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Shear at the Surface of a Lake in Light Winds

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Standard computer cards released at 1-min intervals from the same point beneath a hydrometeorological tower were observed to segregate by color according to their depth of integration of the current. Green cards floated flat at the lake surface. Orange cards, on the other hand, curved downward when placed on the lake surface and averaged the currents in the top 1 cm. The separation of the cards into two distinct plumes resulted from wind-directed shear in the first centimeter below the surface that was superimposed upon a barotropic current flowing crosswind. Using time-lapse aerial photography, the magnitude and direction of the shear was quantified. The mean shear in the top cm was 3.5 s^{-1} and was aligned with the mean wind direction. The wind-directed shear was similar to that expected for a viscous sublayer in light winds (1.3–1.8 m s^{-1}).

INTRODUCTION

The distribution of shear at an air-water interface and the associated momentum input from the wind to surface currents in lakes or oceans is generally complicated by the formation of surface waves. *Stewart and Grant* [1962] suggested that wind energy is largely transmitted to the surface wave field and is transferred from the waves to drift currents through the action of breaking waves. *Baines and Knapp* [1965], on the other hand, reported that surface waves were unimportant to the momentum flux from the wind to the current in their wind wave tunnel. Moreover, both *Keulegan* [1951] and *Van Dorn* [1953] observed that the surface current generated by a steady wind was independent of wave damping produced by an artificial surface film. Under some conditions therefore a significant portion of the momentum may be transferred by the direct action of the shear stress of the wind on the water surface.

Lack of understanding of transfer processes at the air-water interface is partly attributed to the lack of accurate measurements from open water sites. *Churchill and Csanady* [1983] describe some of the difficulties associated with near-surface measurements of simple quantities like velocity shear in large lakes and the ocean. Although *Langmuir* [1938] commented that the rate of momentum transfer to lake currents appeared initially higher following a period of calm than after the surface waves became fully developed, little attention has been focused on transfer processes in very light winds.

In the present paper, time-lapse photographs showing the effects of near-surface current shear on the movement of computer cards and dye plumes during light winds are described. The aerial photographs were taken during an experimental study of windrows on Lake of the Woods [*Kenney*, 1977]. Although the photography was necessarily biased towards windy days by the study objectives, a variety of strong fronts and other highly nonlinear phenomema were photographed as the lake current decelerated following a cessation of the wind [*Kenney*, 1980]. Using largely fortuitous results, a quantitative estimate of the magnitude of the Lagrangian velocity shear was obtained in the top centimeter of the water column for 1 day with very light winds. The shear observed at the lake surface is consistent with known characteristics of a viscous sublayer in classical boundary layers.

METHODS AND PROCEDURES

Vertical aerial photographs of a point-source plume of fluorescent red dye (Rhodamine WT) were taken at 5-min intervals together with simultaneous wind velocity and temperature measurements from a hydrometeorological tower. The dye was discharged at a rate of 4500 mL h^{-1} from a constant head siphon supported from the bottom-mounted tower. The technique of measuring the in situ fluorescence of dye to determine turbulent diffusion in ocean currents was pioneered by *Pritchard and Carpenter* [1960]. *Kenney* [1967] employed time-lapse aerial photography to study the meandering of dye plumes produced by large turbulent eddies. Dye is not an ideal tracer for aerial photography, however, because it is not possible to follow individual particles of dye or to know the exact depth of the center of mass of the dye. Moreover, the near-surface current velocity cannot easily be determined with dye, except by tracking of the center of mass of a sequence of small patches. To complement the limited data that can be obtained from dye plumes, a sequence of computer cards were released precisely at 1-min intervals from the tower. The cards were attached to a pole and released manually at the same point on the lake surface. The cards formed a plume similar to the dye but with discrete elements. Individual computer cards were readily identified in the time-lapse photographs and were used to determine the surface velocity. As an aid in tracking individual cards, the color of every tenth card released was orange instead of the usual green.

