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SURFACE COOLING AND STREAMING IN SHALLOW FRESH AND SALT WATERS*

BY

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Experimental work with thermally unstable air and liquids (Mal, 1931; Graham, 1933; Chandra, 1937; and others) has shown that the convection "cells" formed vary with the amount of shear, which is introduced either by the flow of the fluid or by the movement of its boundaries. Changes in the flight tactics of free soaring gulls over the open ocean show that the pattern of the convectional up-flow within air moving over warmer water varies with the wind speed (Woodcock, 1940). Since the air over warmer sea water moves in a fashion in part comparable to the experimental findings, it was thought that some similar motion might be observed in the water itself.

While looking for possibly related convectional changes in surface waters under natural conditions, it has been found that the first few millimeters of water on the surface of shallow bays and ponds (salt and fresh) on Cape Cod are almost continuously colder than the subsurface water under average fall weather conditions. Associated with this cooled surface film, when winds are blowing, there is invariably found a small scale streaming (Fig. 33) in which the whole surface of the water is divided into a rapidly changing pattern of currents running in lines roughly parallel to the wind direction. These streams are usually about a centimeter across, with a constantly varying distance (usually just a few centimeters) between parallel lines of flow. The surface water between the lines moves transversely to converge in the lines, where it presumably sinks. Individual lines grow or die away within a few seconds time; sometimes converging upon other lines, sometimes diverging and disappearing. The water in the streams themselves moves down-wind much faster than the water between them, which suggests that they are an accumulation of water from the surface film which has been exposed to a maximum of wind drag. This small scale linear streaming is seen on the surface of large waves in the open sea, as well as in comparatively sheltered bays and ponds (where attending thermal instability has been measured) and, in the

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shallow water, it seems to supply a mechanism whereby cooled surface layers of water are drained off to lower depths.

One of the most outstanding features of this surface streaming is the rapidity of the transverse movement of the water as indicated by the lycopodium powder broadcast on the surface. When the powder is dusted over the water it moves into lines so quickly that, even in a moderate breeze, the eye can hardly detect the transition from random scattering to the linear pattern. The speed of this motion suggests that the first few millimeters of water are being drained off to lower depths very rapidly.

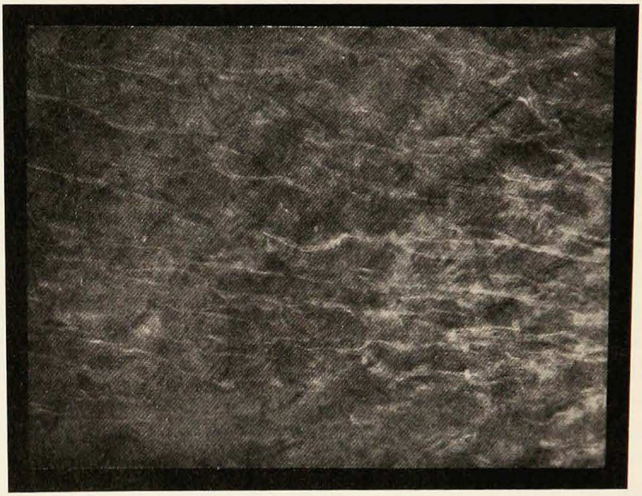

Figure 33. Surface streaming in a brackish pond, indicated by lycopodium powder.

Although the thermally unstable film on relatively open waters and the attending small scale streaming are not commonly recognized, experimental work in fluids by Rayleigh (1916), Phillips and Walker (1932), Mal (1931), and others has shown that thermal instability (introduced by heating below or cooling above), accompanied by sufficient shear, produces longitudinal strip-like convection cells extending in lines parallel to the direction of flow. In liquids they found that the motion was down in the lines and up between them.

Under natural conditions the cooled surface layer of sea water and lake water, plus the shear introduced by winds, apparently produces a patterned surface streaming comparable to the strip-like convection motions produced experimentally. Observations under natural conditions have not been made when there was no possibility of heat loss from the surface film, so there is no positive assurance that the streaming cannot occur in stable water under a wind-produced shear. However, Brunt (1937, p. 283) remarks that ". . . shear does not of itself facilitate the formation of vertical circulations" in unstable air. Whether or not shear facilitates the formation of vertical circulations in stable salt and fresh surface waters remains unknown.

