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An Analysis of Surface Slicks in a Reservoir Receiving Heated Effluent

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With 5 figures and 1 table in the text

Abstract

Large elongate surface slicks are frequently observed on Par Pond, a South Carolina reservoir receiving waste heat. One or more slicks between 50 and 2000 m long and 1 to 50 m wide can be seen on almost any day during the stratification period when the wind strength is between 0.5 and 5.0 m sec^{-1}. Slicks are oriented approximately parallel to the wind and accumulate suspended fragments of macrophytes below the surface as well as debris and organic matter on the surface. An experiment with the surface film indicates that substantially greater amounts of organic compounds are present on the water surface within slicks than outside slicks. Thermal cross section maps demonstrate that slicks are always located above abrupt horizontal temperature discontinuities that ordinarily range between 0.10—0.20° C. Wind driven curents of 4 to 10 cm sec^{-1} converge along the long axis of the slicks and provide the basis for an explanation of the slick phenomenon. Slicks of a similar nature can reasonably be expected on other thermally-altered lakes.

Introduction

Par Pond, a 1130-ha reservoir in South Carolina, is limnologically remarkable due to the frequent presence of large elongate slicks at variable locations over its entire surface. The formation of the slicks is apparently related to the discharge of heated effluent from a nuclear reactor into the lake. Since the artificial heat load of Par Pond is relatively small, the formation of slicks may be generally relevant to the discharge of waste heat from conventional or nuclear power generating stations into reservoirs. Systematic observation of the slicks was consequently undertaken to determine their nature, cause, and limnological importance.

Par Pond has a warm monomictic thermal regime due to its southerly location (33° N, 81° W). Winter minimum water temperature for large unheated lakes of this region is approximately 10° C. Par Pond cools to about 11° C during winter but is frequently somewhat warmer near the surface even during the coldest months due to the discharge. The discharge water, which is withdrawn from the south arm of Par Pond, enters the middle arm at approximately 30° C during winter and 40° C during summer

(Fig. 1). The lake stratifies normally during summer except that the timing of stratification and the exact nature of vertical heat distribution are slightly altered due to the heated effluent. Details of the thermal regime and distribution of artificial heat are given elsewhere (LEWIS 1974).

The relationship of slicks to heated discharges has apparently not been documented. In their comprehensive treatment of physical effects associated with heated discharges into Cayuga Lake, SUNDARAM et al. (1969) mention slicks, but do not indicate any special relationship between slicks and heated discharges. Slicks have been observed under natural conditions in lakes and marine environments but are not ordinarily such a prominent

