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Hydrodynamics in Some Arctic Lakes

CHARLES E. CARSON AND KEITH M. HUSSEY[1]

Abstract. Two hypotheses concerning wind-driven current systems in Alaska's oriented lakes are discussed. The first describes end-currents in the lakes returning upwind due to a hydrostatic pressure gradient on the downwind side. The second describes end-currents flowing in a windward direction and being related to the angle at which the waves approach the shoreline near the ends. These hypotheses are evaluated in the light of recent field work designed to test them.

The purpose of this paper is to report on the field tests of two hypotheses about wind-driven current systems in Alaska's oriented lakes.

The oriented lakes are developed on the low tundra surface of the Arctic Coastal Plain of Alaska (Figure 1). They are sub-elliptical to sub-rectangular in shape, have a length-width ratio of the order of 3:1 to 4:1, are generally less than 10 feet deep, and have their long dimensions oriented 10-15 degrees west of true north. In the vicinity of Point Barrow the lakes are commonly 1 mile to 2 miles long. Lakes and drained lake basins dot the monotonous expanse of the Arctic Coastal Plain by the tens of thousands so that the aspect from the air is quite spectacular.

Oriented lakes have been the object of considerable study and speculation (Johnson, 1944). The Alaskan lakes are no exception. Black and Barksdale (1949), Livingstone (1954), Rex (1958), Rosenfeld and Hussey (1958), Carson and Hussey (1959), and others have considered this problem. Of several proposed interpretations of lake orientation, two have emphasized the possibility of differential scouring by wind-generated currents. These proposals were put forward by Livingstone (1954) and Rex (1958). Carson and Hussey (1959) reported some current measurements and generally questioned the effect currents alone might have on orientation. Additional current measurements have made it possible essentially to deny the mechanism of one hypothesis but partially to confirm that of the other. What follows is a description of the mechanisms postulated in the two hypotheses and the results of measurements made to determine if these mechanisms actually exist.

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part of it for Government purposes. The assistance of the Director and staff of the Arctic Research Laboratory, ONR, is gratefully acknowledged.

Figure 1. Oblique aerial photo showing a view looking south on the lake-covered Arctic Coastal Plain southwest of Point Barrow, Alaska.

LIVINGSTONE'S HYPOTHESIS

In his study of the lakes Livingstone (1954) assumed that the lakes are still in close balance with those forces that produced them. The logical consequence of this premise is that the orienting mechanism should be detectable at the present time.

Livingstone gave careful consideration to the environment of the lakes in order to determine what the significant parameters might be. Of these, two impressed him as being most important. The first was that the ice-choked permafrost in which lake basins are developed enables the mechanisms of erosion and thaw to render the shorelines very mobile. If the mechanism of erosion which produces shoreline mobility were to occur in a preferred manner oriented lakes would result. The second parameter recognized by Livingstone was the relatively bimodal nature of the prevailing winds. During the summer these winds may prevail from several days to a week in the 10-30 mph range from one of two fairly narrow sectors of the compass, ENE and WSW (Figure 2). Livingstone reasoned that these winds could create a system of hydrodynamics with zones of maximum erosive power that would be a function of prevailing wind directions. As the prevailing winds are almost perpendicular to the trend of the long axes of the lakes, it was assumed that the zones of maximum erosive power of any circulation set up must occur at the north and south ends of the lakes. Livingstone then hypoth-

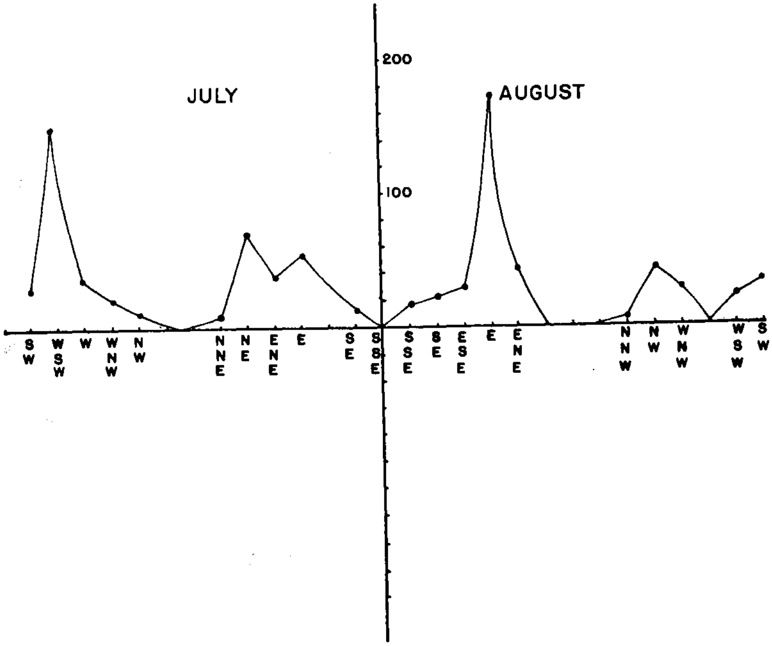

Figure 2. Graph showing the bimodal nature of the winds at Point Barrow, Alaska. The vertical axis reads in mph summed. The data plotted are based on U. S. Weather Bureau records for the months of July and August, 1959.