Langmuir (1938) made measurements of large scale surface streaming (5 to 25 meters between "streaks") in relatively deep water on a lake, and referred to it as "wind induced." He found sinking water under the streaks and ascending water between them, and the slower moving surface water converged upon the lines transversely. He did not associate this motion with thermal instability, though he did say that during late fall "the descent of masses of denser water cooled by exposure on the surface" might accelerate it (p. 123).

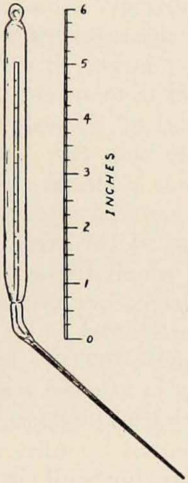

Figure 34. Thermometer used for making surface temperature measurements.

The similarity of the surface motion in the small streams to the surface motion in Langmuir's streaks suggests that they may have a common origin, especially when we consider that the smaller is often found superimposed upon the other. In both cases, when winds are blowing, the surface water between the lines moves to the right and left of the wind to converge in the lines, and the down-wind motion of the water in the lines is faster than the down-wind motion of the water between the lines. The experimental work in thermally unstable films indicates a need for both shear and instability for the formation of the strip-like lines of convergence. However, Langmuir's work on open water suggests that wind shear alone is enough. Perhaps the common occurrence of a rapidly produced unstable surface film on lakes and bays may serve to indicate a possible answer to the question raised, for it seems that this layer might supply the potential energy to drive the vertical circulations in Langmuir's "helical vortices" as well as in the experimental "cells."

Adney (1926) has demonstrated experimentally that the rate of solution of oxygen and nitrogen in de-aerated fresh and salt water is increased a great deal by vertical "streaming" due to surface cooling by evaporation. He found the resulting mixing more effective in salt water, which he said is due "largely if not wholly to the fact that in addition to the cooling effect of evaporation at the surface film, there is also that of concentration of the salts in solution" (p. 214). It seems reasonable to suppose that the surface cooling and streaming which is discussed here serves a similar purpose, under natural conditions, of carrying down oxygen and nitrogen saturated surface waters.

Variations in the spacings of the streams may prove useful as an indication of the depth to which the streams penetrate. In experimental treatment of the "strip" convection cells in unstable fluids, the horizontal dimensions are found to be twice the depth (or height) of the instability layer (Durst, 1932, p. 58). Casual observations of the distances between lines in surface waters on the open sea show that they vary from a few centimeters across up to 100 meters or more. Strip-like lines in air (indicated by mist rising from warm seas into cold air and by soaring gulls) show cell sizes varying from a few centimeters across up to several hundred meters.

An intensive study of the superficial surface water of seas and lakes seems justified, in view of the possible correlations between their various states of motion and temperature distribution, and the transfer of heat, momentum and gasses between the air and the water.

The following description of the methods and apparatus used so far will give the reader an idea of the preliminary nature of this first investigation and of some of the problems encountered. Also included is a table of data which shows the common occurrence of thermal instability in surface layers, and some of the conditions under which the surface cooling takes place.

A very sensitive Richter and Wiese mercurial thermometer (see Figs. 34 and 35) was used to measure the surface water temperatures. This thermometer has a bulb 1.5 mm. in outside diameter and 9 cm. long, and it is calibrated in degrees and tenths Centigrade. The small volume and diameter of the thermometer bulb made it possible to measure temperatures quickly and within small depth ranges. However, it was necessary to stop wave action as much as possible in order to use this instrument satisfactorily. For this purpose a box 60 cm. square with a depth of 30 cm. was used (see Fig. 35). The absence of the bottom in the box allowed free vertical movement to the water inside the box. The grooves in the supporting legs made it possible to adjust the box level so that the edge of the box projecting above the water offered a minimum of interference with the air flowing past and at the same time stopped wave action. Only small waves could be stopped in this way, so it was necessary to work near a windward shore (i. e. where the wind came from over nearby land) or during almost calm conditions. The average total depth of the water, where measurements were made, was about 70 cm. and at a distance of from 3 m. to 30 m. from the shore.