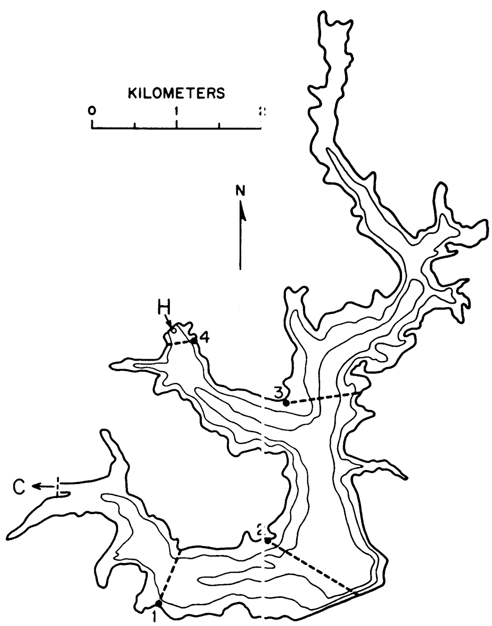
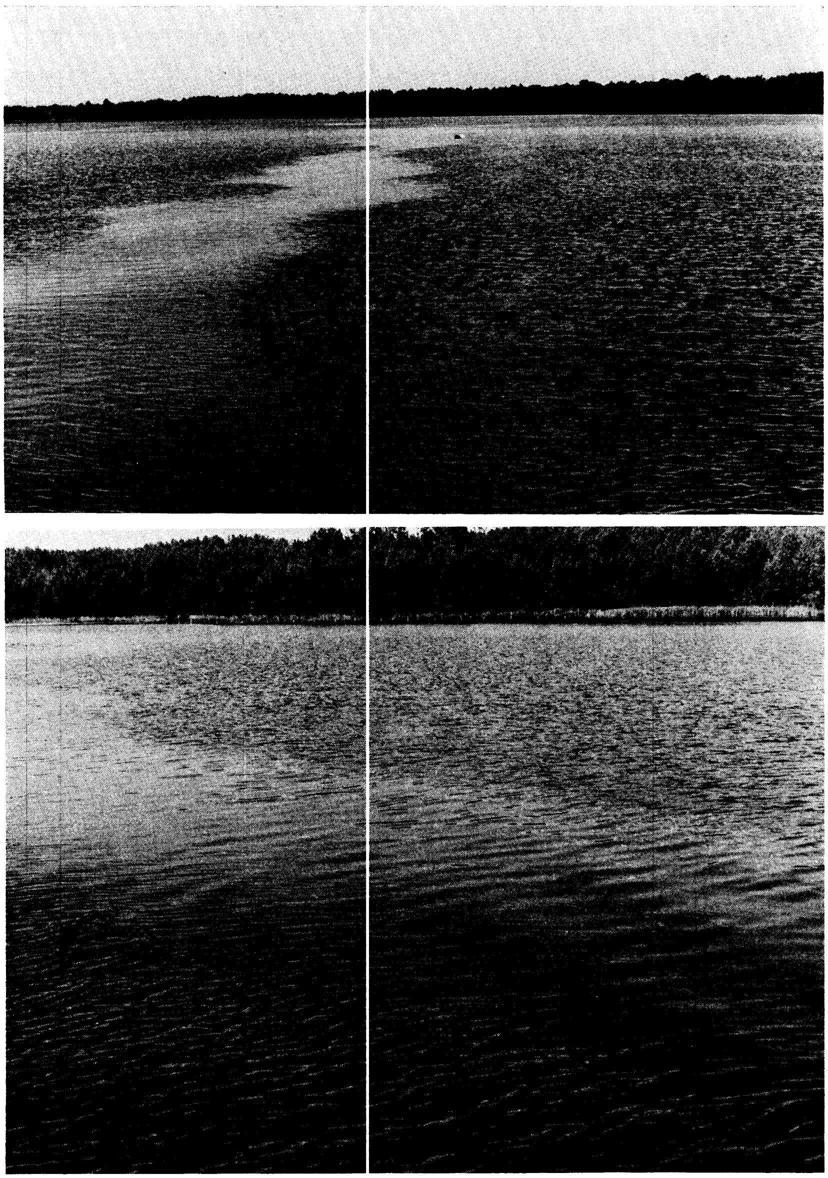


Fig. 1. Bathymetric map of Par Pond showing 5- and 10-m contour lines and the location of 4 transects referred to in the text. Discharge and withdrawal points for cooling water are indicated by arrows.

physical feature as on Par Pond. Smoothing of the water surface within natural slicks is probably due to a surface film of organic matter. Accumulation of the organic material in marine environments is thought to originate in part from the water movements associated with progressive internal waves (EWING 1950), but this mechanism is apparently not important in small freshwater bodies such as Par Pond.

Description of Slicks

Slicks are easily identified during periods of moderate wind as portions of the water surface that remain smooth in contrast with the water surface around them (Fig. 2 A and B). Closer inspection usually reveals a visible accumulation of tiny dust-like particles within such a glassy patch of water



A

B

Fig. 2 A und 2 B. Typical Par Pond slicks.

surface. Slicks disappear if the wind dies completely or increases beyond a certain critical strength leading to the formation of Langmuir spirals. The lower limit of wind strength for maintenance of a slick on Par Pond is about 0.5 m sec^{-1}.

