

Advantages of sampling from stern.—In rough weather, especially when the air is appreciably colder than the water, stern hauls appear to have every advantage over the customary (*1*) ship-side hauls forward. (1) The discharges of the ship are so well mixed with the much greater quantities of ocean water that they do not appear to affect the temperature off the stern of a moving ship. It would seem that there would be a greater chance for taking in some discharge water from far forward in putting the bucket over the side from the bridge than in throwing it over the stern. From the stern there are the additional advantages (2) of working facing the bucket, (3) of getting nearer the water, (4) of dealing with less wind, and therefore, (5) of having less evaporative cooling to lower the water temperature in the bucket. In quiet weather, however, especially when air temperatures are well above the water temperatures, such stern hauls are not so likely to represent the slightly warmer surface layer as are dips from near the bow.

COMPARISON OF SURFACE WITH CONDENSER INTAKE TEMPERATURES

Water well mixed by cool winds.—With temperatures in the wake of the ship essentially the same as those forward under all conditions met, it is fair to assume that with rare exceptions, the temperatures are the same to a depth of several feet, at least nearly to the total depth from which the propellors bring water immediately to the surface. On the 11 occasions when 75 comparative observations were made this was found to be the case.[4] These observations were made over a wide range of wind velocity, Beaufort 2 to 8, and water temperatures 79° to 37° F., on 8 days. On all occasions the wet bulb temperature was appreciably (3.5° to 19.2° F.) below the sea temperature. The same thermometer, tested by Mr. S. P. Fergusson of the United States Weather Bureau, was used for all observations.

The surface temperatures were obtained by quick hauls of a tin bucket well filled mostly by dips from the stern. The individual temperatures so obtained were liable to an error of probably not over 0.2° F. owing to cooling in the air (cf. p. 246, below). The condenser intake temperatures were read from the same thermometer squirted with water from the small faucets attached to the three pumps. There were differences between pumps amounting usually to no more than 0.1° or 0.2° F., though once one discharged water 0.3° to 0.4° F. higher than the other two. Evidently, at times, some warming of the water took place in the ship before it was discharged from the faucet where observed. The readings could be made only with a hand light and in an awkward position near the floor. They are thus liable to a slight error of reading, probably about 0.1° F.

The differences between the observed surface and condenser intake temperatures averaged but 0.13° F.; the condenser intake was the warmer by an average of 0.10° F. There were 4 occasions when the intake was about 0.25° F. the warmer, 2 when it was from 0.15° to 0.05° F. the warmer, 3 with no difference, and 1 when the condenser intake appears to have been 0.15° F. the colder. With the observed surface temperatures subject, apparently, only to a negative departure, owing to evaporation while the samples were being hauled up and observed, while the condenser intake temperatures were subject only to a positive departure, owing to warming within the hot ship, it is surprising that the observed intake temperatures were found to average no more than 0.10° F. higher than the surface temperatures. The difference, even in the most extreme instances, about 0.25° F., was so small as to indicate no appreciable difference between sea temperatures at the surface and down to a depth of at least 22 to 24 feet (that of the intake).

Quiet water in summer.—A series of comparative observations in calm weather in water that is being warmed at the surface is required to show whether or not these conclusions will apply under practically all conditions. Calmness, however, is a condition seldom met at sea; therefore, it seems reasonable to accept as a working basis the observed facts, that in general sea temperatures about a ship are essentially the same fore and aft, both at the surface and at the intake depth. (See further discussion p. 243, below.)

---

[3] A detailed table (I) presenting all data in this comparison has been filed in the Library, U. S. Weather Bureau, Washington, D. C.

[4] For full details a table (II) deposited in the Library, U. S. Weather Bureau, Washington, D. C., may be consulted.

standard for comparison.—It is evident from the ;oing, that under the conditions discussed, quick s with a well-filled tin bucket to a low deck or oles from the condenser intake pumps will give the surface temperature of the sea to within 0.1° or F. This conclusion is based on (1) the considerable ıtity of water involved and the shortness of time illed pail is exposed to the air, (2) the small variation, aging 0.06° F., between the temperatures of im- iately successive hauls, the correspondence (3) een temperatures obtained fore and aft, differing he average by only 0.08° F., and (4) between those ıe surface and at the condenser intake, differing by more than 0.25° or an average of 0.13° F.

ith such "standard" observations it was possible ompare a great many other types of observation e by officers and crew of the R. M. S. *Empress of ain.* Furthermore, it proved possible to use con- er intake temperatures as a semistandard for a r field of comparisons not only on this ship but also thers.

DENSER INTAKE TEMPERATURES AS RECORDED IN ENGINE-ROOM LOG

ondenser intake temperatures are observed by the neer in charge once every four-hour watch. Unfor- tely, the actual time of observation is not noted, so parisons with temperatures obtained by other means r from lack of simultaneity. This is especially im- ant where in the course of a watch the temperatures he waters traversed differ greatly. This lack of ıltaneity, however, is of little consequence in com- ng averages, for a departure one time is likely to be nced by an opposite one another time. Assuming the engineers observations were made near the dle of the watch, as my experience in a few instances cated, 56 comparisons were made between tempera- s obtained, on the one hand, by me with a well filled bucket at about 6 or 10 a. m., or 2, 6, or 10 p. m., and, he other hand, the temperatures recorded for each ch by the engineers. The frequency distribution of ırtures was found to be:

minus tin bucket (°F.)	−5	−2	−1	0	1	2	3	4	5	Total
er of cases	1	1	5	20	21	6	1	0	1	56

average of intake minus tin bucket is 0.5° F. If F. of this is the real excess of intake over tin-bucket peratures (see p. 242 above), we have a difference of F. to account for. The lack of simultaneity does appear to be responsible for any. For if the depar- s or portions of the departures quite evidently due his cause are eliminated from the table we should e:

minus tin bucket (°F.)	−5	−1	0	1	2	5	Total
er of cases	1	4	24	20	6	1	56

average is still 0.5°. The two differences of 5° are ably from the engineers' misreading the thermometer ven 5°. Any other errors, or, rather, coarseness in ing probably also balance.

urves of successive intake temperatures plotted for s of the Caribbean region where sea temperatures were rather uniform show once or twice in six observations a deviation of about 1° F. above and below a line of constant temperature at about 0.5° F. above the line of tin bucket temperatures. The recorded observations, thus, are rather consistent and, on the whole, carefully made.

Sources of error in usual condenser intake observations.—The nature of some of the deviations now and then was indicated by some observations made by me on visits to the condenser room. One sample may be cited. When the temperature of the sea surface as observed by several hauls with a tin bucket was 75° F., the thermometers attached to the condenser pumps read 76°, 76°, and 75.5°, approximately, while water squirting from the faucets read 75.2° to 75.3° in two of them and 75.6° in a third. The fixed thermometers were difficult to read accurately. The graduations were not cut on the tubes, the bore was rather large and the scale divisions small so it was scarcely possible to read closer than about a whole degree. The fixed thermometer on each pump was only a foot or two above the level of the floor. In consequence, the parallax of reading was at times 1 degree, and usually plus, for the top of the scale was nearest the floor. It was so on this occasion, the engineer's recorded observation being 77°. As the difference between the fixed thermometer on each pump and the faucet temperature was usually of the order of 0° to 0.3° F. it appears that the intake pump thermometers were accurate within 0.2° F. The greater differences sometimes observed, of the order of 0.5° F. (once 15° F.), must have been owing largely to heating of the water in the pump. But what can we say about 90° F. intake temperatures for late February in the West Indian region found in the log of a British freighter? The canvas-bucket record was about 10° lower.

With an average plus departure of but 0.5° F., and few deviations exceeding 2° F., from the actual surface temperatures, it is evident that the condenser intake temperatures recorded by the engineer officers in charge on the R. M. S. *Empress of Britain* are dependable, and with an average correction of −0.5° F. may be considered in each case as the sea-surface temperature at some point on the ship's course within about 20 or 30 miles of the position of the ship the middle of each watch. If the minute of each observation were noted the value would be greatly increased, since the location could then be determined with some exactness. The worst instance of time "error" noticed was for a 4 to 8 watch when the reading was not made till 7.18, at which time it showed 54° F. A quarter of an hour earlier the temperature was 67°, and at 6 it was 71°.

The hourly condenser intake observations on international ice patrol ships.—Some of the conclusions reached on the *Empress of Britain* are confirmed by an analysis of about 700 pairs of hourly bucket and intake records during 33 days selected at random from the United States Coast Guard international ice patrol ships, *Tampa* and *Modoc*, from April to July, 1925.[5] In tabulating from the typewritten copies of the "smooth" logs, I was struck by the preponderance of changes occurring at every fourth hour, 1, 5, and 9 a. m., and 1, 5, and 9 p. m., or with the beginning of each watch. Grouping the data by hours of the watch I found that, though the percentage of all data showing changes from the previous hour was 31, the percentages by hours were 40, 25, 30, and 30 for the

---

[5] The courtesies of Capt. F. A. de Otto and Capt. Q. B. Newman, of the U. S. Coast Guard, in making the data available are much appreciated. Their comments and others, especially Lieut. Commander Edward H. Smith's, on the conclusions reached in this sampling study of their data, have been very helpful.

first to fourth hours (excluding the 12 to 4 a. m. watch, for the first hour of which the change data were not tabulated). It is evident (1) that the new observer each watch reads the thermometer differently from the preceding one, (2) that he either does not look at the thermometer or reads it carelessly the second hour, and (3) that he observes it with reasonable care the third hour and probably the fourth.

