Horizontal turbulent energy transfer associated with a great lakes coastal current

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ABSTRACT

The small-scale surface structure of the Keweenaw Current in Lake Superior was measured using aerial photogrammetric techniques several times during the summers of 1971 and 1972. The transfer of kinetic energy from the mean flow by the action of the Reynolds stresses is calculated. Energy transfers both to and from the mean flow occur, and are a significant fraction of the mean kinetic energy. The results suggest that such transfers result mainly in a long-current redistribution of energy. The direction of energy transfer may be related to wind direction: along-current winds occur in conjunction with transfer from the mean flow, cross-current winds with transfer to the mean flow.

I. Coastal currents in large lakes

Strong longshore currents within a few kilometers of the coast dominate organized flow patterns in the Great Lakes. These currents are of fundamental importance to lake dynamics, and are of practical concern owing to their capability to transport pollutants introduced at the shoreline. In general, such currents flow counterclockwise around a lake, although this direction can be reversed within an inertial period by sufficiently strong opposing winds.

Csanady, among others, has performed a number of field and theoretical investigations of Great Lakes coastal currents (1967; 1968*a*, *b*; 1971; 1972*a*, *b*, *c*). These currents are seasonal in character, and may be classified according to whether the warm water is confined to shallow, nearshore regions (the "spring" regime), or a thermocline exists across the entire lake (the "summer" regime). In winter, the lake is closely homogeneous.

Persistent currents above one knot exist in all regimes, and are usually quite well correlated with wind events. Geostrophic equilibrium occurs at times, but not always (Smith, 1972). Barotropic seiching is probably an important factor (Platzman, 1972), and baroclinic Kelvin waves appear to explain some features of these currents (Csanady, 1972). Whatever the general cause, direct measurements have shown the dynamics of Great Lakes coastal currents to be both non-linear and time-dependent. Significant changes of the mean flow within an inertial period are common. Because of this, it is not yet clear whether the meanders and flow instabilities apparently important to intense ocean currents play a significant role in the Lakes.

The Keweenaw (*Kee*-we-naw) Current in Lake Superior (Fig. 1) has been studied by the Marine Studies Center for over ten years (Ragotzkie & Bratnick, 1965; Smith & Ragotzkie, 1970). The flow is roughly eastward along the north shore of the Keweenaw Peninsula, and can attain speeds over 90 cm/sec during the summer months. Most measurements have been carried out near Eagle Harbor. Here, the coastline is quite straight, and the bottom topography regular. The bottom slope is about 0.1, one of the largest in the Great Lakes. Because of the latitude of Lake Superior the spring regime usually begins in July, the summer regime in late August or early September.

In the spring regime, the outer edge of the Current is usually marked by a very sharp

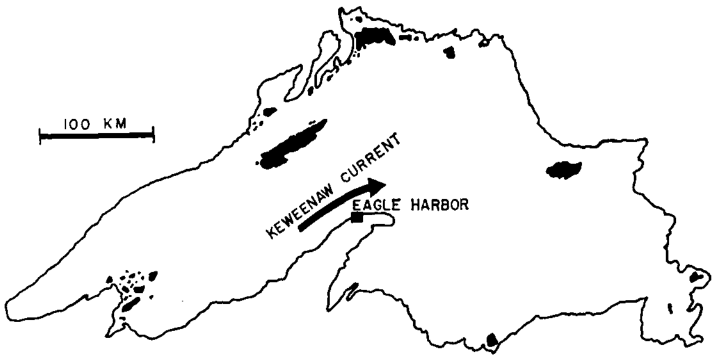

Fig. 1. Lake Superior, the Keweenaw Peninsula, and the Keweenaw Current.

horizontal temperature gradient (on the order of 1°C per 10 m). Here, velocity gradients are correspondingly large, and can reach 3×10^{-3} sec^{-1}. In the summer regime, these large temperature and velocity gradients seem to occur infrequently, and the Current outer edge is less well defined. Strong coastal upwelling marked by cold, nearshore surface water occurs a few times each summer, driven by east winds.

The Current outer edge is rarely more than 20 km from shore during the spring and summer regimes. Thus, rather accurate, densely spaced and nearly simultaneous current measurements are possible. This is particularly valuable in studying the fine structure of such currents. Such measurements can be used to unravel the eddy and meander patterns, and to estimate the interaction between mean and turbulent components of the flow. The work described below is aimed at understanding these interactions in the Keweenaw Current. It is not unreasonable to expect that the same results will apply, at least qualitatively, to other, similar coastal currents.