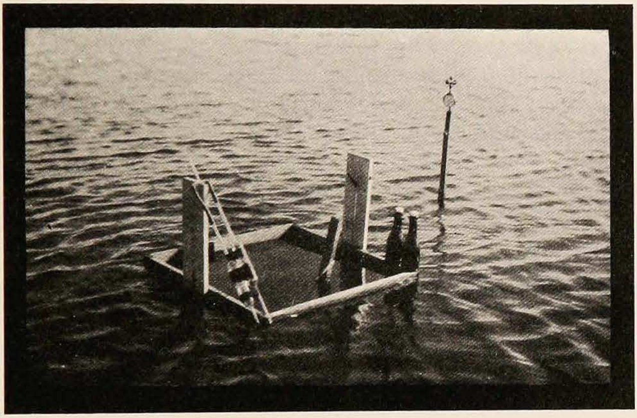

Figure 35. Wave damper in use.

Water samples for chlorinity determinations were taken from the surface and at 2 cm. depth with two pipettes lashed together so that their tips were 2 cm. apart vertically (see Fig. 35). The tip of the pipette sampling the surface was ground at an angle so that while drawing in water one could draw in at the same time a stream of air bubbles. This was done to be sure that the pipette tip was held as nearly as possible at the surface. Tests in the laboratory at a vapor pressure difference* of 15 mb., showed that any excessive evaporation

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* The saturation pressure of aqueous vapor over the sea water sample at water temperature – the aqueous vapor pressure at the temperature and relative humidity of the air in the laboratory.

due to this procedure was not measurable by the standard Knudsen method of chlorinity determination.

Wet and dry bulb measurements were made with a sling psychrometer; the thermometers of which are calibrated in whole degrees Fahrenheit. The readings were taken at about one meter above the surface of the water. Wind speed measurements were made at a height between 50 cm. and 100 cm. above the water (Fig. 35) with a single Casella anemometer. Correction for anemometer error has been applied to the readings.

Observations were made in a harbor where the salinity was about 30 °/₀₀, in a pond just above high tide level where the salinity was about 3 °/₀₀, and in an inland fresh water pond.

Table 1 shows all measurements tabulated according to increasing difference between the water temperatures at 3 mm. and at 20 mm. The first column gives the number of times temperatures were taken at the two levels (3 mm. and 20 mm.) and the figure in the third column is the average of the differences between these temperatures. Column two indicates whether the readings were made inside or outside of the wave damper. Saturation values of vapor pressure were taken from the Smithsonian Meteorological Tables (1933, table 79). Column four represents the saturation pressure of aqueous vapor at the water temperature at two cm. depth minus the aqueous vapor pressure at the temperature and the relative humidity of the air at one meter above the water. Column six lists the difference between the water temperature at one cm. below the surface and the air temperature at one meter above the surface.

The minimum depth (i. e. 3 mm.) at which temperature observations were made in the water is only roughly correct. In making readings in the surface film, the thermometer was adjusted manually so that there was always a layer of water visibly flowing over the top of the thermometer bulb. It is probable that the depth at which the surface temperatures were made varied from 2 mm. to 4 or 5 mm. depending upon the size of the small surface ripples. The 20 mm. level was determined by marking a centimeter scale on the stem of the thermometer; zero depth being at the level of the bulb of the thermometer.

The lack of a clear correlation between the degree of surface cooling (as expressed in the values in column 3) and the cooling factors measured (columns 4, 5 and 6) is attributed in part to inaccuracies in the depth of the thermometer bulb in making surface film temperature readings; also to unknown factors such as possible variations in the rate of sinking of the cooled water with different wind speeds; differences between the rates of sinking of the cooled water inside and outside of the box; variations in solar radiation; variations in radiation absorption and emission of the surface water itself; and the possible influence of different amounts of particulate matter in the water on some of these factors.

In the beginning of this work it was thought necessary to make many chlorinity determinations in order to prove that the colder surface film was not also fresher, hence stable. However, when comparable layers of colder water were found on sea water, on brackish water and on fresh water during the same day under approximately the same weather conditions, it was thought unnecessary to continue the chlorinity titrations. Several times, during the observations in salt water, samples were taken as previously described. These samples showed no marked difference between the salinity at the surface and that at 2 cm., though most of the time the surface proved to be slightly more saline. Tests were made with samples drawn from outside the box as well as inside, though of course samples from outside the box could be taken only near a windward shore or during almost calm conditions.

Temperatures taken inside and outside of the wave damping box, when conditions permitted, showed that the cooling of the surface water was not confined to the inside of the box, but was general over the water surface outside as well. The curved lines connecting the "ins" and "outs" in column 2 indicate series of observations which were made inside and outside of the box under otherwise approximately the same conditions. These transitions were made in fresh as well as salt water. It is not suggested here that the wave damping box does not affect the enclosed water, but merely that the cooled surface layer which is measured in it is roughly comparable in depth and degree to the cooled surface layer on the outside, under the indicated weather and other conditions.