The excess of the changes the first hour over those the third hour may be considered a fair indication of the personal equation in reading a thermometer with markings every 2 degrees, for there is no other reason why more changes should occur between watches than within a watch. The average difference of 0.35° F. corresponds exactly to the personal equation for the canvas bucket observations with 2-degree graduation thermometers on the ice patrol boats for the same dates, 0.35° F.

There is a tendency for observers not to catch small changes, and at times, owing to the difficulty of accurate reading, to record changes of one or two degrees. This results in some lack of simultaneity of change of the same sign as the vessel passes through waters of differing temperature. Out of 217 changes noted in intake temperatures but 122 were recorded simultaneously for surface temperatures, and 21 of these were of opposite sign. It is probable that surface and intake temperatures change in the opposite sense simultaneously at times. But nearly twice as many (39 versus 21) simultaneous changes were allotted to the first hour of a watch as to the last hour of the preceding watch. These suggest that, as in the case of the *Empress of Britain* observations, about a sixth of the changes recorded did not really occur at the hour noted.

The systematic errors of parallax appear to be of the same order as those of the *Empress of Britain* but of opposite sign, for on the ice patrol ships the lower figures on the scale are nearest the floor. With the thermometers low down, their tubes well in front of the scale, and observer reading, as Captain Newman says, from the standing position, the temperature will appear lower than it really is. The amount is at least 0.6° F. as shown by comparisons with the corresponding canvas bucket records for the 23 times with wet bulb temperature a degree or more below the intake figure and with wind velocity 4 (night) or 5 (day time) or more Beaufort. Under such conditions, of cooling at the surface with a strong wind blowing, surely the temperatures at intake depths, about 15 feet on these ships, can not differ appreciably from those at the surface. The error due to parallax is more than 0.6° by the amount the canvas bucket observation is affected by evaporational cooling under the circumstances.

THE BUCKET METHOD

The canvas bucket and its use.—The canvas bucket is a means of obtaining samples of water from the surface, but the observed temperatures of such samples may depart widely from the actual temperature of the surface water. The bucket used on the R. M. S. *Empress of Britain* was a cylinder of canvas 14 inches high and 5 inches in diameter, with a base formed by a heavy wooden block about 1 inch thick, and a top rim of ¼-inch rope. The canvas was made tight to the base with the aid of a strip of leather and copper tacks; on the side the canvas overlapped on the seam 1½ inches, and at the top the canvas was doubled back 2 inches for added stiffness. The bucket had a rope handle reaching 7 inches above the rim to the place where the casting line (small rope about one-fourth inch in diameter) was attached. The bucket was commonly dropped from the bridge, where the log was kept. With the coil of line in hand the bucket was swung well forward on the leeward side of the ship, and allowed to drop into the water. If it failed to make a good catch of water it was hauled up a few feet, swung forward, if possible, and dropped again, then hauled up to the bridge. Once the bucket was set on deck a reservoir thermometer was inserted for a brief period, while the rope was being coiled, then the temperature was read usually to the nearest whole° F. Finally the bucket was tipped on its side to empty the water, the thermometer hung up beside the thermometer screen, and the temperature noted in the log.

This practice conforms approximately to Krümmel's statement of modern methods used (*2*). These methods, he says, belong to the simplest of the operations which the sailor has to do. Perhaps this is unfortunate, for what is simple is often carelessly done. According to Krümmel a bucket is thrown overboard and after letting it drag a little while or after hauling it up and dumping it and then putting it in again it is hauled aboard and in a shady spot the temperature is determined accurately. Earlier methods in which the temperature was read in the sun made the observations somewhat too high. The use of canvas buckets aboard sailing vessels gives readings too low unless they are taken immediately, for there is considerable evaporation from the outside of the canvas. A good thermometer for the purpose is graduated to the tenths of degrees and the mercury cylinder is such that there is rapid response to temperature changes and that it is easy to read. The practice has remained virtually unchanged since systematic observing was begun in the middle of the Nineteenth century. Maury's instructions in 1851 read: "In taking temperatures of surface water, a fresh bucket should be drawn up each time, the thermometer plunged into it immediately, held there for several minutes, and *read while the bulb is in the water*" (*3*).

What advantage a canvas bucket enjoys by virtue of its durability, appears to be more than offset by its tendency to collapse and, therefore, not to fill properly. A tin bucket suffers so from banging against the ship's side that it can not be used more than a few hundred times, but it readily makes a full catch of water. Furthermore, the tin bucket quickly dries. A thick paper or fiber bucket, suggested by Dr. H. B. Bigelow (orally) would combine durability, stiffness (for full catches), and quickness in drying.

Departures of canvas-bucket samples from sea-surface temperatures.—On 10 occasions I made comparisons of sea-surface temperatures obtained by the long-haul canvas-bucket method and the short-haul tin bucket, at practically the same time. In all there were 20 individual observations with the canvas bucket and 29 with the tin.[6] In the five cases with a wet bulb depression exceeding 10° F. the canvas bucket sample appears to have averaged 0.6° F. below the sea temperature, there being three cases with departues of 0.8° or 1° F., one of 0.5, and one of −0.1°. In the three instances with wet bulb depressions of 9.6°, 9.5°, and 9.4° F. the departures were 0.7°, 0.5°, and 0.4° F., respectively. In the remaining two, with wet bulb depressions of 2.3° and 1.8° F. the departures were 0.3° and 0.1° F. There is evidently a connection between the depression of the wet bulb and the cooling of the canvas bucket, the cooling in the course of an observation lasting about one minute being

---

[6] A detailed table (III) is on deposit in the Library, U. S. Weather Bureau, Washington, D. C.

about 5 to 10 per cent of the depression of the sling wet bulb below the sea temperature. Whether the cooling will be nearer the 5 or the 10 per cent appears to depend on the wind velocity, the larger departures going with wind velocities of Beaufort 5 or more, relative to the ship. In these comparisons the temperatures in the canvas buckets were observed immediately after they were landed, the same quickly responding cylindrical bulb thermometer being used, as for the observations in the tin bucket. Corresponding observations made by quartermasters with the ship's spherical bulb thermometer were lower in cool windy weather by about 0.5° to 1° F. owing to the longer exposure before reading. My direct comparison, therefore, does not show departures of canvas bucket temperatures from the sea temperatures as large as those given by the usual, less immediate readings by the quartermasters. Three other comparisons were made, involving the quartermasters' regular observations, on the one hand, and tin bucket temperatures, second dip temperatures, or condenser intake temperatures, on the other.

Temperatures obtained by quartermasters with canvas bucket.—Using as a basis for comparison 79 sets of observations with a well-filled tin bucket hauled up from one of the lower decks at times within 15 minuets of the scheduled hour of observation with the canvas bucket, and when it appears the water temperatures themselves were not changing rapidly, as many as 23 of the 79 hauls of the canvas bucket differed from the apparent water temperature by 2 to 7° F. Half of these important departures occurred north of latitude 35° during cold winds, in fact, 12 of the 14 comparisons made in these latitudes deviated by 2° F. or more:

Depression of canvas below tin bucket temperatures (°F)	−2	−1	0	1	2	3	4	5	6	7	Total cases
Observation latitude 35° and north	0	0	1	1	1	5	3	1	1	1	14
Observation between latitudes 35° and 9°	2	8	22	23	9	0	1	0	0	0	65
Total	2	8	23	24	10	5	4	1	1	1	[1] 79

[1] For more detailed treatment, see below.

The average was 1.0° F. lower temperature for the canvas bucket observations than for those by the tin bucket.

Another set of 24 observations in which the pail temperatures were obtained in the course of oceanographic soundings by Lieut. Commander Edward H. Smith, have been kindly submitted by him. These observations were made on the international ice patrol ships *Tampa* and *Modoc* in the Grand Banks region from April 26 to June 29, 1926.

The average depression of the surface temperature obtained by bucket from the bridge is 1.4° F., but for the warmer water 1.8. These are to be compared with 1.0 for all and 3.4 for the 14 cases in the northern zone in the wintertime table above. Even in the warmer months the evaporational errors of the usual bucket observations are considerable.

Depression of bridge bucket below pail temperatures (°F.)	−15	−4	−1.1 to −0.1	0.1 to 1.1	1.2 to 2	4.1 and 4.5	5.8 and 7.4	Average
Observation in cold water (32–44)	1	1	2	2	3	2	----	[1] 0.9
Observation in warm water (49–64)	----	----	3	5	2	1	2	1.8

[1] The −15 case omitted.