II. The field experiment

The principal data were surface velocities, obtained using aerial photogrammetry. The general experimental procedure is shown schematically in Fig. 2. In each experiment, surface craft laid floats (ordinary white posterboard) at intervals of 10–100 m across the Current, about one kilometer upstream of an array of moored buoys. An aircraft equipped with a precision mapping camera flew a racetrack pattern, passing over the buoy array on each outward leg and taking a series of overlapping pictures of the floats. Since most pictures contained no ground features, the buoys were positioned at the same time using two shore-based theodolites with one-second accuracy to provide photogrammetric control. Continuous theodolite positioning was needed because of the mooring motion of the buoys.

The experiments were in the early morning or late afternoon, lasted two or three hours, and were limited by the amount of film in the camera magazine, sun glitter, or darkness. The aerial passes over the buoy array were spaced about 10 minutes apart. Over 1 500 floats were used in most experiments. The experiments were only conducted in very calm weather, with the lake surface frequently glassy. One could usually see the reflections of the positioning flags on the buoys several kilometers out in the lake through the theodolites. Thus, there was no surface motion due to surface waves. There was also no stress on the lake surface, and hence no surface shear. Because of this, surface velocities are quite likely to reflect the subsurface structure. However, the fair weather bias in the data should be noted.

Average velocities over the time between aerial passes were found from two successive float positions. The iterative photogrammetric technique used to calculate these positions and velocities is discussed by Yeske (1973). Corrections were made to account for the time taken by the aircraft to fly the outbound leg, for aircraft roll, and for variations in flying height.

Much of this work was necessitated by the fact that many photographs contain no, or only one, buoy.

The velocity errors are always less than 2 cm/sec in speed and 3° in direction. To arrive at these estimates, the most adverse photogrammetric conditions encountered during the project were assumed: large camera tilts, flying height variations, and theodolite positioning errors. The effects of these conditions were evaluated using the equations for tilted photographs (Moffitt, 1967). The maximum error bounds thus obtained were corroborated by comparing photogrammetric velocities to velocities obtained by direct theodolite tracking of drogues.

The photogrammetric measurements are usually supported by data from suspended and moored current meters, geostrophic calculations based on bathythermograph sections, and airborne thermal scanner and radiometer flights. Details of the complete field operation are give in Yeske (1973).

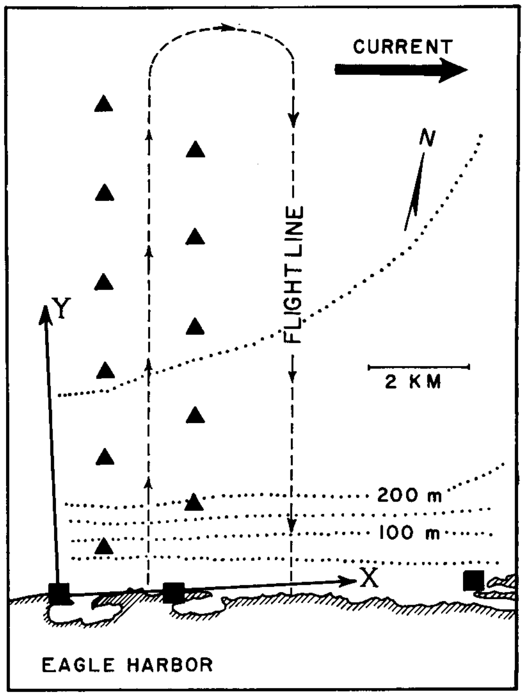

Fig. 2. The study area on the Keweenaw Peninsula, showing the location of buoys (▲) and theodolites (■) in 1972. The flight track for photogrammetric operations is shown as a dashed line, and bottom contours as dotted lines. The coordinate system is also shown.

III. Computing the transfer of surface kinetic energy

The coordinate system used is shown in Fig. 2. The x axis is roughly parallel to shore (directed at 081°T), the y axis perpendicular to shore (351°T). To simplify the computing of spatial derivatives, the raw velocity data were interpolated to grid points spaced either 100 or 300 m apart using an objective analysis technique due to Whittaker (1974). In this technique, the interpolated velocity is determined from the four raw velocities nearest the grid point, each of which is weighted by the factor $(R-D)/(R+D)$. Here, R is the distance from the grid point to the point midway between the third and fourth closest raw velocities, and D the distance from the grid point to the raw velocity being weighted. This method was designed for atmospheric budget studies, and preserves local features near each grid point better than more commonly used atmospheric objective analyses (e.g., Cressman, 1959). A number of tests revealed that this method reproduces the raw data nicely. The isotachs in Fig. 3 are based on interpolated, not raw, velocities. The interpolated surface velocity is $\mathbf{v}=(u, v)$ where u, v are in the x, y directions.

