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SURFACE MOTION OF WATER INDUCED BY WIND

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ON August 7, 1927, when about 600 miles from New York on an Atlantic crossing to England I noticed that there were large quantities of floating seaweed, most of which was arranged in parallel lines with a somewhat irregular spacing ranging from 100 to 200 meters. These lines, parallel to the wind direction, which I shall call streaks, often had lengths as great as 500 m. Between these larger streaks, which contained vast quantities of seaweed forming continuous bands 2 to 6 m wide, there were smaller streaks which were made up of detached masses of seaweed along nearly straight lines. At this time the wind was from the north with a velocity of approximately 10 m/sec (22 miles/hr) and the waves roughly 4 m high.

A day later the waves were larger and the streaks of seaweed were still abundant. On the afternoon of this day a sudden change of wind direction occurred (of about 90°); within 20 min all the seaweed was arranged in new streaks parallel to the new wind direction, although the waves continued to move in the old direction.

It was clearly not cohesion between masses of seaweed that held them together in the streaks. At that time it seemed to me that the only reasonable hypothesis was that the seaweed accumulated in streaks because of transverse surface currents converging toward the streaks. The water in these converging currents descends under these streaks. Between the streaks rising currents, upon reaching the surface, flow out laterally toward the streaks.

The action of the wind on the water sets up longitudinal surface currents in the direction of the wind. The effect of the wind is thus to produce a series of alternating right and left helical vortices in the water having horizontal axes parallel to the wind. If we face in the direction toward which the wind blows we should observe that the water between two adjacent streaks forms a pair of vortices: The water on the right-hand side of the vertical plane halfway between the streaks has a clockwise rotation (right helix), that on the left a counter clockwise rotation (left helix).

During the years 1928 and 1929 I made a large number of experiments on Lake George, near Bolton, New York to test this hypothesis of helical motion and to make observations on other water currents produced by wind.

This lake and the location chosen have many advantages for such studies. The depth is about 50 m and the water so clear that white objects at 8 m depth can be seen. Since the lake lies between two parallel mountain ridges, rising from 300 to 700 m above the lake surface, the wind usually dies down completely at night and during the day blows only in one of two directions (southwest or northeast). Most of the experiments were made at a point about 1 km from the nearest land with a clear fetch of from 4 to 7 km in the direction from which the wind was coming.

With wind velocities of 4 m/sec or more, streaks become visible because of the accumulation of traces of oil from motor boats, floating leaves or bubbles. Streaks are usually much more prominent in rivers contaminated by industrial oils or by organic matter from swamps.

A gram of oleic acid or olive oil applied to the surface of the lake spreads out to form a monolayer, covering about 1,000 square meters, and this area, because of the damping and elimination of capillary ripples, is sharply distinguishable from the surrounding uncontaminated surface by its smoother surface. After the oil has spread to its maximum area, however, it soon becomes invisible and no longer retards the formation of ripples. Oxidized lubricating oil after spreading to its maximum area leaves a still visible film which accumulates in the streaks and is thus more effective in rendering them visible.

In the autumn floating leaves are particularly useful to show the downward motion of the water under the streaks, for it can be seen from a motor boat brought over a streak that a large number of leaves are gradually carried down and disappear from sight under the streaks. The number of such descending leaves seems to be far too great to be accounted for by leaves which have gradually become denser than water. Some of the leaves placed on the water halfway between streaks reach the streaks, 6 to 10 m away, in about 5 min.

In November, 1929, further study of those motions was made by pouring 50 ml of a 2 per cent. fluorescein solution into the water from a bottle on the end of a bamboo pole. The motor boat was then moved away a suitable distance to prevent disturbance of the surface, and after definite time intervals the boat was brought over the place to observe the motion. It was found that when fluorescein was introduced at the center of a well-defined streak with a wind velocity of 6 m/sec it gradually moved downwards, taking 5 min to go 4 to 6 m. This corresponds to a vertical motion of about 1.6 cm/sec. The horizontal motion of the water on the surface was 15 cm/sec and 10 cm/sec at a depth of 3 m.