The photography was taken from a Piper PA22 aircraft modified to accommodate a Fairchild F56 aerial camera in the baggage compartment and a Hasselblad 70-mm camera in front of the passenger seat. With 178-mm film and a 210-mm focal length lens, the F56 camera had roughly the same cone angle as the Hasselblad with an 80-mm lens. Both cameras were fired simultaneously from a single 3B3 intervalometer with the Hasselblad acting as the viewfinder. Kodak Plux X Aerographic film was used in the F56, and Ektachrome Aerographic 2448 was used in the Hasselblad. Ground control necessary for orientation of the photographs was provided by two bottom-mounted towers and floats anchored in three directions.

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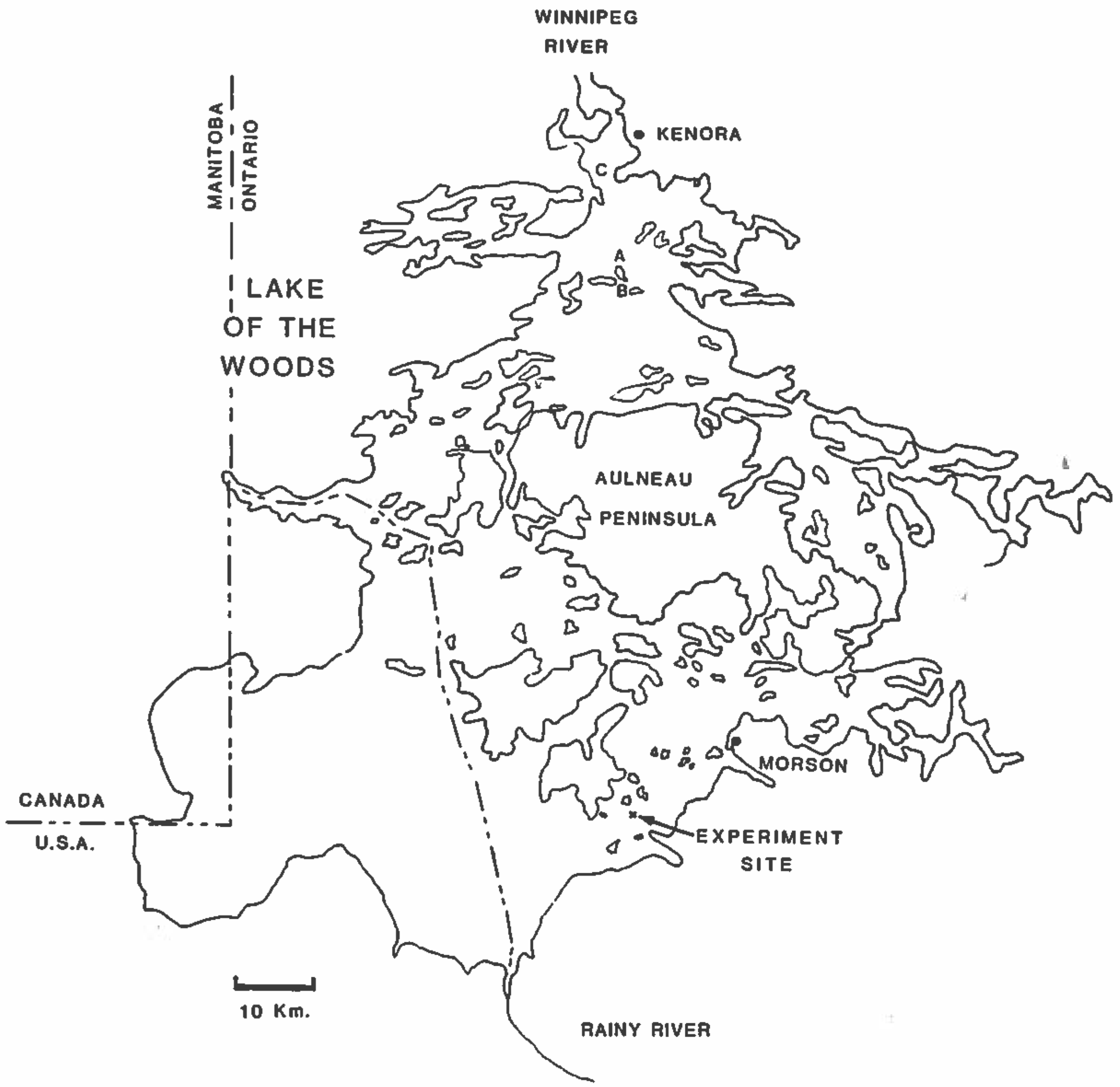

Fig. 1. Map of the Lake of the Woods showing the Morson Channel and the location of the experimental site.