Slicks transmit gravity waves but not capillary waves, hence the water surface is essentially flat within them at the lowest wind speeds (0.5—2.0 m sec^{-1}). Crests and surfaces of gravity waves are smoothed within slicks, which accounts for the realtively undisturbed appearance of the water surface even in moderately windy weather. At wind speeds above approximately 5.0 m sec^{-1}, slicks are dissipated by wave action at the surface. Langmuir patterns first become evident at about 5.5 m sec^{-1}.

Slicks on Par Pond are almost always elongate with the long axis oriented approximately parallel to the wind. Some instances of orientation across the wind have been observed, but slicks under these circumstances are in a transitional state and change form rapidly. The length of slicks varies from about 50 to 2000 m with a mode of about 750 m, and their width varies between approximately 1 and 50 m with a mode of about 10 m. The width of a given slick increases or decreases in an inverse manner with wind strength within the range of wind strengths for which slicks are stable.

The number and location of slicks on Par Pond varies according to weather conditions and activity of the reactor. Maximum number of slicks sighted on a single cruise of Par Pond was 31. Mean number of slicks longer than 100 m for 7 cruises of the entire lake between June and September 1973 was 11, but abundance of slicks declined during October to about half this number. Provided that wind strength is within the 0.5—5.0 m sec^{-1} range, it is virtually always possible to find at least one slick on the lake. Slicks appear to form in greatest numbers when the wind blows from the heat source toward the main body of the lake, but they may also be prominent on days when the wind blows from any other direction. Slicks may persist when the reactor has been shut off, but at such times they are fewer in number and eventually dissipate. Steady winds more frequently accompany the formation of slicks than do shifting or intermittent winds. Often a major change in wind direction dissipates a slick entirely, although it may also lead to the formation of another slick or reshape an existing one.

The relative frequencies with which slicks occur at various locations on Par Pond are indicated in Fig. 3 A. The area just in front of the hot water discharge is almost always occupied by one or more slicks oriented parallel to the direction of flow from the discharge (Fig. 3 B). At other locations slicks are much more variable in occurrence and orientation. Incidence of slicks is highest at all of the major bends in the lake (Fig. 3 A). They are least likely to form in shallow parts of the lake remote from the discharge, but their formation is by no means limited to the immediate area of the discharge.

Slicks routinely contain many large macrophyte fragments. These fragments typically remain suspended some 10 cm below the water surface and show no tendency to rise or sink unless the slick disappears. The plant fragments move as the slick moves.

During August and September individual slicks were observed for periods as long as 4 hr. Longer observation periods proved impossible because wind strength was quite likely in the course of a day to pass outside the range required for maintenance of slicks. In 8 observational tests of temporal continuity, slicks persisted for continuous periods ranging from $^1/_2$ to 4 hr with a mode of about 1 hr. Lifespans of the slicks would presumably exceed these figures since they were already in existence at the time observations were initiated. During the 8 observation periods the slicks moved perpendicularly to their long axes at rates between 38 and 180 m hr^{-1}. Mean net rate of movement was 74 m hr^{-1}.

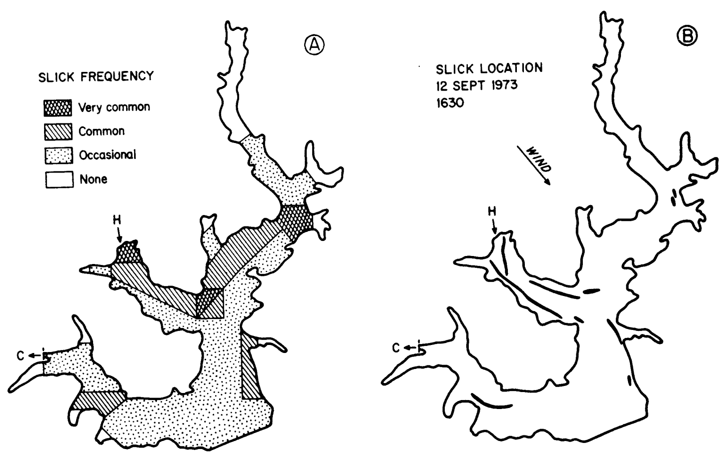


Fig. 3. A. Relative frequency of slick sightings over the surface of Par Pond during summer 1973. B. Position and orientation of slicks on Par Pond on 17 July 1973.