esized, on the basis of what was known of longshore currents, that water drifting under wind stress to the downwind, or leeward, shore would tend to return to the upwind (windward) side of the lake in the form of longshore currents. These currents would flow parallel to the downwind shore and attain maximum velocity as they swept windward around the ends. The idealized deductive system designed to describe this hypothetical mechanism, and the diagram to illustrate it are as follows:

Livingstone considered a small circular lake subjected to a wind of uniform velocity and direction. Under these circumstances the water would be drifted to the downwind shore, the rate of transport to a point A on the downwind shore depending upon the average velocity of the water arriving at A. This in turn would depend on the width of the lake and also upon the acceleration. Figure 3, a modified version of Livingstone's original figure, indicates the configuration used to illustrate his mathematical representation of what he proposed the actual relations to be. These relations are as follows:

$$2s = u_a t$$

$$= \frac{at^2}{a} \quad (\text{because } u_a = \frac{at}{2})$$

$$t = \sqrt{\frac{4s}{a}}$$

Substituting this value of t in $u_a = \frac{at}{2}$

$$u_a = \frac{a\sqrt{\frac{4s}{a}}}{2}$$

$$= \sqrt{as}$$

where u_a is the average velocity, a the acceleration due to wind force, t the time a water particle takes to cross the lake, and s is half the distance across the lake in the direction of the wind at point A. The total amount of water arriving per unit time at any point on the downwind shore is:

$$t'\sqrt{as}$$

where t′ is a dimension constant with a numerical value of one in the cgs system.

The amount of water arriving at the downwind shore depends upon s, and therefore the water will pile up in differing amounts along this shore creating a hydrostatic pressure difference between any two adjacent points, A′ and A. The pressure gradient will tend to accelerate the water over the interval A′ to A at a rate depending on the steepness of the gradient and g, the acceleration due to gravity:

$$\text{acceleration} = g\frac{d(t'\sqrt{as})}{dx}$$

where x is the distance of A from the center of the lake in a direction normal to the wind. By differentiation:

$$\frac{t'\sqrt{a}}{2\sqrt{s}} \quad \frac{ds}{dx}$$

$$= \frac{t' \text{ x } \sqrt{a}}{2\sqrt{s}} \text{ because } \frac{ds}{dx} = \frac{x}{s}\text{, the slope of the tangent at A.}$$

The acceleration producing the longshore current from A′ to A is, according to the above, greater near the ends of the lake than on the downwind side. However, as the current sweeps around the ends of the lake it will tend to be reduced by the opposing wind force. The retardation depends upon the ratio between the component of longshore velocity directly opposed to the wind force and the total longshore velocity, that is, $\frac{s}{y}$ or $\frac{x}{r}$, and also upon the accelerating effect of the wind force in the following way:

$$\text{negative acceleration} = \frac{ax}{r}$$

The net acceleration, N, of the longshore current would be the difference between the accelerating and the retarding forces,

$$N = \frac{gt'\sqrt{x}\quad a}{2s\sqrt{s}} - \frac{ax}{r}$$

$$= \frac{gt'\sqrt{r^2-s^2}\sqrt{a}}{2s\sqrt{s}} - \frac{a\sqrt{r^2-s^2}}{r}$$

If s is equal to r as on the extreme downwind side of the lake, N becomes zero. If we let s equal zero, as it does at the ends of the lake, N becomes infinite.

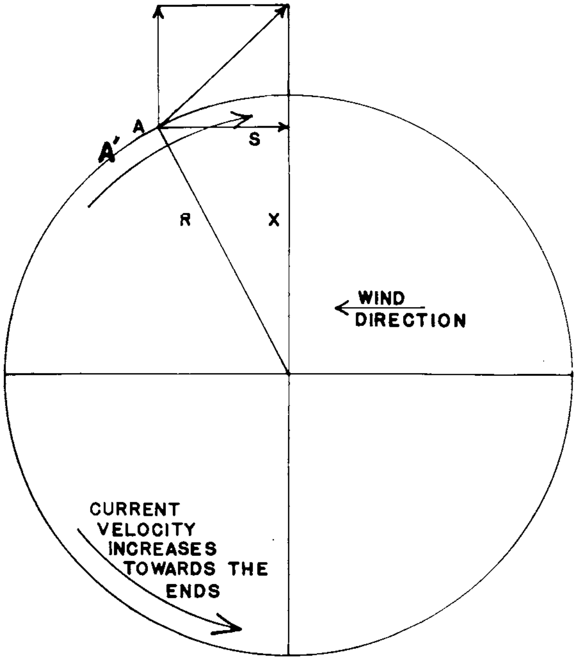

Figure 3. Diagram modified from Livingstone (1954).