Sources of error in the bucket method.—In the course of an observation with any type of bucket there are numerous influences tending to make the final record depart from the actual surface temperature: (1) The bucket is not likely to have the same initial temperature as the sea surface; (2) the water sample being hauled up is usually cooled by evaporation; (3) the thermometer inserted is seldom at the same temperature as the water in the bucket; and (4) while it is resting in the bucket further cooling, or perhaps heating, of the water may take place; (5) when the thermometer is read it may not have reached the temperature of the water in which it is immersed; and (6) if it is withdrawn, to be read more easily, the temperature of the very small sample in the reservoir may change before the temperature is observed; furthermore (7) after the markings and numbers have become indistinct errors of reading creep in, and it is easy to see the same temperature as at the last reading, (8) the thermometer itself may be inaccurate, and (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. Of course, many of these sources of error are usually negligible, but the total effect is not infrequently a departure of several degrees Fahrenheit from what appears to be the true surface temperature. Some attempt will now be made to specify and evaluate these.

Predip temperature of the canvas bucket.—The canvas bucket itself is usually at a different temperature from the sea. If the bucket were always dry and of low heat capacity and if the samples obtained were full buckets, this temperature of the bucket would be of little consequence. Often, however, the bucket can not dry between one observation and the next. Even when there is no spray flying over the ship, some time is required to dry out the thick wet canvas, rope, leather, and wood, particularly since some residue of water usually remains when the bucket is emptied. When the bucket is wet, its temperature approaches that of the wet bulb, as is shown in the following four cases. The figures show temperature depressions of the objects specified below sea temperatures obtained with tin bucket:

Case No.	Sling wet bulb	Wet bulb in shelter on bridge (behind weather-board)	Residue of water in canvas bucket	
	Cooler than the sea	Cooler than the sea	Cooler than sea	Time since last dip in sea
	°F.	*°F.*	*°F.*	*Hours*
1	22	18	16	½
2	12	10.5	10	1¼
3	11.5	10	8	¾-1
4	11.3	8	7.7	[1] ¾-1

[1] One-fifth of a bucketfull.

In case 4 the cool bucket, when heaved over about one-fifth full of residual water 7.7° F. cooler than the sea, brought up a sample 1.8° F. cooler than that of a second casting immediately after. With the use of a dry bucket, at about 4° F. below the sea temperature, however, at another time, a first dip brought up a sample 0.1° F. warmer than a short tin bucket haul on the opposite (windy) side of the ship. A wet bucket warmed in the sun to 2° F. above the sea temperature brought up two samples of the same temperature, probably the true sea temperature. It seems evident, therefore, that a canvas bucket should be dry or, if wet, at about the temperature of the sea water before it is used. Perhaps a regular practice could be made of hanging the bucket upside down at the top of one of the outlet ventilators. While this might make the bucket too warm, it would be dry and its heat capacity small, and its extra warmth would usually tend to offset the cooling by evaporation as the sample was being hauled up. Differences between first and second hauls with a canvas bucket, including the effects of the predip temperature of the canvas bucket were found from 14 pairs of my own observations to be as follows:

	Second bucket the cooler by—			Second same temperature as first	Second bucket the warmer by—					
°F	0.7	0.2	0.1	-------	0.3	0.4	0.5	0.9	1.7	1.8
Cases	1	1	2	4	1	1	1	1	1	1

The number of seconds warmer than firsts were 6, versus 4 cooler, while the average of seconds is 0.3° F. higher than that of the firsts.

After noting the apparent effect of a cool bucket on the temperature of the sea surface sample, the officers and quartermasters kindly cooperated in obtaining temperatures by double dips each hour while at sea. Usually the bucket was still wet from the hour previous, and being in an exposed position near the rail its temperature was probably generally below that of the sea surface. While reasonable care was exercised in the observing, the temperatures were not often noted closer than the nearest half or whole degree Fahrenheit. Furthermore, with two values to record, some errors were occasioned by the observers not recording either temperature till both had been obtained. From some checks, however, these deviations do not appear to have been serious. The 262 pairs of observations showed the following distribution of differences:

	Second bucket the cooler by—					Second same temperature as first	Second bucket the warmer by—				
° F	1.0	0.5	0.4	0.3	0.2	-------	0.2	0.3	0.5	0.8	1.0
Cases	4	21	2	5	3	187	1	1	35	2	1

The results were disappointing—the effect of the original temperatures of the bucket became almost submerged in the longer period of general cooling of the wet bucket after it left the sea, and in the less detailed reading of the thermometer. Since only 4 of my 14 comparisons showed no difference, it seems that perhaps half of the 187 of the quartermasters' cases of no recorded difference were in reality differences of a few tenths of a degree.

The averages of the recorded temperatures of the first and second dips differ by 0.14° F., the second bucket being the warmer. This is half the average difference in my 14 comparisons. This small difference shows that practically nothing is to be gained in eliminating the effects of a cool bucket by having quartermasters make two consecutive dips when the throw is from so high as the bridge, the action of the observers not very fast, and, therefore, the wet bucket so exposed as nearly to return to a wet bulb temperature between dips. The numerous cases of the second dips cooler than the first may indicate lower evaporative temperatures of thoroughly wet buckets than those of partly dried ones.

Since we are considering errors arising from evaporation, these must show some relation to the depression of the wet bulb thermometer and perhaps to the wind velocity relative to the ship. If the bucket is still wet from the previous hour, the greater the evaporation the more the temperatures of two successive buckets of the new observation should tend to depart from one another. The averages here given, including as they do, so many zero differences, are very small—perhaps insignificantly so; nevertheless, there is no break in their progressive increase with atmospheric dryness or wind velocity.

Sling wet bulb below sea temperature, ° F	0 to 3	4 to 6	7 to 9	10 to 13	0 to 13
Average difference between first and second dips, ° F	0.090	0.145	0.154	0.210	0.14
Cases	48	114	70	30	262

Screen wet bulb below sea temperature, ° F	−2 to +1	2 to 3	4 to 5	6 to 7	8 to 12	−2 to 12
Average difference between first and second dips, ° F	0.100	0.136	0.141	0.153	0.176	0.14
Cases	20	61	102	49	30	262

Wind velocity (Beaufort) relative to ship	0 to 3	4 to 5	6 to 9	0 to 9
Average difference between first and second dips, ° F.	0.13	0.14	0.16	0.14
Cases	74	98	90	262

Cooling of canvas bucket from the time it leaves the sea till the temperature is observed.—Though the observed difference between a first and second dip with a canvas bucket at no time was greater than 1.8° F., and but few times was as much as 1° F., the depression of the water temperature observed in the canvas bucket below that obtained more accurately by other means was usually 1° F. or more. The cooling of the bucket after it leaves the sea evidently adds a further depression of temperature that usually equals or exceeds that already caused by a bucket cool on entering the water. Even a full bucket was observed to cool 1° F. in three minutes on deck in a moderate wind with the sling wet bulb at 22° below the water temperature. A number of direct comparisons of observations with a canvas bucket under different weather conditions with those made with a tin bucket at practically the same time have already been referred to (p. 245, above). Other less immediate and less definite comparisons will be found below. Unfortunately, I made no observations with the ship's canvas bucket from low in the stern to discover to what extent the evaporative cooling could be reduced by getting full buckets and hauling them up but a short distance more or less out of the wind. As a substitute, I can offer a series of observations with tin buckets. The well-filled tin buckets showed the small variability, between immediately successive hauls, of less than 0.1° F., already referred to. Canvas buckets, however, with a greater surface relative to weight of water and with a more persistent wetness than the tin buckets might have shown slightly less consistent results than did the tin buckets.

Cooling of tin buckets of sea water in quick hauls.—During a fresh gale over the Gulf Stream between Burmuda and New York, March 22, 1924, I made 67 observations with a 4-quart tin bucket from 10 to 20 feet above the sea on the leeward stern. The wet bulb was 14°–25° F. below the sea temperature. With each haul the approxiiate fullness of the bucket and the quickness of the haul as noted and tabulated, and the following conclusions ached from a comparison of the temperatures obtained intervals of one or two minutes. (*a*) One-third to one-alf pails of water would be cooled usually one-third to vo-thirds of a degree Fahrenheit more than full pails ere, before the temperature could be taken, while (*b*) ne-fifth to one-eighth pails would be cooled generally to 2° F. in the same time, about a minute, usually less;) in quick hauls taking one-third to one-half minute the ss in temperature would be but 0.1° or 0.2° F., even for ne-fifth of a bucket. At the same time the temperatures tained from the bridge by quartermasters averaged 5° F. lower—evidently owing to the cooling in the longer posure to the stronger wind along the side of the ship.