The wind speed and direction were measured 4 m above the lake surface at 10-min intervals using a Plessey Electronics, Hymet model MM-1 recording system [*Elder and Brady*, 1972]. Note that the wind speed was integrated over the 10-min interval (±2% accuracy for wind speeds greater than 2 m s^{-1}). The wind direction was the instantaneous compass value at the time of recording. The high-frequency response of the direction vane was limited, however, both directly by a viscous damper and indirectly by coupling the vane to an oil-damped magnetic compass (resolution 1°, accuracy ± 5° relative to magnetic north). Air temperature was measured 3.5 m above the interface and water temperature was measured approximately 2 cm below the interface using individually calibrated thermistors housed in radiation shields (accuracy ± 0.1°C).

RESULTS AND DISCUSSION

Lake Current Regime at the Experimental Site

The experiment was conducted in 3 m of water in the Morson channel, which is bounded on the north by numerous islands and on the south by a series of small but complex bays (Figure 1). Because of the complicated morphometry, lake currents in the channel frequently had a significant crosswind component [*Kenney*, 1977]. The cross-wind transport could be either to the right or the left of the wind, depending upon the direction of the wind and the morphological constraints on the lakewide circulation. When crosswind transport occurred, the variation of current velocity with depth consisted of a shear colinear with the wind direction that was superimposed upon a depth-uniform (barotropic) component at some angle to the wind. The magnitude of the wind-directed shear usually increased toward the surface, although on one occasion the shear was constant with depth. The barotropic component was often at right angles to the wind.

Effect of the Near-Surface Shear on the Dye Plume

A scale drawing shows the relative locations of the computer card and dye plumes as they appeared in the vertical aerial photograph at 1640 CDST (Central daylight saving time) on August 22, 1973 (Figure 2). Some subjectivity was