Livingstone pointed out that infinite net acceleration is not obtainable due to imperfections in the circularity of any lake in nature and the limited amount of water involved. However, he felt that obviously, according to the above system, longshore currents would have a higher velocity at the ends than elsewhere. Livingstone also makes it clear that his scheme is a first approximation only and does not take into consideration many factors. Nevertheless, he thought it likely that currents in the oriented lakes should obey the predictions of the theory rather closely.

THE HYPOTHESIS OF REX

Rex (1958) assumed essentially the same premise as did Livingstone, namely, that the lakes are still in close balance with the forces that produced them. He also emphasized the same two parameters—the high potential mobility of shorelines and the effect of prevailing winds. From a careful examination of the literature on experimental and theoretical studies of currents in the surf and near shore zones Rex concluded that under the strong prevailing winds on the Arctic Coastal Plain circulation systems would be set up in the lakes which would feature a zone of maximum littoral drift, or current, in the transitional area between the downwind and end shores.

Citing the work of Johnson (1950), Saville (1950), and Bruun (1954), Rex noted that the littoral drift of the downwind shore had been described by a sine function where maximum drift occurs at $\propto_0 = 30°$ for a straight beach (Saville) and $\propto_0 = 50°$ for a curved beach (Bruun) where $\propto_0$ is the angle between the wave orthogonals and the normal to the shoreline (Figure 4A). The nodal point of littoral drift, $\propto_0 = 0°$, is the zone of minimum transport at the center of the downwind shore. According to Bruun (1954) the equilibrium shape for a shoreline of finite length composed of easily moved material is a cycloid the equations of which are:

$$x - \frac{A}{K}\left(\frac{\sin 2\propto}{4} + \frac{\propto_0}{2}\right)$$

$$0 \leq \propto_0 \leq \frac{\pi}{2}$$

$$y - \frac{A}{K}\left(\frac{\sin^2 \propto_0}{2}\right)$$

where k is a constant, A can be identified as the wave-effect, and $\propto_0$ is the deep water of the waves. The diameter of the corresponding circle is $\frac{A.}{2k}$

Rex pointed out that inspection of actual bays and lagoons where waves have dominant directionality shows a minor departure from the predicted equilibrium form for angles of $\alpha_0 = 50°$ with a sharper shoreline curvature in this range (Bruun, 1954). This deviation from expectation was thought to be better understood if one considers the wave orthogonals as not uni-directional, but rather as an array from one sector. Rex felt that a shift of wind direction of as much as 45° would cause an almost proportionate shift of the nodal point, but the zone of maximum littoral drift would at the same time show practically no change. Because of the very small shift of the zone of maximum erosion with moderate shifting of winds, there should be a concentration of erosive action in small zones at $\alpha_0 = 50°$ and the wave equilibrium shape should change from a cycloid to a more squared configuration (Figure 4B). Rex further emphasized that this squaring effect is often evident in the oriented lakes of the Arctic Coastal Plain (See Figure 1).

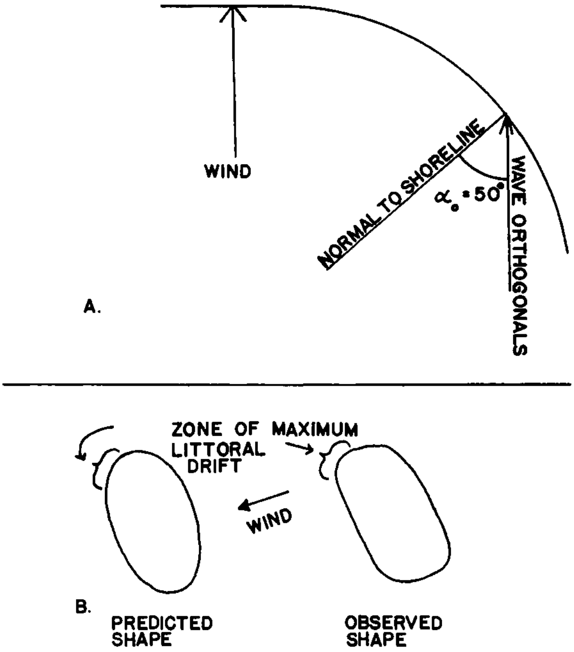

Figure 4. A. Diagram illustrating the zone of maximum littoral drift—where $\alpha_0 = 50°$. B. Illustration of the observed difference in actual shape from predicted shape.