In areas where the raw velocity data density is at least equal to the grid point density, the interpolated velocities were partitioned into mean and fluctuating components

$$\mathbf{v}=\bar{\mathbf{v}}+\mathbf{v}'$$

To do this, the surface area of the Current over which measurements were made was divided into a number of zones parallel to the x axis, thus running along the Current. There were from ten to twenty zones, either 200 m or 300 m wide. Lines, or sections, were drawn perpendicular to the zones, either 100 m or 300 m apart. Along a given section across the Current, the mean velocity in each zone, $\bar{\mathbf{v}}$, was found by taking the arithmetic average of all interpolated velocities in the zone which

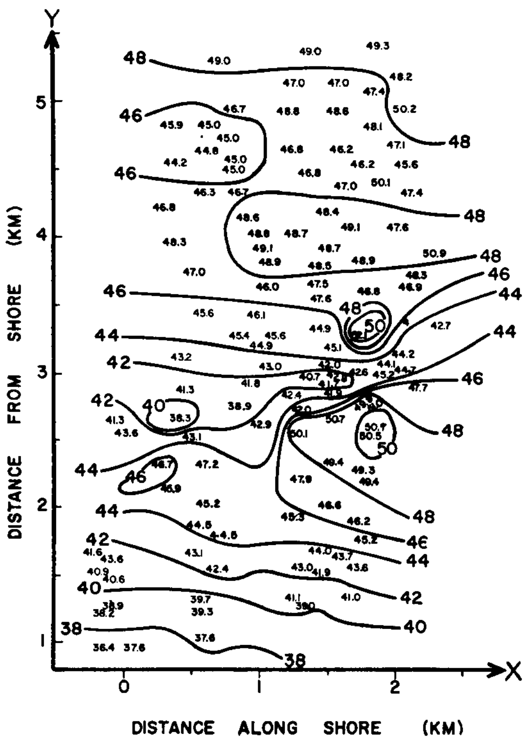

Fig. 3. A comparison of raw and interpolated surface speeds (cm/sec) obtained photogrammetrically on 4 August 1971 (time 1834). Small numbers are raw values at locations where they are plotted. Speed contours are based on the values obtained using an objective analysis technique (see text) over a 300 m grid, which is not shown.

were also within the time interval for which data were sufficiently dense in all zones to give reasonable confidence limits. Time intervals ranged from one to somewhat over two hours. There were usually at least fifteen interpolated velocities averaged over in each zone. The fluctuating components, $\mathbf{v}'$, were found in each zone by subtracting the zonal average from the interpolated velocities. The averaging procedure is similar to that used by Webster (1961, 1965) in computing surface energy transfers in the Gulf Stream.

An equation describing the balance of mechanical energy can be obtained by taking the scalar product of $\bar{\mathbf{v}}$ with the momentum conservation equation, and then performing a similar average (see, e.g., Hinze, 1959). This gives

$$\varrho \bar{u}_j \frac{\partial}{\partial x_j}\left(\frac{\bar{u}_i^2}{2}\right) + \varrho \bar{u}_i \frac{\partial}{\partial x_j}\overline{(u_i' u_j')} + \varrho \frac{\partial}{\partial x_j}(\bar{p}\bar{u}_j) - \mu \bar{u}_i \frac{\partial^2}{\partial x_j^2}(\bar{u}_i) = 0 \qquad (1)$$

where p is pressure, ϱ is density, μ is viscosity, and the usual subscript notation and summation conventions apply. The second term represents the decay of mean-flow kinetic energy by the working of the mean flow against the Reynolds stresses. This term can be estimated at the lake surface from our data. Neglecting vertical motions at the surface, the energy transfer from the mean flow becomes

$$T = \varrho\left\{\underset{①}{\bar{u}\frac{\partial}{\partial x}\overline{(u'^2)}} + \underset{②}{\bar{u}\frac{\partial}{\partial y}\overline{(u'v')}} + \underset{⑧}{\bar{v}\frac{\partial}{\partial x}\overline{(u'v')}} + \underset{④}{\bar{v}\frac{\partial}{\partial y}\overline{(v'^2)}}\right\}. \qquad (2)$$

The computations of T were carried out along the same sections and for the same time intervals that were used to find $\bar{\mathbf{v}}$ and $\mathbf{v}'$. Averages were also carried out in the same manner. Spatial derivatives of mean quantities are approximated by centered differences either from zone to zone (for $\partial/\partial y$) or from section to section (for $\partial/\partial x$).