When fluorescein was similarly placed in the clear water between the two well-defined streaks it spread out irregularly over the surface and gradually moved toward the two neighboring streaks. The motion could not be followed as far as the streaks, as the fluorescein gradually became very diffuse, showing that although the motion was very slow it was very turbulent.

In other experiments a white cord 2 mm in diameter having small fragments of cork along its length at 10 cm intervals was floated on the surface of the lake in a straight line perpendicular to the wind direction. After 10 min this cord had developed well-defined waves, being displaced forward in the direction of the wind in the streaks and backward in the spaces between them, indicating that the forward velocity of the water was greater in the streaks than in the spaces between them. The water rising from deeper levels has a low forward velocity, but this increases steadily through the action of the wind so that when the water reaches the streak it has its maximum velocity.

A few measurements were made of the vertical components of motion by means of a large square sheet of aluminum suspended in a horizontal plane from a small lamp bulb so weighted as to give practically zero buoyancy. This device was calibrated in quiet water to determine the rate of descent or ascent when small weights were added or removed. This apparatus was lowered a few meters below the surface and attached by a light horizontal cord, 2 m long, to a lead weight suspended at an equal depth from a bulb floating on the surface. In this way the tendency of the aluminum plate to rise or fall could be observed without fearing the loss of the apparatus and without subjecting it to appreciable horizontal or vertical forces. In the streaks it was thus found that two meters below the surface there were descending currents of about 2 to 3 cm/sec and rising currents of from 1 to 1.5 cm/sec midway between adjacent streaks. This method appears particularly promising for future investigations.

To measure currents in the lake set up by wind, at depths from 5 to 30 m, some umbrellas, 60 cm diameter, were tilted 90° from their normal positions and suspended, with proper counter weights to hold them in this position, by light cords from small lamp bulbs floating on the surface. A painted bulb floating on the surface attached to a lead weight resting on the bottom served as a marker buoy. By placing umbrellas at different depths close to the marker buoy and observing the motion of their floats the velocities and directions of the currents at different depths could be determined. The distances traversed by the floats were measured by the time required to cover the distance from the marker buoy to the float by a motor boat moving at a known speed.

In experiments on October 6, 1929, it was found that a "velocity indicator" at depths less than 5 m gradually drifted under a streak, but one suspended 10 m deep had no tendency to do so. Perhaps at a greater depth the indicator would move into a position midway between streaks, since there must be horizontal currents which converge under the rising currents between the streaks.

Between September, 1926, and August, 1929, on 28 separate days well distributed throughout the years, I measured the water temperatures at different depths (0 to 58 m) with an electric resistance thermometer.

When the lake freezes over, usually about January 10, the temperature at depths from 3 to 58 m is very uniform at about 1.2° C. By the end of March the temperature at the bottom rises to about 2.2°; but the increments are smaller at lesser depths.

This warming is due to the absorption of the sun's rays which penetrate the ice. The warmed water, being denser, sinks to the bottom and slowly flows to the deeper parts of the lake. Measurements have shown that in parts of the lake which have a depth of 5 to 10 m there is often a layer of warm water of 3 to 4° C. of 1 m thickness close to the bottom.

By the time the ice breaks up, about the middle of April, the temperature is again rather uniform, and is about 3° C., except for a thin layer of cold water under the ice. The rapidity of the breaking up and disappearance of the ice, which often takes only 10 to 20 hrs, is due to the warm underlying water stirred up by the wind as patches of open water are formed.

After the ice breaks up and while the water is within 1° or 2° of the temperature which gives maximum density (4° C.), the temperature on windy days is the same at all depths and rises at a rate of about 4° per month. At this time of the spring overturn, however, the temperatures on quiet days are especially non-uniform over different parts of the lake. In shallow places the temperature rises far more rapidly than in deep parts, for there are then no appreciable density differences to equalize the temperatures.

In 1926 the maximum temperature at 58 m was 9.6°, which occurred about November 10. In 1927 the temperature at 58 m depth rose at a gradually decreasing rate from 7° on June 1 to a maximum of 10° on November 15. During 1928 on June 1 the temperature at the bottom was only 5.3° and rose at a steady rate of only 0.7° per month until August 1. On October 20 the bottom temperature was 8.4°, which had been reached the previous year early in July. In 1929 a bottom temperature of 8.4° was reached as early as June 15, and it was 9.2 on July 6.