Minor sources of error in canvas-bucket method.—Three her minor sources of error not always operative, though times very large, are the cooling of the water by the ermometer, the cooling of the thermometer if withawn for reading, errors in reading or recording, and exactness in the time of observation. The coolness of e thermometer before it is plunged into the water may count at times for a few tenths of a degree lowering of e temperature of a poorly filled bucket. If the therometer is of the reservoir type, and especially if it reins a little cool water from the last observation, the nall amount of water that comes into contact with the lb may be cooler than the general body of water in the cket. The thermometer is usually stirred but little, if all. Withdrawing it from the water for reading almost ways introduces errors. A reservoir thermometer, with ll reservoir, exposed to a moderate wind with a wet lb depression of 22° below the initial water temperare cooled 6° F. in 3 minutes. A nonreservoir thermeter cools much more, —5° F. being that described Dr. James as the common depression found in me night observations in the Caribbean region in mmer. The quartermaster, he said, took the thermeter from the bucket to a light for reading. Even ch a demonstration as getting the quartermaster to ve his wet hand and feel the cooling did not induce n to change his practice.

Actual errors in reading are not often of consequence, d, usually being large, are rather easily discovered. the *Empress of Britain* observations an error of just 10°, or 15° F. occurred, apparently, about once in 100 nes. Such errors always were at night and are not to wondered at, in view of the difficulty of keeping ermometer markings readily legible when they are so quently wet with sea water. One of the most interest- pairs of errors in reading or noting came just after the *npress of Britain* crossed the "cold wall" from the Gulf eam. At 7 p. m. the temperature recorded was 67°, 8 it was 66.5°, though in the meantime the sea temperae had fallen to 54°. It seems likely that in the cold e the bucket sample had a temperature of about 52°, below the entry. Sixty-one degrees was the record 9, and 51° at 10. The quartermasters appear to have n loath to believe their eyes. On the score of thermeter errors, Helland-Hansen and Nansen say that 30 50 per cent of the thermometers used are bad. (*4*)

When observations are required hourly, as on the ice rol ships, on the Grand Banks there is a decided dency for the observations at the second and fourth rs of a watch to repeat those at the first and third rs. In a selection from the typed records for about days, scattered from April to July, 1925, of the ice rol 48 per cent of the observations in the first hour were different from those of the last hour of the preceding watch, 29 per cent the second hour, 35 per cent the third hour, and 21 per cent the fourth hour. These correspond fairly well to the 40, 25, 30, and 30, for intake temperatures mentioned above. Twice as many changes at 5 and 9 a. m., and 1, 5, and 9 p. m. as at 8 a. m., noon, 4, and 8 p. m. and midnight surely did not occur. In the excess of changes for the first hour of each watch is included, of course, the personal difference in reading a thermometer, which appears to average 0.35° F. for readings to 1° made on a 2° thermometer.

Finally, inexactness in the time of observation is an error to be contended with. Usually a difference of a few minutes from the recorded time of observation is of no consequence, but at times it may mean a difference of 10°, 20° F. or more in actual sea surface temperature. The quartermasters' observations made "on the hour" varied from about 20 minutes before to 10 minutes after, with no note made of the deviations.

Comparative evaluation of errors from canvas-bucket observation.—With the total average and some extreme deviations known, it is possible roughly to divide the total error among the several causes. The initial coolness of the bucket when wet, as usual, seems to have accounted for 0.2° F. and the further cooling of the bucket while being hauled up, for 0.3° F. of the 0.5° F. average difference found when quickly observed temperatures in the canvas bucket were compared with those of the tin bucket. (See p. 245, above.) An additional evaporative cooling of 0.2° F. seems to have taken place on the average before the quartermasters got the temperature, while cooling by or of the thermometer, the average error in reading and from inexactness in time of observation, each perhaps 0.1° F., make up 0.5° F. additional, bringing the total depression of the quartermasters' observations to an average of 1° F. below the sea temperature. (See p. 245, above.)

Some comparisons of canvas bucket with condenser intake temperatures are interesting in connection with the frequencies of different sizes of errors and the averages for different wind and wet bulb conditions. One striking fact is that while the quartermasters on the *Empress of Britain* lost only 3° to 4° F. from the surface water temperature, the observers on the S. S. *Fort Victoria*,[1] in the same sort of severe weather, commonly lost over 10°, and several times 20°, the extreme being 24° F. This difference and the comparisons made with observations of the S. S. *San Lorenzo*,[1] and the R. M. S. P. *Orca*[1] appear to indicate that the observers on the *Empress of Britain* were more careful than most.

Depressions of canvas-bucket temperatures as functions largely of evaporative cooling.—In the following tabular summaries is presented the relation between the apparent cooling of canvas buckets below tin-bucket or condenser intake temperatures and the depression of the wet-bulb temperature and the wind velocity. It will be noted that the departures are (1) distinctly a function of the wet-bulb or air temperature depression below the water temperature and (2) less obviously, if at all, related to wind velocity, (3) that the departures are different on different ships, and (4) that on all ships cited the usual departures are greatest in the Gulf Stream region east and northeast of Hatteras.

Comparisons of the 79 canvas-bucket temperatures were made with the nearly simultaneous tin-bucket

---

[1] The officers of these several ships very kindly provided me with the data here discussed. I wish to acknowledge especially the assistance of Second Officer R. McMeekin of the *Fort Victoria*, Capt. J. O. Foss of the *San Lorenzo*, and Senior Second Officer J. M. Fletcher of the *Orca*.

temperatures on the *Empress of Britain* (see p. 245, above), according to depression of the sling wet bulb and the wind velocity relative to the ship.

Depression of sling wet bulb below tin-bucket temperature		0 to 5		5 to 10		10 to 15		15+		0 to 15+	
		Average	Cases	Average	Cases	Average	Cases	Average	Cases	Average	Cases
		° *F.*		° *F.*		° *F.*		° *F.*		° *F.*	
Wind velocity (Beaufort) relative to ship.	7 to 9	−0.5	6	------	0	1.9	10	3.2	5	1.7	21
	4 to 6	−0.4	10	0.8	17	1.3	9	1.5	2	0.65	38
	0 to 3	0.0	4	0.2	5	1.7	9	3.0	2	1.2	20
Averages	0 to 9	−0.35	------	0.59	------	1.68	------	2.8	------	0.99	------
Cases	------	------	20	------	22	------	28	------	9	------	79

The values in the table, representing the average of the quartermasters' recorded canvas-bucket temperatures subtracted from my tin-bucket temperatures, show larger depressions with the larger wet-bulb depressions and with the larger wind velocities. Only with wet-bulb depressions below 10° F. were the errors of the canvas-bucket observations under 1° F.

If the condenser intake temperature is used instead of tin-bucket temperature as the basis of comparison, much the same results are obtained, though the departures are greater, owing to the addition of the several sources of error to which the condenser intake observations are subject. (See p. 243, above.)

Depression of sling wet bulb below probable true surface temperature		0 to 5 (average °F.)	5 to 10 (average °F.)	10 to 15 (average °F.)	15+ (average °F.)	0 to 15+ (average °F.)
Wind velocity (Beaufort) relative to ship	7 to 9	1	2	1	9.5	2.3
	4 to 6	0.8	1.2	1.6	2	1.2
	0 to 3	0.8	2.3	5.2	7	3.1
Averages	0 to 9	0.8	1.4	2.3	7	2.0
Cases	-------	11	25	20	4	60

The values in the table indicate the average depression of the recorded canvas-bucket temperature at hours 2, 6, 10, etc., below those of the condenser intake each watch (centered on 2, 6, 10, etc.).

For comparison with observations available from other ships, the summaries of the *Empress of Britain* data must also be stated in terms (1) of air temperature instead of wet-bulb temperature (not available) below the sea temperature, (2) of sea temperature as indicated by the condenser intake instead of by the more exact tin-bucket method, and (3) of actual wind velocity as estimated, instead of that relative to the ship. In spite of these three approximations to more desirable values, the tabulations based on them reflect the major features of the more exact comparisons just given. Here I can present the observations from the January to February, 1924, as well as from the February to March, 1924, West Indies cruise of the *Empress of Britain*. The routes of the two were essentially the same. Data from the February to March, 1924, West Indies cruise of the R. M. S. *Orca*, and from the March, 1924, round trip of the S. S. *San Lorenzo* from New York to Porto Rico, are likewise given.