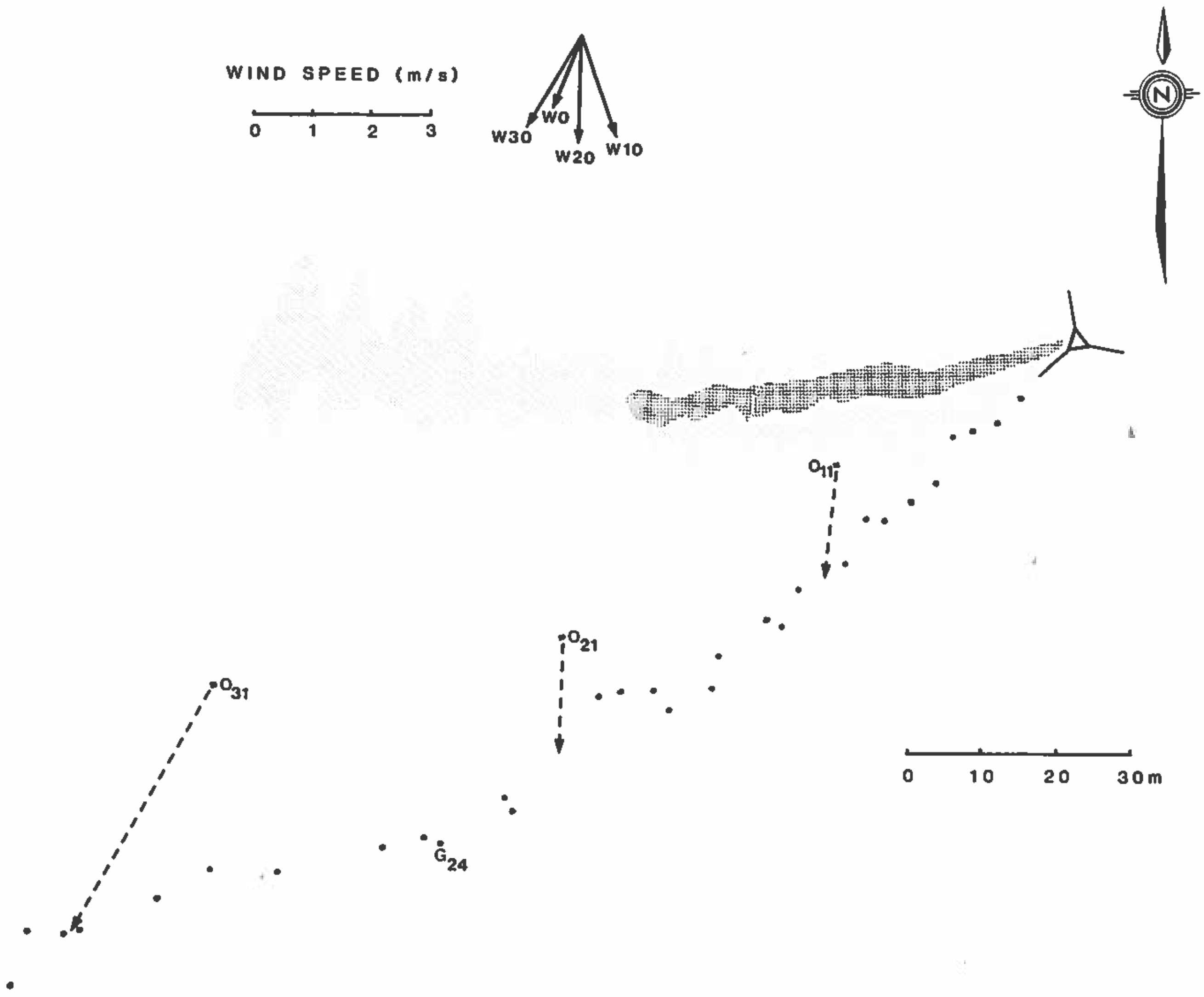

Fig. 2. Schematic diagram of dye and card plumes plotted from vertical aerial photograph taken at 1640 CDST, August 22, 1973. A total of 34 cards were plotted from this photograph, 3 orange and 31 green cards. Labeled cards are designated according to their color and the number of minutes from their release (e.g., O_{11}, G_{24}). Each card was positively identified in each photograph in the sequence taken at 5 minute intervals. The dashed lines illustrate the average direction of the shear in the top centimeter of the water column from the time of release of each orange card. Wind vectors are also labeled according to the number of minutes prior to the photograph (e.g., W10 represents the wind at 1630 CDST).

involved in depicting the dye plume in this figure because only two tones were used to represent a continuous change in color intensity. The location of the central core of high concentration (i.e., approximate center of mass of the plume) that extended about 60 m from the source is accurately plotted, but the transition to lower concentrations at the downstream end of the plume was more gradual than is shown in Figure 2.

The triangle of dye, extending 30 m from the source and lying between the central core and the computer cards, was a thin surface layer of high concentration that was being swept downwind by the surface shear. Wind-directed shear at the surface coupled with a crosswind barotropic current tends to sweep dye near the surface downwind away from the center of mass of a plume as it moves crosswind. Diffusion of dye relative to its center of mass is thereby accelerated [*Kenney and Jones*, 1971]. Although the triangle of dye appeared to be of lower concentration in the photographs and is plotted as such in Figure 2, samples taken from the boat confirmed that it was actually a thin surface layer of high concentration (<1 cm deep). The triangle extended only 30 m from the source because of accelerated diffusion produced by the shear near the surface. Although dye continued to mix upward from the core of the plume, the surface concentrations past 30 m downstream were reduced to the point that the thin surface layer was no longer visible in the photographs.

Effect of the Near-Surface Shear on the Computer Cards

As the sequence of green cards were released from the tower, they were observed to form a line that diverged significantly from the dye plume. This divergence was the expected result of the wind-directed shear. It was surprising, however, that the orange cards did not track with the green

TABLE 1. Hydrometeorological Conditions at 10-min Intervals from 1510 on August 22, 1973

Time, CDST	Wind Vector*	Wind Speed, m s^{-1}	Wind Direction, °T	Air Temperature, °C	Water Temperature, °C
1510		4.0	216	20.1	22.4
1520		4.0	208	20.3	22.3
1530		4.0	213	20.4	22.3
1540		3.6	203	20.8	22.3
1550		3.6	210	21.1	22.3
1600		2.2	216	21.2	22.3
1610	W30	1.8	209	21.2	22.3
1620	W20	1.8	180	21.1	22.4
1630	W10	1.8	159	21.2	22.5
1640	W0	1.3	200	21.4	22.5

The wind speeds are integrated, and the directions are instantaneous values from a damped vane. To facilitate comparison with shear directions, vector wind directions (i.e., direction toward which the wind was blowing) are given.