Examination of the temperature-distribution curves at different depths shows that between May and November a few quiet sunny days cause the development of a nearly uniform temperature gradient of as much as 0.7°/m which may extend to 10 or 15 m depth. A windy day causes the temperature gradient to disappear down to a certain depth, but produces a very sharp temperature gradient (as much as 5°/m) at the lower limit of the isothermal layer (thermocline). After alternating warm and windy periods the topmost 15 m of water may contain several of these isothermal layers (or epilimnions) with intervening thermoclines. The most marked gradients have always been observed at depths between 10 and 15 m.

I believe this represents the maximum depth to which the helical vortices descend with the wind velocities ordinarily occurring during the summer months.

When the surface temperature falls during the autumn the cooled water sinks to the level of water already of similar temperature. Thus the depth of the epilimnion increases during late September and October and reaches the bottom of the lake and produces the maximum bottom temperature about the middle of November. During this cooling the thermocline disappears, for the gradient below the bottom of the epilimnion is usually less than 0.3°/m.

Measurements with the velocity indicators have shown that longitudinal currents set up by wind extend to very different depths at different seasons. On June 20, 1929, at 9:00 A.M. when there was a 2 m thick, sharply defined, isothermal layer of water at 22°, overlying 16° water, a wind having an estimated velocity of 2 to 3 m/sec set the whole epilimnion into motion at 30 cm/sec. This lasted all day and continued for a couple of hours after the wind died down in the evening. The epilimnion was still 22° but had increased in depth to over 4 m.

Observations showed that after windless nights the water velocities at various depths were usually of the order of 2 to 3 cm/sec (rarely as high as 6) and had different directions at different depths. Within less than an hour after a wind of 4 to 8 m/sec springs up the water near the surface is set in motion parallel to the wind direction with velocities of 10 to 20 (rarely as high as 30), but the velocity and direction of the currents at depths greater than 10 m usually remains unchanged for at least 6 hours.

On July 27, 1929, the epilimnion (21.8°) had a depth of 6 m; the temperature gradient in the thermocline was 1.0°/m to a depth of 15 m (12.5°). Below that, in the hypolimnion the gradient was only 0.07°/m. After a windless night a southwesterly breeze of 2 m/sec started about 8: 00 A.M. (E.S.T.) and gradually increased to a velocity of 6 m/sec at noon, reached a maximum of 7m/sec at 2: 00 P.M. and fell to 5 at 4: 00 P.M. and to 1.5 at 7: 00 P.M.

At a depth of 10 m the velocity during the whole afternoon was about 5 cm/sec in a direction 90° to the left of the wind direction, but at depths from 12 to 15 m the velocity was about 1 cm/sec in a direction which was 30° to the right of the wind. At depths less than 6 m the motion of the water was parallel to the wind. The momentum delivered to the water by the force of the wind must therefore be distributed within a layer 6 m deep.

At 12: 30 P.M. the velocity of the surface was 20 cm/sec, and this rose to 24 at 3: 20 and then increased slowly to 27 at 5: 00 and decreased to 15 at 7: 00 P.M. and was still 14 at 7: 30 P.M. 20 min after the wind had died down completely. At a depth of 3 m the velocity was 14 at 4: 00 P.M. and 10 cm at 7: 30 P.M. At 6 m it was 9 at 4: 30 and decreased to 7 at 6: 00 P.M. and to 5 at 7: 0 P.M. The velocities were also frequently measured at 1.3 m depth and were approximately halfway between those observed at depths of 0 and 3 m.

A rough estimate of the increase of momentum of the water which was caused by the wind was made by integrating $(v - v_0)dx$ from the surface down to a depth $x = 600$ cm, where the velocity remained approximately 6 during the day. The momentum/cm^2 of lake surface rose from about 6,000 (g. cm^{-1} sec^{-1}) at 4: 00 P.M. to a maximum of about 7,000 at 5: 00 P.M. and then slowly fell to 3,000 at 7: 30 P.M. The maximum occurred about 3 hours after the maximum wind velocity and at a time when the wind velocity was only half its maximum velocity.