Analysis of Slicks

Surface film

The reduced surface disturbance characteristic of slicks in Par Pond is associated with the presence of foreign material on the water. Portions of the surface film from slicks were therefore occasionally returned to the laboratory for microscopic examination. Particles floating on the surface consist principally of plant debris ranging in size from 50 to 500 μ. This debris is probably not sufficently concentrated to account for the smoothness of the surface within slicks. Damping of waves is presumably due to a thin film of organic compounds on the water surface that accumulates the particulate debris.

In a test of the hypothesis that significantly greater amounts of organic compounds are found within slicks than outside them, the surface film of 4 slicks was compared with that of 4 control areas. Samples were taken with a 250-cc volumetric flask immersed in such a manner that the surface film flowed into the flask along with water as the flask was filled. One 250-cc sample was gathered within each slick and one (control) sample was taken 100 m outside the boundary of each slick. The samples were all treated with 25.0 cc of enthanol to solubilize a portion of the organic compounds. The absorbance of the resulting mixture was then measured in a 10-cm cell at 375 nm. Table 1 gives the results of the test. Absorbances of the slick samples are all higher than the controls, which is consistent with the hypothesis that greater amounts of organic compounds are present on the water surface within slicks than outside them.

Table 1. Absorbance of ethanol-treated surface samples. One sample was taken within each of 4 slicks and one matching (control) sample was taken in each case 100 m outside the slick. All samples were drawn from the surface with a narrow-mouth flask in such a way that a maximum amount of surface film was collected with the water. Exactly 25.0 cc of ethanol were added to each sample and the absorbance was measured in a 10-cm cell against a mixture of 250 cc distilled water and 25 cc ethanol at 375 nm.

	Absorbance — 375 nm		
Replicate	Slick	Control	Difference
1	1.133	1.118	0.015
2	1.131	1.118	0.013
3	1.140	1.116	0.024
4	1.182	1.120	0.062
Mean	1.146	1.118	0.028

No unusual sources of organic compounds affect Par Pond. Lubricating oils are added at rates below those of most reservoirs because only research vessels are allowed on the lake. The dispersion of surface debris aggregates during calm weather suggests that the slick phenomenon in Par Pond is due to hydrodynamic events rather than the presence of unusually large coherent amounts of organic compounds. It is possible, however, that the heating of large amounts of plankton biomass within the reactor cooling system results in the formation of substantial amounts of floating organic matter.

Thermal structure

Initial observations on large slicks in Par Pond suggested the existence of separate water masses that might not mix readily due to a density difference. Slicks were consequently checked with a thermistor to determine if the underlying water column might be a thermal boundary zone of some kind. In more than 25 temperature tests, slicks were without exception located over or very near a horizontal discontinuity in temperature near the surface. A thermistor probe mounted at a fixed depth revealed abrupt horizontal temperature discontinuities ranging from 0.05 to 1.00° C, usually 0.10—0.20° C. The thermal boundary associated with slicks is characteristically most pronounced between the surface and 1.5 m. At greater depths the discontinuity fades, although it may still be detected as deep as 5 m. The temperature transition is typically abrupt in the immediate vicinity of the slick but occasionally extends in a more gradual manner 10 m or more to either side of the slick.

Complete thermal cross sections were made of several slicks, two of which are shown in Fig. 4. The fixed positions required for such cross sections were established by stretching a calibrated floating polypropylene line from one buoy to another over a slick. A thermistor probe was then lowered to a fixed depth and heavily weighted to maintain the depth as the boat moved. As the boat passed along the transect, temperatures were read at 5-m intervals marked on the calibration line. The probe was then lowered to another depth and the procedure repeated until a two dimensional thermal map was obtained.