Canvas bucket below condenser intake temperatures, R. M. S. "Empress of Britain," West Indies cruise

FEBRUARY-MARCH, 1924

Depression of air temperature in screen below condenser intake		Ocean colder than air: −4 to −1		Ocean warmer than air								All	
				0 to 4		5 to 9		10 to 14		15 to 25+		−4 to 25+	
		Average °F.	Cases	Average °F.	Cases	Average °F.	Cases	Average °F.	Cases	Average °F.	Cases	Average °F.	Cases
Wind velocity (Beaufort)	7 to 9	-----	0	2.7	3	5.3	3	2.5	2	----	0	3.5	8
	4 to 6	0.7	3	0.7	36	3.4	10	6	1	5.0	3	1.8	53
	0 to 3	−0.6	3	0.9	29	2.2	6	10	1	9	1	1.4	40
	0 to 9	0.1	6	0.8	68	3.7	19	5.3	4	6.0	4	1.8	101

JANUARY-FEBRUARY, 1924

(This cruise was warmer and less windy than the February-March one)

Wind velocity (Beaufort)	7 to 9	-----	0	----	0	4.5	2	-- -	0	----	0	4.5	2
	4 to 6	−1.2	6	0.7	32	3.0	14	4.3	6	3.5	2	1.5	60
	0 to 3	−1.3	6	1.0	32	2.4	11	3.0	2	----	0	1.2	51
	0 to 9	−1.2	12	0.9	64	3.0	27	4.0	8	3.5	2	1.4	113

SUMMARY

February-March cruise	0.1	6	0.8	68	3.7	19	5.3	4	6.0	4	1.8	101
January-February cruise	−1.2	12	0.9	64	3.0	27	4.0	8	3.5	2	1.4	113

Class	−4 to −2		−1 to 1		2 to 4		5 to 9		10 to 14		15 to 25+		−4 to 25+	
	Average °F.	Cases	Average °F.	Cases	Average °F.	Cases	Average °F.	Cases	Average °F.	Cases	Average °F.	Cases	Average °F.	Cases
Both cruises	−0.2	9	0.1	65	1.5	76	3.3	46	4.2	12	5.2	6	1.6	214

R. M. S. P. "Orca" February–March, 1924, West Indies cruise and S. S. "San Lorenzo" March, 1924, New York to Porto Rico and return

Depression of air temperature in screen below condenser intake (° F.).	Ocean colder than air				Ocean warmer than air								All	
	−10 to −6		−5 to −1		0 to 4		5 to 9		10 to 14		15 to 20		−10 to 25	
	Average °F.	Cases	Average °F.	Cases	Average °F.	Cases	Average °F.	Cases	Average °F.	Cases	Average °F.	Cases	Average °F.	Cases
Orca	−0.2	5	−4.6	5	−3.7	12	0	5	2.5	2	1.3	4	−1.7	33
San Lorenzo	0	2	1	2	1.4	18	4.3	15	4.2	5	7.4	5	3.1	47

Something seems to be the matter with the *Orca* temperatures. Possibly the trouble is with the condenser intake observations, for it seems unlikely that the canvas bucket observations should average nearly 2° F. above the condenser intake. The *San Lorenzo* observations are consistent with those of the *Empress of Britain*. The higher general average, 3.1° F. versus the 1.6° F. intake nus canvas bucket, is due to the fewer observations in .pical waters. Half of the *Empress of Britain* obser- tions were made in waters south of the latitude of rto Rico.

Canvas-bucket observations in the Gulf Stream region.— om the standpoint of the weather in eastern North nerica, one of the most important regions of the ocean that portion of the Gulf Stream east and northeast of atteras. It is highly desirable to know accurately what e temperatures of these warm waters are, especially in nter. To what extent, therefore, are canvas bucket observations made in this region during the severest weather to be relied on? From the tables, the data for this portion of the Atlantic were selected, covering 4 crossings of the Gulf Stream by the *Empress of Britain*, 2 by the *Orca*, 2 by the *San Lorenzo*, and 5 by the *Fort Victoria*.

As a background, the following tabulation of frequencies of different departures of canvas bucket from condenser intake temperatures is presented for the two West Indies cruises of the *Empress of Britain*. (Cf. p. 248.)

ondenser intake each watch minus canvas bucket at middle hour (°F.)	Bucket warmer than intake						Bucket cooler than intake										Total
	—13	—4	—3	—2	—1	0	1	2	3	4	5	6	7	8	9	10	
ı. 22-Feb. 20, 1924	0	1	3	6	13	18	29	14	15	2	4	1	1	5	0	1	113
b. 23-Mar. 23, 1924	1	2	1	1	9	16	29	16	13	3	2	5	1	0	1	1	101
Total, both cruises	1	3	4	7	22	34	58	30	28	5	6	6	2	5	1	2	214

In the Gulf Stream region east and northeast of Hatteras the following are the frequencies of the depressions f canvas bucket below intake temperatures:

ondenser intake each watch minus canvas bucket at middle hour (°F.)	Bucket warmer than intake								Bucket cooler than intake																				Total
	—13	—7	—5	—4	—3	—2	—1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	20	21	22	24	
mpress of Britain	1			1		1	1	2	2	6	3	2	2	3	2	3	1	1											31
rca		1		2			1	1			1	1	1																8
an Lorenzo						1		1				3	1	3		1				2									12
ort Victoria			1		1	2		1		3	1	2	1	3	2	3		2	1			2	2	1	1	1	1	1	32
Total	1	1	1	3	1	4	2	5	2	9	5	8	5	9	4	7	1	3	1	2	-----	2	2	1	1	1	1	1	83
Total by threes	1	2		8			9			22			18			11			3			5			3			1	83

These occurrences may be classified according to coolness of the air relative to the water and according to wind velocity:

Canvas-bucket compared with condenser-intake temperatures

Air temperatures below condenser intake (° F.)	Bucket warmer than intake (° F.)					Bucket cooler than intake (° F.)												
	−13	−7	−6, −5	−4, −3	−2, −1	0, 1	2, 3	4, 5	6, 7	8, 9	10, 11	12, 13	14, 15	16, 17	18, 19	20, 21	22, 23	24
25+									1	1						*m* 1	1	1
20 to 24						2	1	1	*m* 1	*m* 1	2			1		1		
15 to 19					2		3	3	*m* 2	3		2	4					
10 to 14					2	2	2	3	*m* 8	1	2							
5 to 9	1		1			2	*m* 7	5	1	2								
0 to 4		1		3	*m* 2	1	1	1										
−1				*m* 1														
WIND VELOCITY																		
Beaufort:																		
9 to 10							1		2	1	*m* 1		1	1			1	
7 to 8	1		1			1	3	2	*m*		2	1	3			2		
4 to 6				2	2	5	5	*m* 9	6	4		1						1
0 to 3		1		2	4	1	*m* 5	2	5	3	1							

m Stands for median.

Both for depression of air temperature below water temperature and for wind velocity there is a well defined slant to the tables. The median (*m*) is without exception among lower and lower canvas-bucket depressions with lower and lower air-temperature depressions and wind velocities. But since the stronger winds were also the colder ones, as shown in the table below, the effect of wind velocity *per se* is not established by this table. There is usually enough wind about a ship to provide nearly the maximum rate of evaporation possible under the coincident saturation deficit. Averaging the depressions of the canvas-bucket temperatures below condenser-intake temperatures by depression of the air temperature below the water temperature we have, finally, the following:

Depression of air temperature in screen below condenser intake temperature (°F.)	Air warmer —1	Air cooler than ocean					All: —1 to 25+
		0 to 4	5 to 9	10 to 14	15 to 19	20 to 25	
Average (°F.)	—3	—1. 9	2. 2	4. 6	7. 3	9. 4	4. 8
Cases	1	9	19	20	19	15	83

From these tabulations it is evident that canvas-bucket temperatures in the northern Gulf Stream region are not reliable in the cool windy weather so common in winter. On the whole, it seems that if the air temperature is 5° F. or more below the surface water temperature as shown by the condenser intake the canvas-bucket temperature is likely to be well over 1° F. too low. With depressions of air temperature of 5° to 15° F. all wind velocities, canvas-bucket data averaged 2° to 6° F. too low for the warmer waters of the southwestern Atlantic in winter.

Canvas-bucket observations on the ice patrol.—A wider range on the negative side is provided in the following table from ice patrol data in the Grand Banks region in spring and summer, which show what may be expected under conditions of wet-bulb temperatures usually above sea temperatures. The condenser intake values, taken as standard, averaged 1° F. below the canvas-bucket temperatures, so when the wet bulb was the same temperature as the intake is was probably 1° F. below the sea surface temperature. The following table shows the average depression of canvas bucket below intake temperatures for the wet bulb depressions and wind velocities specified. With two exceptions all values are negative, indicating that canvas-bucket temperatures are prevailingly above intake temperatures, the latter, however, being systematically 0.6° F. or more too low.

Departures of condenser intake from canvas-bucket temperatures, °F., U. S. S. "Tampa" (international ice patrol), April–July, 1925, Grand Banks region

Depression of wet bulb in screen below condenser intake temperature (°F.)	Ocean colder than air				Ocean warmer than air				−10 to 22					
	−10 to −3		−2 to −1		0 to 6		7 to 22		Day		Night		All	
	Average °F.	Observations	Average °F.	Observations	Average °F.	Observations	Average °F.	Observations	Average °F.	Observations	Average °F.	Observations	Average °F.	Observations
Wind velocity (Beaufort) 7	0	1	−1.0	1	-----	0	-----	0	−0.5	2	-----	0	−0.5	2
4–6	−2.0	26	−0.4	16	−0.6	37	3.0	3	−1.2	48	−0.4	34	−0.9	82
0–3	−2.0	50	−1.4	28	−0.2	49	−1.0	8	−1.2	63	−1.2	72	−1.2	135
0–7	−2.0	77	−1.0	45	−0.3	86	0.1	11	−1.2	----	−0.9	106	−1.0	219
Corrected for parallax	−1.4	----	−0.4	----	+0.3	----	0.7	----	−0.6	113	−0.3	----	−0.4	----

Stated in general terms, this table shows surface waters warmer than those at a moderate depth only when the wet bulb temperature is higher than that of the ocean, the average being 1.4° F. when the wet bulb temperature is considerably the higher, and 0.4° when it is but slightly the warmer. For all the data the surface averages 0.4° F. warmer than intake levels. Such variations as there are with wind velocity show a decrease in the excess of surface temperature over intake temperature with increase in velocity. This naturally is to be expected through better mixing of the water by waves, even if there were no effect of the wind on the temperatures of the canvas bucket samples. But evaporational cooling evidently takes place. Forty of the 113 daytime observations and 39 of the 106 nighttime observations showed lower canvas bucket than intake temperatures. Fifty-five per cent of these 40 in the daytime and 80 per cent of the 39 in the night attended wet bulb temperatures equal to or below the intake temperatures. Without exception, the 9 cases of canvas bucket 3° or more cooler than intake were with wet bulb below condenser intake temperatures. The most extreme instance, not included in the above, was a canvas bucket record of 53° F. while intake was 60° and wet bulb 41°.