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TABLE I

TEMPERATURE READINGS AT 3 MILLIMETERS AND AT 20 MILLIMETERS. OBSERVATIONS ARRANGED IN ORDER OF INCREASING THERMAL INSTABILITY

1	2	3	4	5	6	7	8	9	10
Number of readings	*Inside or outside of box*	*Av.* $T_{3\,mm.}$ *−Av.* $T_{20\,mm.}$ °*C*	*Vapor Press. mb.*	*Wind m sec*$^{-1}$	$T_W - T_A$	*Cloudiness 1–4*	*Water*	*Time E.S.T.*	*Date 1940*
15	in	+0.1	0.8	4.7	−0.7	hazy	Salt	1040	Oct. 15
11	out	0.0	3.1	4.7	-1.0^5	1	Brackish	1150	Oct. 15
27	out	−0.1	1.5	1.3	$+0.3^5$	4	Salt	1515	Oct. 8
9	out	−0.2	3.4	4.4	0.1	hazy	Brackish	1455	Oct. 13
22	in	−0.2	4.6	4.2	0.0	2	Salt	1200	Oct. 6
14	in	−0.2	7.0	2.4	2.7	2–3	Salt	1015	Sept. 12
10	in	−0.3	5.4	3.4	0.8	0	Salt	0855	Sept. 28
4	out	−0.3	6.0	5.1	1.8	4	Salt	1540	Oct. 2
8	out	−0.3	13.0	0.7	0.7	0	Fresh	1150	Oct. 14
7	in	−0.3	5.9	3.6	2.7	0	Brackish	0950	Oct. 19
18	in	−0.3	6.0	5.1	1.8	4	Salt	1500	Oct. 2
13	in	−0.3	7.7	4.8	1.0	2	Brackish	1215	Oct. 18
39	in	−0.3	6.2	1.7	0.0	2	Brackish	0900	Sept. 19
10	in	−0.3	9.3	3.2	2.1	1	Salt	1135	Oct. 10
8	out	−0.3	9.3	3.2	2.1	1	Salt	1155	Oct. 10
22	in	−0.3	8.0	2.7	1.1	0	Salt	1105	Sept. 27
13	in	−0.4	13.0	0.7	0.7	0	Fresh	1210	Oct. 14
9	in	−0.4	3.6	4.1	1.1	hazy	Brackish	1620	Oct. 12
5	out	−0.4	13.0	0.7	0.7	0	Fresh	1220	Oct. 14
25	in	−0.4	8.0	2.0	1.7	0	Salt	0920	Sept. 13
8	in	−0.4	6.2	1.8	0.7	1	Salt	0650	Sept. 18
20	in	−0.4	7.3	3.9	1.8	0	Salt	0900	Sept. 27
7	in	−0.5	8.6	4.9	4.9	0	Salt	1115	Oct. 16
7	out	−0.5	8.9	3.3	1.4	4	Salt	1300	Oct. 9
20	in	−0.5	9.6	2.1	0.0	0	Salt	0950	Oct. 14
10	in	−0.5	13.1	1.5	10.0	0	Fresh	1140	Oct. 19
5	in	−0.5	8.9	3.3	1.4	4	Salt	1245	Oct. 9
11	in	−0.6	11.0	2.1	5.9	1	Fresh	1120	Oct. 18
5	out	−0.6	11.0	1.0	13.4	2	Fresh	2310	Oct. 10
7	in	−0.6	9.3	0.8	4.2	1	Fresh	1615	Oct. 10
23	out	−0.6	9.3	0.8	4.2	1	Fresh	1540	Oct. 10
21	in	−0.7	8.7	2.5	1.8	0	Brackish	0750	Sept. 23
10	in	−0.7	9.0	6.6	3.9	0	Brackish	0940	Sept. 26
12	out	−0.7	13.1	0.9	10.0	0	Fresh	1055	Oct. 19
12	in	−0.7	8.4	3.6	2.9	0	Salt	1025	Oct. 18
1	out	−0.8	12.7	0.8	11.9	0	Fresh	2130	Sept. 29
6	out	−1.0	9.9	0.9	9.7	1	Fresh	2230	Oct. 15