Numerous mapping attempts were thwarted by rapid movement or disappearance of slicks. On these occasions it became clear that the thermal discontinuity shifts as the slick shifts. An abrupt change in wind direction fractionates a slick and causes the warm and cool water masses to interdigitate and then mix to a variable degree.

Although all slicks in Par Pond are situated above a thermal boundary, not all thermal boundaries are accompanied by slicks. The horizontal variation in temperature near the surface was determined on numerous occasions for several transects across Par Pond (Fig. 1) in order to test the relationship between slicks and thermal discontinuities. Figure 5 shows typical temperature variations across various portions of the lake. There is a marked tendency for hot water from the discharge to form a longshore current, which appears most distinctly in transect 4. In parts of the lake more remote from the discharge, discrete masses of warm water can be found, as shown by transects 1—3 in Fig. 5. Warm water masses are ordinarily located near the shoreline, but there is characteristically a buffer zone of cooler temperatures separating the shore from the warm water

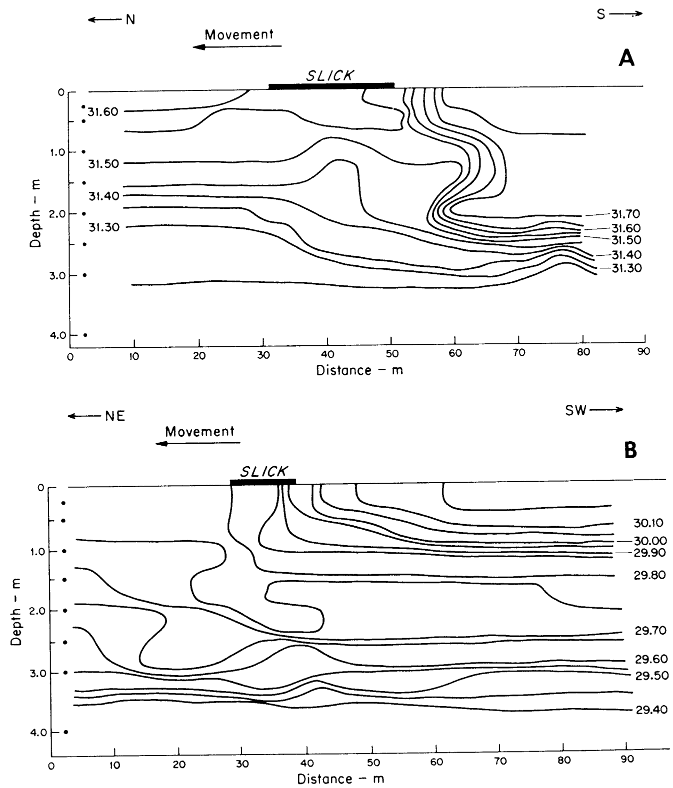


Fig. 4. Temperature cross sections of two slicks constructed from thermistor data as described in the text. A) July 13, North arm near mouth. B) August 7, North arm at bend.

mass. This buffer zone is undoubtedly maintained by extensive beds of macrophytes that retard the movement of water near the shore. Slicks are usually located at the interface of warm and cool water masses that faces the open water. It is clear from Fig. 5 and numerous other such transect studies that thermal boundaries are a necessary but not a sufficient condition for the formation of slicks in Par Pond.

Currents

The coherence of fine debris and organic matter that form slicks and the concentration of large macrophyte fragments within slicks strongly suggest that slicks are zones of converging water currents. Convergence of currents has of course been successfully used as an explanation for accumulation of material at the surface associated with Langmuir circulation and with marine slicks following progressive internal waves. Some simple tests were therefore formulated to demonstrate the patterns and rates of flow in an around slicks on Par Pond.