Field Tests

During the 1958 and 1959 field seasons, studies of the circulation systems in the lakes near Point Barrow were made utilizing current meters, floats of various kinds, and sodium fluorescein dye. Considerable experimentation was required before reliable techniques were developed. Current meters proved to be of little use as the low velocities encountered were below their sensitivity. Floats made of cork or wood with aluminum vanes worked very well. The most efficient design was the product of many experiments. The use of dye also required extensive trials. Exact location and timing are very important to any method used for determining currents, and since these are factors difficult to ascertain, all current determinations are at best only approximations. However, if persistent and systematic field work is executed, fairly reliable data on circulation can be obtained. The general pattern of wind-driven circulation systems in the Barrow area lakes were determined to be as follows:

The flow systems of the larger lakes are very similar and can be considered as being of one type. At a short distance from the upwind shore, a distance dependent upon the height of the bank, fetch becomes sufficient for waves to be produced. In the surficial portions of the water there is a net drift downwind, but at depth, especially near the upwind shore, dye movement indicates a slow return upwind. Lakeward, the downwind drift is characterized by long lines of foam at intervals of a yard or so and parallel to wind direction. This is believed to indicate a helical structure in the

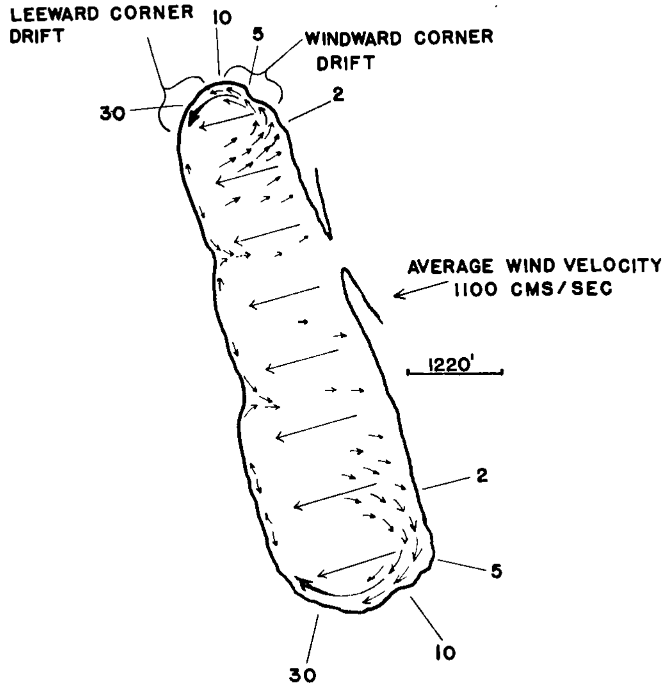

Figure 5. The configuration of the circulation system in an open lake near Point Barrow during a 25 mph wind. The long straight arrows indicate leeward surface drift, the small curved arrows the circulation at depth, and the large curved arrows the drifts at the ends. Current velocities are in cms/sec and are shown in their approximate sites of measurement. ffl

drift such as that described by Langmuir (1938). At the downwind shore the waves break in the shallows and longshore drift is negligible where their approach is normal to the shore. However, if the waves approach the shore at some other angle, longshore drift flows parallel to the shore from the acute angle between the line of breakers and the shoreline. Where there are projections in the shore, currents sometimes move windward into the lake. At the upwind corners of the lakes a slow longshore drift occurs which slowly accelerates until it reaches the downwind corners (in the $\alpha_0 = 50°$ range of Bruun) where it speeds up rather rapidly and beach drifting becomes very noticeable. Farther along the shore on the downwind side of the lake the corner currents are no longer evident in the near shore zone. Figure 5 illustrates the circulation pattern and associated velocities in an open lake near Point Barrow.

DISCUSSION

As can be seen from the foregoing description of currents, the mechanism hypothesized by Livingstone (1954) was not observed. A component of return due to a hydrostatic pressure gradient such as he envisages may occur in some instances, but certainly it does not maintain itself in the face of the strong downwind corner currents, even in highly circular lakes. In the absence of waves (and their associated longshore currents) as in a pond treated with soap or detergent (Keulegan, 1951), a wind-driven circulation similar to that which Livingstone discusses might be in evidence, but such conditions would hardly obtain in nature. In small shallow pools on the tundra near Barrow a slow circulation approximating Livingstone's conception was recognized, but its erosive powers were nil.

It is seen then, that Livingstone's mechanism can be substantially eliminated from any system of multiple hypotheses applied to the lakes. That of Rex, however, appears to merit further study.

Rex' prediction that the zone of maximum littoral drift, or current, occurs where $\alpha_0 = 50°$ is approximately correct. How influential this aspect of circulation is in lake orientation is yet to be determined, but its existence has now been definitely established and must be considered in any quantitative approach to the lake problem.

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