Thus, as in the case of the other groups of observations studied in warmer waters during the colder season, errors of evaporational cooling enter into a sizeable percentage of the canvas bucket records obtained from a cold water region in the warmer season, and appear in the averages for observations made when wet bulb temperatures were low.

PRACTICABLE METHODS FOR ACCURATELY OBSERVING SEA SURFACE TEMPERATURES

Now arises the question as to the best and most practicable method of observing the temperature of the general surface layer of the sea. Two have been discussed: (1) The generally used bucket method, and (2) condenser intake observations. A third may be mentioned—the difficult trailing of the thermal element of a thermograph. Of these it appears that the condenser intake offers the best possibility for consistently reliable temperatures, while certain changes in the usual method of handling a canvas bucket for surface temperatures can probably lead to better results. Especial care is required in the northern Gulf Stream region to minimize the occurrence of errors of the order of 5° to 20° F. or more.

Notwithstanding the large errors to which the canvas bucket method is subject, ocean temperatures can be accurately obtained with a canvas bucket, or, better still, a heavy paper, fiber or wooden bucket, if the following precautions are taken: (1) Use dry bucket, or at least empty all residual water before a throw; (2) obtain full bucket of water (use lead sinker and stiffenings in canvas bucket to prevent collapse); (3) make the dips from low deck and haul up fast; (4) protect bucket from the wind during haul, and especially after it is landed, e. g., by heaving over leeward stern in cold windy weather; (5) stir the water with a quick thermometer without obstructing reservoir, and, within a small fraction of a minute, as soon as it becomes nearly stationary, read it as closely as possible; (6) if the haul was not a full and quick one, or if the bucket was rather exposed to the wind after wetting, repeat at once; (7) record the minute of each observation, which is as important as the nearest tenth or half degree of temperature. Such specifications presumably require the immediate supervision of all hauls by the officers in charge of the meteorological observations.

The condenser intake offers probably the most satisfactory opportunity for obtaining accurate temperatures of the stirred surface layer of the ocean. The engineers' observations (*Empress of Britain*) average within 0.5° F. of the apparent true temperatures, and rarely deviate as much as 2° F. from what appear to be the actual temperatures. Since many deviations and perhaps portions of most appear to be due to occasional pockets, or locally reduced circulation about the fixed thermometers in the pumps, errors on this score may be avoided by placing thermometers in the intake pipe between the intake and the pumps. Recording apparatus may readily be installed in this position if a continuous record is desired.

Conclusion.—Briefly stated, we need to do two things: (1) insure the collection of accurate water temperature data in the future, by installing thermographs and by encouraging observers to guard against the sources of error besetting their methods[8] (*1*), and (2) make the best of the great body of data already gathered, not discarding it because beset with numerous errors, but using it with a discrimination begot of an understanding of its limits of accuracy.

DISCUSSION

The discussion after the paper (American Meteorological Society, January, 1925), turned mostly on the best means for obtaining water-surface temperatures at sea. The first question was pointed: "If it seems so easy to take intake temperatures, why do you take temperatures from the side?" Dr. S. J. Mauchley said the canvas bucket was a relic from sailing days, and Prof. R. DeC. Ward added that such observations were continued for that reason.

Obtaining accurate data.—Speaking from considerable experience Professor Ward told of the difficulties of getting men to be accurate who are not interested and who do not want to take the observations. Ordinarily, he said, the ship officers do not care enough about the work to do it.

Prof. C. F. Marvin thought the time was coming when doubtless one could get far more accurate and more abundant water temperatures from ships at sea, and he asked how accurate such observations should be and how they should be obtained. The best you can expect the average seaman to do is to read to the nearest whole line. He will not bother about the fractions of a degree. Doctor Brooks replied that the nearest whole degree (F.) should be close enough, though he would not want to have the observer make an error and then use the nearest whole degree.

Dr. V. Bjerknes, emphasized the importance of reading to the nearest half degree (C)., and showed that in making adequate synoptic maps at sea the equatorial and the polar air streams were to be identified by their air temperatures relative to the water surface temperatures. If the air were 15° C. and the water 14.5° C. one would be dealing with the equatorial air stream, while if the air were 15° C. and the water 15.5° C. one would have the polar air stream. An observer who was not particular would be likely to report air and water temperatures the same in both instances. Doctor Bjerknes said that on the Norwegian ships the radio men do the observing, and that under conditions of frequent inspection, encouragement and a salary good results were being obtained.

Sea-temperature thermographs in the Pacific.—Mr. J. Patterson, in response to a question from Mr. Calvert told in detail how the Canadian Meteorological Service was obtaining accurate records of temperatures in the North Pacific, thanks to the installation of thermographs attached to the condenser intake pipes of some Canadian Pacific liners.

Mr. Patterson expressed himself as agreeably surprised at the close correspondence Doctor Brooks had found between condenser intake and surface temperatures. He had thought the temperature difference much greater. This difference would be most pronounced on warm sunny days, when one would expect the surface layer to be appreciably warmer than those at a depth of 20 or 30 feet, but evidently the mixing is very complete to that depth and consequently an accurate record of sea water temperature can be obtained at the condenser intake.

Remarking on observers, Mr. Patterson called attention to the fact that the engineers do not have close contact with the officers on the bridge and that in consequence the men in each set go about their observations in their own way and do not take much cognizance of each other's observations. The engineers are chiefly interested in the efficiency of the condensers and this is given by the difference in temperature between the water entering and leaving the condensers. If required to take a special set of observations it means extra work for them for something in which they are not interested and they can hardly be blamed if the work is done in a haphazard way. A platinum thermometer with a potential indicator was tried out on one of the boats. By turning a wheel the instrument could be read to 0.1° F., but the observers had all sorts of trouble with it and did not get satisfactory results. The wires broke or the insulation went bad and it was not a success.

Mr. Patterson found that the engineers like the recording thermometers, as the chart has to be changed only once a week and the record is always in view. It has explained some things they could not understand before. The best thermographs have a range of 50° F. on a 3-inch scale, from about 35° to 85° F.; this range will cover all the temperatures experienced in the North Pacific. The thermal element is a large bulb filled with mercury and connected by fine capillary, 8, 10 or 12 feet long as required, to a Bourdon tube compensated; while the accuracy may not be consistently up to the manufacturers claim of 0.1° F., these instruments are reliable within 1° F. A change of 40° or 50° in temperature of the capillary would not affect the readings by 0.1° F. Since the bulb is of steel it is necessary to put it into a copper well inserted in the intake of the condenser so as to protect the bulb from corrosion. The bulb cannot be replaced if once damaged, but if the outer tube is destroyed by the sea water it can easily be replaced. The records show that the ordinary fluctuations from hour to hour are very slight, only about a degree in a whole day, but on the edge of the Japanese Current there is a very rapid variation, even in the course of an hour or two; in the current itself there is always considerable variation.

Experimental work on the Grand Banks.—Mr. Eaton described a durable electrical resistance thermometer devised at the Bureau of Standards for aircraft. With unpainted bridge and constant voltage the accuracy is within 0.5° F.

Dr. H. C. Dickinson told of some means of measuring sea temperatures he had devised about 12 years ago. He used a sounding mechanism that gave a continuous record of temperature, accurate to about 0.01°. The point was to detect any relation between water temperature and near-by icebergs. A platinum resistance thermometer was used in the intake and another in a thin flat sheet against the outer shell of the ship. Still a third was trailed behind on the surface, but it got involved with the propellor. These methods of recording can be made fairly satisfactory, but the equipment is rather expensive, and it would require occasional overhauling, perhaps at the end of each trip.

Temperature differences found at sea.—At about latitude 40° in the western Atlantic, as much as 20° F. difference in temperature was found in the length of the ship, said Doctor Dickinson. There were warm masses one-fourth to one-half mile wide. The record in traversing these is an irregular curve (*5*). Professor Ward mentioned an instance of 30° F. difference between bow and stern.

---

[8] U. S. Weather Bureau, "Instructions to marine meteorological observers," Circ. M, 4th ed., Jan., 1925, devotes a whole page (14–15) to a summary of the larger sources of error discussed in this paper, calls attention to the importance of sea surface temperature data, and encourages observers "to exercise their best judgment and skill in making these observations."