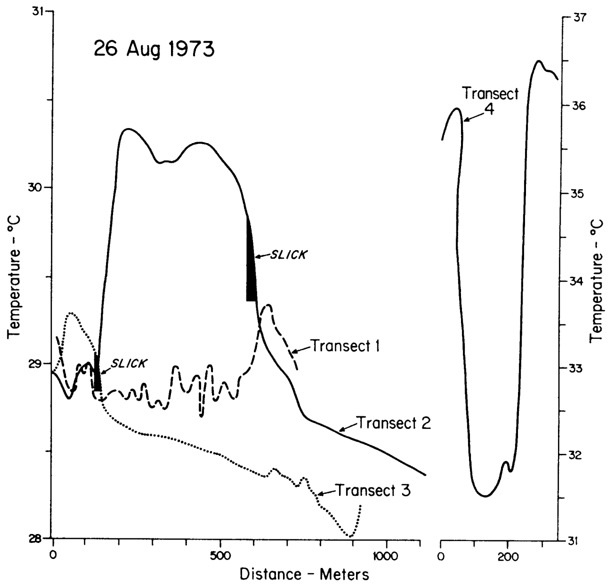


Fig. 5. Temperature transects across Par Pond at a depth of 15 cm. Location of the transects is shown on the bathymetric map (Fig. 1). Note that the temperatures of transect 4 are graphed on a compressed scale. The positions of slicks along transects 2 and 3 are indicated by dark bars.

A set of 2-oz glass bottles was used to mark flow from a fixed buoy by a method similar to that used by Langmuir (1938). The weight of each bottle was adjusted by addition of water until its overall density was sligthly greater than that of lake water. The bottles were then counterbalanced with a small cork attached to a variable amount of monofilament line connecting cork and bottle. Depth of a bottle in the water column could thus be adjusted by changing the length of the monofilament strand connecting it to the cork. Movement of the bottle at any depth could be observed at the surface, since the cork moved with the bottle as the bottle responded to water currents. Mobile buoys fixed the start and end points of individual bottle movements so that the angle and distance of movement could be accurately determined.

Observations on currents in the vicinity of slicks are typified by data taken on a slick bisection at transect 1 (Fig. 1) on 4 October 1973. This slick measured approximately 250×4 m and remained in a fixed location ($\pm$ 5 m) during the 45-min study period. The temperature shift at 10 cm depth beneath the slick was from 27.20° C (shore side) to 27.00° C (lake side). The warmer water mass was on the right of the slick for an observer facing downwind or down current. The wind was ENE (80°), and the long axis of the slick was ESE (110°) to WNW (290°), or 30° counterclockwise from the wind. The current at 10 cm depth on the warm side of the slick and 20 m from its boundary was 12.0 cm sec^{-1} and was directed toward the central axis of the slick at a slight angle (0—10°). The current on the cool side of the slick was 13.3 cm sec^{-1} and was flowing either parallel to its axis or at a slight angle toward its center.

Examination of similar data on winds and currents on other dates shows that slicks are only approximately aligned with the wind but are precisely aligned with currents near the water surface. The currents are primarily wind driven and typically flow at an angle of 10—45° to the wind. The angle between wind stress and current is of course divergent from fluid mechanical theory of geostrophic deflection, since the basin is shallow, finite, and dendritic. A special case exists just in front of the discharge, where the currents around slicks frequently flow in a direction opposite that of the wind due to the force of the discharge. Currents are as high as 31 cm sec^{-1} around slicks in front of the discharge, but only range between 4 and 10 cm sec^{-1} in other parts of the when slicks are prominent. Currents never flow at angles greater than 15° to the central axis of a stable slick, and generally appear to be slightly convergent on the center of the slick.

Conclusions

The information on currents suggests a specific mechanism for slick formation that is consistent with the other data. Water masses of different density are created by the artificial heat source and maintain their integrity for long periods. A wind blowing over the lake generates currents that are similar but not identical in speed and direction within two such water masses. If the convergence of currents at the boundary of the two water masses is strong, or if one water mass is driven directly against another, mixing may occur and no slick will form. If the currents are nearly parallel, however, components of force acting perpendicular to the interface of the two masses may be insuffiecent to overcome the resistance to mixing that is maintained by the density difference. Debris and organic matter are thus skimmed from the surface of the two water masses as they converge, and this material accumulates as a slick. If the currents are diverging, as they may often be, no slick is formed. This explains why horizontal temperature discontinuities are not always marked by slicks.