If we consider an infinite body of water the momentum per unit area due to the wind should be equal to $\int F dt$ where F is the horizontal force per unit area exerted by the wind. To estimate the order of magnitude of F we may assume that a momentum of 7,000 was delivered by wind acting for 3 hrs and so get $F = 0.65$ dynes/cm for a wind velocity of 5 m/sec (measured 2 m above the lake surface).

It is very evident from the measurements that the momentum does not increase steadily in proportion to $\int F dt$. There must then be some mechanism by which the momentum is transferred to the shores of the lake. A current of 10 cm/sec is only 0.36 km/hr, so that with a wind sweep of 5 km it should take 14 hrs for the effect of the shores to make themselves felt.

An unusual opportunity to study the effect of wind on the momentum of the water occurred on August 2, 1929, when there was a sudden reversal in the wind direction. At 9: 00 A.M. on this day there was no wind and the surface water had a velocity of 2.9 cm/sec. By 10: 00 A.M. there was a wind of 5.6 m/sec and the azimuth of the wind direction was 140°. The surface water was then moving 11 cm/sec (145°) and at 3 m depth the velocity was 6.3 (225°). At 12: 20 the wind had increased to 8 m/sec, 120°, and at 2: 50 P.M. had fallen to 3.5 m/sec, (90°), and the surface water was then moving 22 cm/sec in the same direction as the wind.

At 2: 50 P.M. the wind suddenly reversed its direction. At 2: 55 P.M. the wind velocity was 4, and the direction was 240°. The velocity decreased to 3.3 at 3: 30 and rose to 7.0 at 3: 45, the direction staying constant at 240°.

The surface water had a velocity of 13 at 3: 12 P.M. and 18.5 at 3: 35, the direction being 210° at both times. At 3: 12 the velocity was 5.3 (185°) at 3 m depth and at 3: 35 it was 3.2 (240°) at 6 m depth. Using these rather meager data, but assuming that the depth distribution curves were similar to those found on other occasions, I estimate that at 2: 50 P.M. the momentum per cm^2 was about 6,000 in a direction at 90° and it was 4,000 (200°) at 3: 12 and 6,500 (220°) at 3: 35. This would mean a change of momentum of 8,300 in the first 22 min after the wind reversal and a further change of 3,000 during the next 23 min. A change of 8,300 in 22 min means $F = 6.3$ dynes/cm^2, a value 10 times as great as given by the data of July 27, although the wind velocity was lower than on that occasion. The rate of increase of momentum, however, rapidly decreased during the next 20 min.

On August 4 after 28 hrs of strong wind, 8 to 15 m/sec, of steady direction, the surface water had a velocity of 24 cm/sec, while the wind velocity ranged from 8 to 10 m/sec. This is a much lower velocity than was produced in June by a wind of only 2 to 3 m/sec.

On August 24 after 8 hrs of strong northeast wind the water velocities were 30 on the surface, 20 at 2.1 m and 19 cm/sec at 4.6 m depth, while the wind velocity was 11 m/sec 2 m above the surface.

Temperature measurements were made on the morning of August 25 after this storm had died down. The epilimnion (19.9°) had a depth of 10.1 m and the gradient in the thermocline was 1.4°/m to a depth of 14.6 m.

The velocities observed on September 2, 1929, with an isothermal layer (20.2°) of 11.5 m showed several interesting features. There was no wind until 9: 30 A.M. and the wind velocity rose to 3.5 at 10: 30, 5.0 at 11, 6.5 at noon, 9 at 1: 00 P.M.; the velocity then decreased slowly to 5 at 3: 00 P.M. Between 3: 00 and 5: 00 P.M. the wind was somewhat variable but averaged 5 m/sec. It then decreased gradually to 3 at 6:00 P.M.

The velocity at 0.2 m depth was 11 cm/sec at 11:00, reached a maximum of 16 at noon, and decreased to 14 at 4:00 P.M. to 11 at 5:00 P.M. and to 4 at 6:00 P.M., although there was still a wind velocity of 3 m/sec.