Mr. Patterson, replying to a question by Prof. Milham, said that the annual range of temperature in the coldest part of the ship lane across the North Pacific was of the order of 15° F. from January to August, while the difference between one month and the next might be 4° F. In the Japanese Current the variations were even more. Mapping and averaging the temperatures by 5° squares presents difficulties when the Japanese Current is included in part of a square. The ships in the lane, however, are in this current for only a day; and as the lane never varies more than 50 or 100 miles across, the Pacific region from which data are obtainable is in consequence very limited in extent. It is perhaps interesting to know that ships from San Francisco traverse practically the same course as those from Vancouver.

Are condenser intake temperatures always representative of surface temperatures?—The discussion of the paper concluded with Dr. W. J. Humphreys objecting to the use of condenser intake temperatures as representing the surface in quiet sunny weather, since it is the actual surface temperature that affects the air temperature and the actual surface that discharges the moisture into the air. While admitting this, Doctor Brooks pointed out, however, that appreciable differences between surface and condenser intake levels observable by usual methods must be rare.

THE CASE FOR CONDENSER INTAKE THERMOGRAPHS [9]

Do condenser intake temperatures, accurately obtainable by thermograph, always fairly represent surface temperatures as well as do canvas bucket observations? In other words, how well do canvas bucket temperatures represent the true water surface temperatures; and what differences in temperature occur between the surface and a depth, say, of 5 meters? Mr. H. W. Harvey (*6*), believes the usual dip with canvas bucket represents the top 6 inches of water, and not the true surface layer of occasional high temperature. Prof. James Johnstone, referring to bucket observations, says: "By 'surface' is meant the stratum of water to a depth of about a foot" (*7*). U. S. Weather Bureau instructions, in force till 1925, called for water "drawn from a depth of 3 feet below the surface" (*8*). Canvas bucket observations, as shown in detail above, are usually subject to errors due to evaporation, while large unsystematic errors occasionally enter.

The temperature of the surface rarely differs greatly from that at a depth of 5 meters. In winter and early spring the average difference found was but 0.1° F. In calm clear weather in August, however, Mr. Harvey says the surface temperature of the English Channel 20 miles southwest of Plymouth sometimes reaches 19° C., though the general body of the surface layer has a temperature of 14° to 15° C. in that month (*6*). The most extreme case of surface heating mentioned was an excess of 1.5° C. at a depth of half an inch over that at 8 inches. A bucket, however, can not fill with the warm thin surface sheet unmixed. Thirty-eight observations of surface temperatures (wooden bucket) with those at 5 meters depth were kindly furnished in manuscript by Mr. Harvey. They were made during the warmer months, May to September, 1921 to 1925, at the western end of the English Channel. On the average, the surface was 0.32° C. warmer than the water 5 meters below. Fourteen of the 38 had a difference of 0.1° C. or less; 21 of the 38 were within 0.2° C.; 10 differed by 0.5° or more, and 3, by 1° or more, the extreme being 1.52° C. These differences are somewhat less than the diurnal range of surface temperature (*9*). Mr. Harvey's observations show that the well-mixed surface layer of relatively warm water is usually 12 to 20 meters thick (*6*).

Some figures picked at random by Dr. H. B. Bigelow from his oceanographic notebooks show a similar small difference in the Gulf of Maine region. In May, 1920, and August, 1922, the average of four surface temperatures was 0.33° C. warmer than the corresponding temperatures at 5, 9, or 10 meters depth. The individual differences were 0.1°, 0.2°, 0.3°, and 0.7° C. Harvey's and Bigelow's observations show that in midlatitudes in summer, condenser intake temperatures should average about 0.3° C., or not more than 0.6° F., below the surface temperature, and that differences of 0.5° to 1.5° C (0.9° to 2.7° F.) are to be expected a quarter of the time.

Three series of less direct observations substantiate this conclusion. On the line from New York to Trinidad in mid-August, 1924, 38 bucket observations by Dr. P. E. James averaged 0.4° F. higher than the intake temperatures, while the bucket observations by the quartermasters averaged below the intake temperatures. Nighttime bucket observations by Doctor James were the same as the intake ones in temperature, as were also those on windy, cloudy days. During a hurricane, however, his canvas bucket observations were, for a time, 1° to 2° F. lower than the condenser intake values. Afternoon surface temperatures on fair days were 1° or 2° F. above the condenser intake temperatures.

On the S. S. *Meline*, crossing the Atlantic in latitudes 53° to 41° N., late in June, 1922, but 12 of the 40 observations (four hourly) showed bucket warmer than intake; 8 of these were 1° warmer and 4 were 2° F. warmer. The average of all 40 was bucket 0.1° F. cooler than intake.

Perhaps as great a contrast between surface and intake temperatures as is to be found anywhere should be expected in the Grand Banks region in spring and summer. The international ice patrol ships, *Tampa* and *Modoc* keep an hourly record of bucket and intake sea temperatures. A selection of 345 pairs of these observations was made from the typewritten copies of the logs of these ships for 26 to 30 days, April to July, 1925, on file in the Washington office of the United States Coast Guard. At odd-numbered hours—those when the observations seemed most carefully made—the averages of canvas bucket minus condenser intake after the latter was corrected 0.6° F. for error of parallax (which made the readings too low, were as follows:

	Hours, a. m.						Hours, p. m.					
	1	3	5	7	9	11	1	3	5	7	9	11
°F.	−0.2	0	−0.1	0.6	0.6	0.6	1.1	0.5	1	0.9	0.3	0.1

Throughout the 24 hours the surface temperatures averaged from 0.2° F. below to 1.1° F. above those at intake depth, about 15 feet. The average of the daytime hours, taken as 7 a. m. to 5 p. m. was 0.7° F., and of the nighttime hours, 0.3, and of all the data 0.5° F.

To afford more certain comparisons Lieut. Commander Edward H. Smith kindly made 24 observations of sea temperatures at the surface and 5 meters depth and submitted the corresponding bridge and engine room determinations. These were from April 26 to June 29,

---

[9] Presented at U. S. Weather Bureau Staff Meeting, Washington, D. C., Mar. 10, 1926.

1926, on the *Modoc* and *Tampa* in the Grand Banks region. The average difference between surface and 5 meters down was but 0.02° C. (0.04° F.), the surface being the cooler. In 23 of the 24 observations the difference did not exceed 0.2° C., in the other it was 0.8° C. (1.4° F.) the warmer on the surface. The surface was slightly warmer than at 5 meters 6 times, the same temperature 7, and cooler 11. The corresponding temperatures obtained from the bridge and the condenser intake in the engine room differed an average of 0.2° F., the surface being the cooler. One pair of the 24 was omitted in making this average, for the two differed by 15°, evidently owing to lack of simultaneity of the observations as the ship crossed a boundary between warm and cool water. Four other pairs differed 5° F. or more. The 23 comparable surface reports averaged 1.4° F. lower than Commander Smith's observations, a difference probably owing largely to evaporational cooling, for the 13 cases of warm water averaged 1.8, and the 10 of cool water 0.9. The engine room temperatures averaged 1.1° F. lower than observed temperatures at 5 meters depth, divergence which appears to be due largely to parallax in reading. Thus, the fairly close correspondence between surface and intake temperatures as observed regularly on the bridge and in the engine room is in this small group not significant.

Altogether, these several sets of observations from different regions are fairly consistent indications (1) that the average summer time difference between the surface and intake depths is of the order of 0.6° F. or less, the 66 oceanographic observations averaging 0.4, (2) that in only a quarter or less of the time in summer will the surface layer be 1 or 2° F. warmer than intake levels, and (3) that departures of more than 2° F. are rare.

Conclusion.—The case for condenser intake thermographs rests on the following points in their favor: (1) They have much greater accuracy than the canvas bucket method usually employed; (2) they show true surface temperatures in winter and in windy weather anytime; and (3) their indications in summer will differ from surface temperatures by no more than 0 to 0.6° F. on the average, not over 2° F. oftener than once in 40 to 60 times. The thermograph's accuracy in winter is to be compared with an average depression of 1° F. found for canvas bucket observations in this season; and its 0 to 0.6° F. "inaccuracy" in summer is to be compared with equal if not greater ones in the same direction found in the usual bucket observations. Bucket observations *can* be made accurately, but they commonly are not; a thermograph trace is more dependable.

LITERATURE CITED

(1) U. S. WEATHER BUREAU.
1925. INSTRUCTIONS TO MARINE METEOROLOGICAL OBSERVERS. Circular M, 4th ed., p. 15.

(2) KRÜMMEL, OTTO.
1907. HANDBUCH DER OZEANOGRAPHIE. Stuttgart. Vol 1:373.

(3) MAURY, M. F.
1851. EXPLANATIONS AND SAILING DIRECTIONS, ETC. Washington, D. C., p. 58.

(4) HELLAND-HANSEN, B., AND NANSEN, F.
1920 (1917)., TEMPERATURE VARIATIONS IN THE NORTH ATLANTIC OCEAN AND IN THE ATMOSPHERE. Smithsonian Misc. Colls., 70: no. 4, p. 3.