The slicks observed on Par Pond are undoubtedly analogous in many ways to the "taches d'huile" that are observed on lakes under completely natural conditions. Taches d'huile are still poorly understood, although they have been observed since the time of Forel (1895). Hutchinson (1957) summarizes the older literature. In an excellent modern study, Schröder and Grunewald (1967) lave shown by use of dyes that water currents are intimately related to the formation of taches d'huile. Their findings are in fact completely consistent with the explanation proposed here for slicks on Par Pond. It is uncertain at present whether natural taches d'huile are always associated with a thermal boundary as are the slicks on Par Pond. This question will probably be answered by some investigations that are now in progress in Germany, which are intended to extend by modern methods the observations of MERZ (1920) on the thermal microstructure of lake surfaces.

If the Par Pond data have been interpreted correctly here, slicks should be prominent features of thermally-polluted lakes. The effect will be most pronounced during summer and at low latitudes due to the marked effect of heat on water denisity at high temperatures. Slicks in heated lakes may thus prove to be useful visual indicators of water mass boundaries, and could also be of direct biological significance as a mechanism for the accumulation of debris and organic matter on the water surface.

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Zusammenfassung

Während der Schichtungsperiode des Par Pond, eines Reservoirs in South Carolina, das aufgeheiztes Kühlwasser empfängt, wurden häufig lange und breite, strichartig ausgebildete Ruhezonen auf der Wasseroberfläche beobachtet. Man könnte sie als „tâches d'huile" bezeichnen, wie man sie auf fast allen Oberflächengewässern der Erde beobachten kann und vielfach beschrieben hat. Die ungewöhnliche Größe, Häufigkeit und Dauerhaftigkeit dieser strichartigen Ruhezonen des Par Pond wiesen auf eine Beziehung zu dem Einfluß des erwärmten Wassers hin. Entsprechende Untersuchungen wurden im Laufe der Sommermonate durchgeführt.

Bei Windstärken von 0,5 m/sec bis zu 5 m/sec traten die genannten Zonen regelmäßig im Par Pond auf. Bei höheren Windstärken dagegen verschwimmen die lang ausgezogenen Zonen und werden durch ein typisches Langmuir-Muster ersetzt. Die strichartigen Ruhezonen wurden in einer Länge von 50—2000 m und in einer Breite von 1—50 m festgestellt. Ihre Längsachsen liegen meistens in Windrichtung. Auf dem 1130 ha umfassenden Gewässer bildeten sich durchschnittlich 11 derartige Strichzonen. In diesen Oberflächenbereichen des Sees wurde regelmäßig eine größere Konzentration an organischen Stoffen und Überbleibseln von Pflanzen zum Unterschied von der umgebenden Wassermasse festgestellt. Die organischen Komponenten waren in Äthanol löslich.

Die strichartigen Ruhezonen zeichnen sich ständig durch horizontale Temperaturunterschiede von 0,05—1,00° C (gewöhnlich 0,10—0,20° C) gegenüber der Umgebung aus. Daraus ergibt sich, daß sich die Ruhezonen nicht mit der umgebenden Wassermasse vermischen, weil eine Dichtedifferenz vorliegt. Ob-

gleich die im Kontakt mit den Ruhezonen stehenden angrenzenden Wassermassen Strömungen in gleicher Richtung aufweisen, tritt doch keine Vermischung ein. Es handelt sich also um Konvergenz ohne Mischung der angrenzenden Wasserzonen. Voraussetzungen für die Entstehung solcher Ruhezonen werden durch den stetigen Zufluß heißen Wassers geschaffen und treten daher im Par Pond häufiger als unter natürlichen Verhältnissen in anderen Gewässern auf.

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