At a depth of 1.3 m the velocity was only about 1.5 cm/sec less than at 20 cm. At 3 m depth the velocities decreased gradually from 10 cm at noon to 2 cm at 6:00 P.M. At 6 m the velocities ranged from 4 to 2.

The marked decrease in water velocity during the afternoon after 3:00 P.M. in spite of a nearly steady wind is in striking contrast to the observations earlier in the year in which currents were observed to continue with little decrease for hours after the wind died down. The falling off of velocities in September is undoubtedly due to the cooling of the isothermal layer by radiation into a clear afternoon sky which induces instability and causes the surface water to sink to the bottom of the isothermal layer, carrying its longitudinal momentum with it.

There is thus every reason to believe that the helical vortices set up by the wind extend to the depth of the epilimnion but do not penetrate through the thermocline. The surface of the lake is a free surface in the sense that there is no frictional force to restrain horizontal motion. The thermocline, however, is practically a fixed surface like that of a lake bottom, for it is not set in motion by the overlying layers. The longitudinal and transverse velocities of the water in the vortices have their maximum values at the surface and gradually decrease to zero at the thermocline. Thus the vortices are unsymmetrical in respect to depth, being increasingly diffuse at greater depths.

Observations of the streaks at different seasons show that in May and June, especially after quiet days when the epilimnion is shallow or is not strictly isothermal, the streaks are close together (5 to 10 m), while in October and November well-defined streaks usually have spacings of 15 to 25 m. The spacings are presumably approximately proportional to the depths to which they penetrate. Quantitative measurements of the streak spacings are difficult because between the well-defined streaks there are numerous smaller and less well-defined streaks. Just as large waves have smaller waves upon them, it appears that the surfaces of the larger vortices contain smaller and shallower vortices. The patterns of streaks on the lake surface are slowly changing; some growing, others dying out. On some days the streaks are much more regular than on others.

During the spring and fall overturns in April and early December when the whole lake is isothermal, the vortices may extend to the bottom of the lake, but they would then be very diffuse in their lower portions. On clear, cold windy nights in October the lower parts of the vortices should have their greatest velocities, since large-scale turbulence would then be stimulated by the descent of masses of denser water cooled by exposure on the surface at temperatures sufficiently above 4° C. to give a reasonably large coefficient of thermal expansion.

The helical vortices set up by wind apparently constitute the essential mechanism by which the epilimnion is produced. The currents thus set up at the bottom of the epilimnion may sweep off the upper part of the thermocline, making it thin and of increased gradient.

I have never observed in Lake George any reverse flow in the lower part of the epilimnion, but have frequently found an increase in the depth of the epilimnion at one end of the lake and a corresponding decrease at the other due to the wind. The return flow apparently usually takes place slowly at night and is not accompanied by the turbulence associated with the helical vortices and so does not give vertical velocity components which alone can give thermal transport to the deeper layers.

I have not made any search of the literature on this subject, but conversations with many students of turbulent flow and oceanography have indicated that the helical vortices induced by wind are not commonly recognized.

Professor C. Harold Berry has called my attention to a paper by James Thomson[1] in which he explains calm lines seen on a rippled sea" as the lines of convergence of surface currents. There is no suggestion, however, that the streaks seen with strong winds are caused in this way.

H. Jeffries[2] shows that there must be transverse circulation in streams with straight channels. He draws this conclusion from the fact that the greatest longitudinal velocity is observed at a certain depth below the surface near the middle of the stream. There are thus descending currents near the center and rising currents near the shores. Jeffries was not able to explain these transverse currents on the basis of hydrodynamical theory. Undoubtedly the mechanism is similar to that which causes helical vortices on the surfaces of lakes.

In 1933 I made numerous studies of the growth of waves under the influence of wind. I have found that the momentum carried by the waves and delivered to the shore as a radiation pressure accounts satisfactorily for the fact that the momentum of the water increases rapidly at first (before the waves have had time to build up) and then remains nearly constant. I expect to give an account of this work in another publication.

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[1] *Phil. Mag.*, 4th series, 24: 247, 1862.

[2] *Proc. Camb. Phil. Soc.*, 25: 20, 1929.