*Wind vectors are shown in Figure 2.

cards but formed their own plume about half way between the green cards and the dye plume.

The segregation of the orange and green computer cards was first noted from the air because the cards could not be seen very far from the tower. The cause of the color separation was the subject of considerable speculation in the air-ground communications that followed. Other than color, no physical differences were noted between the orange cards and the green cards prior to deployment in the lake. Following the termination of the experiment, the boat was directed from the air to several of the orange cards. The orange cards were observed to float with the (long) ends curved downward about 1 cm below the center of each card, thereby averaging the current over the top centimeter. The green cards, on the other hand, were floating flat at the lake surface and moved with the surface current. The divergence of the two lines of cards was caused by the wind-directed shear in the top centimeter of the water column.

Tests were subsequently conducted on these cards in the laboratory with similar results. Twenty cards of each color were selected at random from the same batch of cards used in the experiment. The orange cards curled downward 1 cm (±10%) at each end immediately when placed on the water surface, while the green cards remained flat on the surface. The reason for the different behavior of the two colors of cards was not resolved. It may have been a consequence of the coloring process or age of the cards or simply a result of their being from different batches of pulp.

Estimates of the Lagrangian Currents

From 1510 to 1550 CDST the wind speed decreased only slightly from 4 to 3.6 m s^{-1} (Table 1). The wind direction remained steady at 210° ± 4° (±1 standard deviation). The wind speed then diminished to 1.3 m s^{-1} from 1550 until 1640. In response to the dying wind, the current also decelerated. The mean surface current, based on the displacement of the three orange cards from the source, decreased from 6.3 cm s^{-1} for O_{31}, to 6.1 cm s^{-1} for O_{21}, to 5.2 cm s^{-1} for O_{11}. Because of the surface shear, the mean speed of the green cards was higher than that of the orange cards, but the trend in speed of the green cards also indicated that the current was decelerating. The deceleration of the current may also be seen in Figure 2 where the spacing between adjacent green cards tend to be smaller close to the source.

The crosswind barotropic current had an average value of 4.9 cm s^{-1} in a westerly direction. The slight curvature in the centerline of the dye plume suggests that the barotropic current may have been shifting a little toward the south during the experiment. A discontinuity in the line of green computer cards (near green card G_{24}) suggests the surface current changed direction more abruptly at about 1616, perhaps in response to the shift towards a more northerly wind that occurred after 1610.

The average surface current in the wind direction (based on the green card transport relative to the dye) was 3.8 cm s^{-1} which is about 2% of the wind speed averaged from the time of release. This is within the 1–3% of the wind speed usually quoted in the literature for wind-driven surface currents over a wide spectrum of wind speeds [*Hutchinson*, 1957; *Bowden*, 1983].

Magnitude and Direction of the Near-Surface Shear

The three orange cards (labeled O_{11}, O_{21}, and O_{31} in Figure 2) were released 11, 21, and 31 min, respectively prior to the photograph at 1640. A dashed line is also shown between each orange card and the interpolated position of an imaginary green card released at the same time. This dashed line represents the average direction of the surface shear from the time of release of each orange card. Four wind vectors given in Table 1 are also plotted in Figure 2. The average direction of the shear (193°) is similar to the vector average wind direction in the 30 min prior to the photograph (187°).