(5) U. S. COAST GUARD.
1916. INTERNATIONAL ICE OBSERVATION AND ICE PATROL SERVICE IN THE NORTH ATLANTIC OCEAN FROM FEBRUARY TO JULY, 1915. Washington, D. C., Bull. No. 5, curves 1–27, p. 53–64.

(6) HARVEY, H. W.
1925. EVAPORATION AND TEMPERATURE CHANGES IN THE ENGLISH CHANNEL. Jour. of the Marine Biol. Assn. of the Un. Kingdom, 13: 683–687.

(7) JOHNSTONE, JAMES.
1923. AN INTRODUCTION TO OCEANOGRAPHY. London, p. 168.

(8) HEISKELL, H. L.
1910. INSTRUCTIONS TO THE MARINE METEOROLOGICAL OBSERVERS OF THE U. S. WEATHER BUREAU. Washington, D. C., 3d ed.: 48.

(9) KRÜMMEL, OTTO.
See (2) above, p. 382–385.

COMMENT

By F. G. TINGLEY

Doctor Brooks has performed a valuable service in investigating the methods whereby the temperature of the surface sea water is obtained. Meteorologists have always assigned to the oceans such an important part in the scheme of weather causation that anything bearing on the subject of their temperature is always welcomed. The present article forms an important contribution to the technique of ocean temperature observations and any one reading the account of Doctor Brooks's experience on board the *Empress of Britain* will gain a very clear idea of the conditions under which such observations are made and the hazard of error to which they are subject. Moreover, they will doubtless gain a better appreciation of the esteem in which such observational material is held by meteorologists. Observers on board ship, especially, should realize the high value that is placed on their work.

The cruise of the *Empress of Britain* afforded an opportunity to study the making of surface-water temperature observations under almost every condition met by observers. Beginning at New York in February, under winter conditions, the course of the vessel lay southward across the Gulf Stream, through waters of different origin and varying temperatures, to the Tropics, where summer conditions and uniform surface temperatures prevailed. That Doctor Brooks took full advantage of his opportunities is attested by the wealth of detail that characterizes the paper.

The outstanding fact he discloses is the large element of error apparent in observations made by the canvas bucket method in the region between New York and Bermuda. On this is based his argument for using intake temperatures instead of those taken by canvas bucket. At first sight the case against the bucket appears rather serious, but investigation of the large amount of data collected by the Weather Bureau through the cooperation of vessel masters and other officers leads to the belief that the rather numerous and, in some cases, large errors reported by Doctor Brooks were exceptional. In the compilation of water temperature data it is generally possible to detect erroneous readings where the error is large. Small errors, including those due to lack of calibration of thermometers and those coming under the head of personal equation may be depended upon to offset one another in any considerable body of data.

The purposes of Doctor Brooks's investigation and of the Weather Bureau's were somewhat different. Doctor Brooks's was the two-fold one of emphasizing the value of water temperature observations and of calling attention to the importance of using every precaution to insure the highest attainable accuracy in their making. The bureau's object has been not so much to determine the absolute temperature of the sea water as to establish the degree of accuracy with which the data show its *changes* of temperature. The data have been subjected to various forms of analysis which need not be described here. As a result, it is felt that they are entirely adequate to show the changes that are taking place in any region in which the areal distribution of temperature is fairly uniform and the disposition of the observations reasonably constant. A region like that between New York and Bermuda must, however, be excepted, on account of the great mixture of warm and cold waters found there. Probably no single group of observations, such for instance as those taken by all vessels crossing the region in a given month, could be depended upon to give the true mean surface temperature of such a region as a whole, even though the individual observations were highly accurate. Even continuous records of temperatures, obtained by means of sea water thermographs, might not suffice for more than the ships' courses in these regions of exceptional temperature range. The Weather Bureau has recently installed such an instrument on a vessel plying between New York and Porto Rico and it hopes that the data which will soon be available will shed further light on this important subject.

RECENT INVESTIGATIONS ON THE ENERGY IN THE EARTH'S ATMOSPHERE, ITS TRANSFORMATION AND DISSIPATION

By EDGAR W. WOOLARD

In the physical system of the earth's atmosphere, we find numerous forms of energy displayed on a gigantic scale; and transformations from one form to another are continually taking place (*1*). Kinetic energy, in particular, is constantly being dissipated—transformed by friction and turbulence into heat which is ultimately radiated away—and hence a continuous supply of energy must be available to maintain the ceaseless activity of the atmosphere against the action of the resisting influences. The only available adequate source of all except an infinitesimal amount of atmospheric energy is ultimately the solar radiation which is intercepted by the earth (*2*). The atmosphere acts like a gigantic heat-engine, transforming radiant energy from the sun into the energy of atmospheric phenomena; and the general problem of meteorology consists of elucidating the details of the mechanism and the processes by which, under the usual laws of dynamics and thermodynamics, this energy results in the production and maintenance of the sequence of atmospheric phenomena, these phenomena collectively making up the continual activity in the atmosphere, and involving the changes in the daily distribution of the meteorological elements that provide the daily weather for every part of the globe (*3*).

From the approximately known mass (*4*) of, and mean wind velocities in, the earth's atmosphere, Brunt (*5*) concludes that the total *kinetic* energy of the *general* or *planetary* circulation is of the order of 3 x 10^{27} ergs; considerable additional kinetic energy is frequently developed in storms, as Shaw has pointed out (*6*). The equations of motion show that the rate of dissipation of kinetic energy due to the virtual internal friction introduced by turbulence is equal to the product of the pressure gradient into the component of wind velocity in the direction of that gradient. In steady motion along an isobar (frictionless gradient wind) there is no dissipation, but if, due to turbulence, there exists any motion across an isobar into lower pressure, there is a dissipation; and a steady motion can be maintained only if energy is supplied at a rate equal to the product of velocity of inflow and gradient (*5*).

The theory of the variation of wind velocity with height, produced by turbulence, makes possible an integration which shows that the total loss of energy due to turbulence in a column extending from the surface to the limit of the atmosphere is practically equal to the loss in the column extending from the surface to that height (about one kilometer) at which gradient direction is first attained, consequently the dissipation of energy by turbulence is, as we might expect, effectively restricted to the layer below this height (*5*). At greater heights, the changes of wind with elevation are determined, not by turbulence produced at the ground, but by the horizontal distribution of temperature; and the rate of loss of energy must be determined in a different way (*7*).

Neglecting the dissipation above 10 kilometers, Brunt finds, finally, for the rate of loss of kinetic energy above one square meter of the earth's surface (*5*): From surface to 1 kilometer, 3 x 10^{-3} kw./m.^{2}; from 1 to 10 kilometers, 2 x 10^{-3} kw./m.^{2}

If the rate of dissipation be assumed proportional to the energy remaining, the kinetic energy of the general circulation would be reduced to 0.1 its value in three days. This loss must be made up by the conversion of solar energy into kinetic energy of winds. After allowance is made for the earth's albedo of 37 per cent, the remaining 67 per cent which constitutes the effective incoming solar radiation (i. e., that which is absorbed, and in some way used up in the production of weather phenomena, before being again returned to space) is found to average for the whole earth 0.22 kw./m.^{2}; the conversion of a little over 2 per cent of this into the particular form of kinetic energy of winds in the planetary circulation would make up for the continual dissipation of the latter[1] (*5*).

No completely satisfactory and universally acceptable theory has yet been put forward, however, which explains the details of the mechanism of the continuous dynamic and thermodynamic process by which solar energy is converted into atmospheric energy. The major actuating cause of atmospheric activity is undoubtedly the unequal heating and cooling in different latitudes. This sets up temperature differences that in turn set up pressure differences, and lead to a planetary circulation involving interzonal exchange of air by way of the cyclones, anticyclones, and other secondary phenomena which come into existence in the temperate zone. The highly complicated and irregular circulations thus set up are, however, far from being completely understood or accounted for.

If we regard the phenomena exhibited by separate masses of air, we have little difficulty in finding evidence of all the separate stages of the thermal cycle of a heat-engine (*8*). A thermodynamic engine must operate between two different temperatures. The "boiler" of the atmospheric engine is that part of the land and sea warmed above the temperature of the overlying air by

---

[1] The cross section of the solar beam constantly being intercepted by the earth is πR^2. R=radius of earth; averaging the energy in this beam over the entire surface of the earth, and taking the solar constant to be 2 g. cal. per cm.^{3} per min., we find that if the solar energy were spread uniformly over the whole earth at all times, each square centimeter would continually receive $2\frac{\pi R^2}{4\pi R^2}=.5$ g. cal. /min.; considering .37 of this to be reflected and scattered to space without ever taking any part in the thermodynamic processes of the atmosphere, we are left with .315 g. cal. per cm.^{2} per min., or .22 kw. /m.^{2} for the effective incoming energy; 2 per cent of this is 4.4 x 10^{-3} kw./m.^{2}, while the total dissipation is 5 x 10^{-3} kw./m.^{2}.