It was noted previously that the orange computer cards averaged the current over approximately the first centimeter below the surface, while the green cards moved at or very near to the surface velocity. If it is assumed that the combined skin friction and pressure drag was the same in the top and bottom half of each card and that the velocity varied linearly over the top centimeter of the lake, the orange cards represent the velocity at 0.5-cm depth. Without additional information on the orientation of the cards relative to the current, however, it is not possible to assess the drag distribution with depth. Although we have no other data on the current structure, the assumption of a linear velocity profile in the top centimeter is not unreasonable. *Csanady* [1984] discussed the possible existence of a viscous sublayer (with constant velocity gradient) occurring in light winds. *Wu* [1975] found that wind-driven flow produced in a laboratory tank had thin layers immediately below the free surface where the velocity gradient was constant. *Kenney* [1990] also reported observations of thin surface shear layers on Lake of the Woods and Big Whiteshell Lake where a linear variation of velocity in the top cm was observed. Moreover, *Churchill and Csanady* [1983] showed that a modest gradient in the shear affects the representative depth only slightly. Assuming therefore that the orange cards represented the current at a depth of 0.5 cm, the magnitude of the shear was calculated between orange cards O_{11}, O_{21}, and O_{31} and their interpolated position in the line of green cards (Table 2).

These shear estimates are larger than the few other

TABLE 2. Surface Current and Shear Characteristics at 1640 on August 22, 1973, as Calculated From Computer Card Trajectories

Shear Vector*	Surface Current, cm s^{-1}	Shear Magnitude, s^{-1}	Shear Direction, °T	Friction Velocity, cm s^{-1}	Sublayer Depth, cm
031	6.3	4.2	210	0.20	0.5
021	6.1	2.4	182	0.15	0.7
011	5.2	4.0	188	0.20	0.5
Average	5.9	3.5	193	0.18	0.6

*Shown in Figure 2.

available measurements of shear made at the surface of lakes or oceans in light winds. For example, *Csanady* [1984] presented data derived from "horsehair" drogue measurements at depths of 1.8 and 5 cm in Lake Huron and Cape Cod Bay where the shear was typically 1 s^{-1} in moderate to light winds. More recently, *Kenney* [1990] reported a constant shear of 0.5 s^{-1} in 1-cm-thick surface layers by observing the motion of algal cells during very faint breezes.

A direct comparison with other observations is complicated by lack of information on the distribution of shear with depth. It is clear from Figure 2, however, that the shear was not constant with depth below the top centimeter. The angle subtended at the source between the lines of green and orange cards was only slightly smaller (about 14°) than the angle between the orange cards and the centerline of the dye plume (about 19°). In the former case the angle was produced by velocity differences occurring over the top 1 cm of the water column, whereas in the latter case the shear was spread to the depth of the center of mass of the visible dye plume. Although not measured during these observations, the depth of the center of mass of dye visible in the photographs typically exceeded 50 cm during light winds. It is unlikely that the center of mass of the dye exceeded 150 cm, however, since the water depth was only 300 cm at the experimental site. Although no attempt was made to estimate the magnitude of the shear below the top 1 cm, there is little doubt that the wind-directed shear increased rapidly near surface during this experiment.

The Viscous Sublayer in Light Winds

The magnitude of the shear is consistent with estimates derived by assuming the shear existed within a viscous sublayer produced by the measured winds. The friction velocity u_*, calculated from the average shear ($u_*^2/\nu = 3.5$ s^{-1}), was 0.19 cm s^{-1}. The corresponding surface stress ($\tau = 0.036$ dyn cm^{-2}) could be produced by winds of $(\tau/\rho C_D)^{1/2}$ or about 1.7 m s^{-1} if a drag coefficient C_D of 10^{-3} is assumed appropriate for slightly unstable conditions in very light winds. This calculated wind speed is very close to the measured winds given in Table 1 from the time that the first orange computer card was released (1609). *Smith* [1988] suggested that the sensitivity of the drag coefficient to stability increases at low wind speeds, but few supporting data exist for wind speeds less than 2 m s^{-1} to warrant refining the estimate of the drag coefficient used above [*Wu*, 1990; *Smith*, 1990].

The expected depth d of a viscous sublayer ($d \sim 10\nu/u_* = 0.5$ cm) is also similar to the depth spanned by the orange computer cards. The appropriate time scale for a viscous sublayer is d/u_* which, for the data in Table 2, lies between 2.5 and 5 s. More frequent wind direction data and photographs would be necessary to quantify response times of the surface shear to wind shifts. Other visual observations of the movement of algae in thin surface shear layers produced by very faint breezes suggest that the appropriate time scale for the reorientation of shear in the top centimeter of the water column is of the order of a few seconds [*Kenney*, 1990].

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