This procedure is similar to that used for the corresponding computations of surface energy transfer in the Gulf Stream, mentioned above. However, only one component of the full horizontal transfer, $W = -\varrho\overline{u'v'}(\partial\bar{u}/\partial y)$ was calculated in the Stream. This estimate is based upon the not unreasonable choice of $\varrho\bar{u}(\partial/\partial y)(\overline{u'v'})$ as the dominant term in T, and the fact that the cross-stream integral of this term is closely $-\varrho\int\overline{u'v'}(\partial\bar{u}/\partial y)dy$ (Webster, 1961). The available data were apparently insufficient to calculate all terms in T. We will discuss the validity of this approximation below.

Errors were calculated on the basis of small-sample statistics. The standard deviations σ were estimated by $s/\sqrt{N}$, where s is the rms deviation of the sample, and N the number in the sample. All results are presented $\pm\sigma$. In part, these considerations fixed zone widths: smaller widths gave greater flow resolution (thus, more accurate derivatives of mean

Table 1. *Photogrammetric experiments used to compute surface kinetic energy transfer*

Date	Number of velocities obtained (time interval, hrs)	Wind during experiment (direction, kts)	Lake surface condition	Resultant wind for the eight-hour period just before experiment	
				Direction (°T)	Speed (kts)
4 August 1971	1 352 (2.4)	0	Flat calm	260	3
13 July 1972	1 278 (1.3)	0	Flat calm	161	4
19 July 1972	1 515 (1.0)	E, 2	10 cm ripples	109	1
27 July 1972	1 293 (1.0)	W, 1	Flat calm	218	3
27 July 1972	2 464 (1.1)	NE, 2	Flat calm	330	2

quantities), but also wider confidence limits. The changes in W due to variations in zone widths and direction are within the limits of statistical significance. It will be seen below that the statistical uncertainty overshadows errors associated with the photogrammetric method.

IV. The data

A summary of the photogrammetric experiments is given in Table 1. A number of other experiments were performed; only those where data density is acceptable for calculating all terms in the expression (2) for horizontal surface kinetic energy transfer are listed. By happenstance, all these experiments occurred during spring-regime conditions.

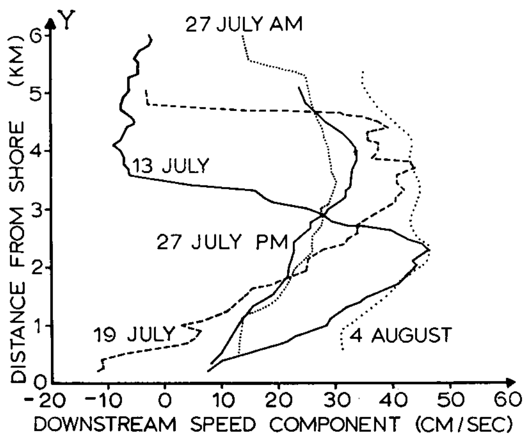

Fig. 4. Mean downstream velocity component profiles $\bar{u}(y)$ across the Keweenaw Current, obtained photogrammetrically.

The data are sufficiently dense to allow the computation of horizontal energy transfer along 22 sections. Regions of nearshore countercurrents were not included in computations. The approximate transfer W was also calculated, for comparison. The density ϱ is always taken to be 1 g/cm^3.

V. Results

(a) *Introduction*

Among the experiments conducted, those on 13 and 19 July, 1972 stand out as being of the highest quality, and spanning the entire current. These days, both clearly in the spring regime, will be emphasized below. July 13 was a day of high energy transfer; July 19 one of modest transfer. On both days, the Current was limited at the outer boundary by a countercurrent. The offshore limit coincided quite closely with the thermal bar (see, e.g., Rodgers, 1966, and Fig. 7). An inshore

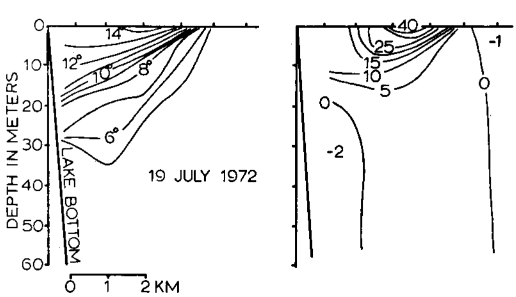

Fig. 5. Temperature cross section (°C) and longshore geostrophic currents (cm/sec) off Eagle Harbor on 19 July 1972. Positive isotachs denote flow to the east.

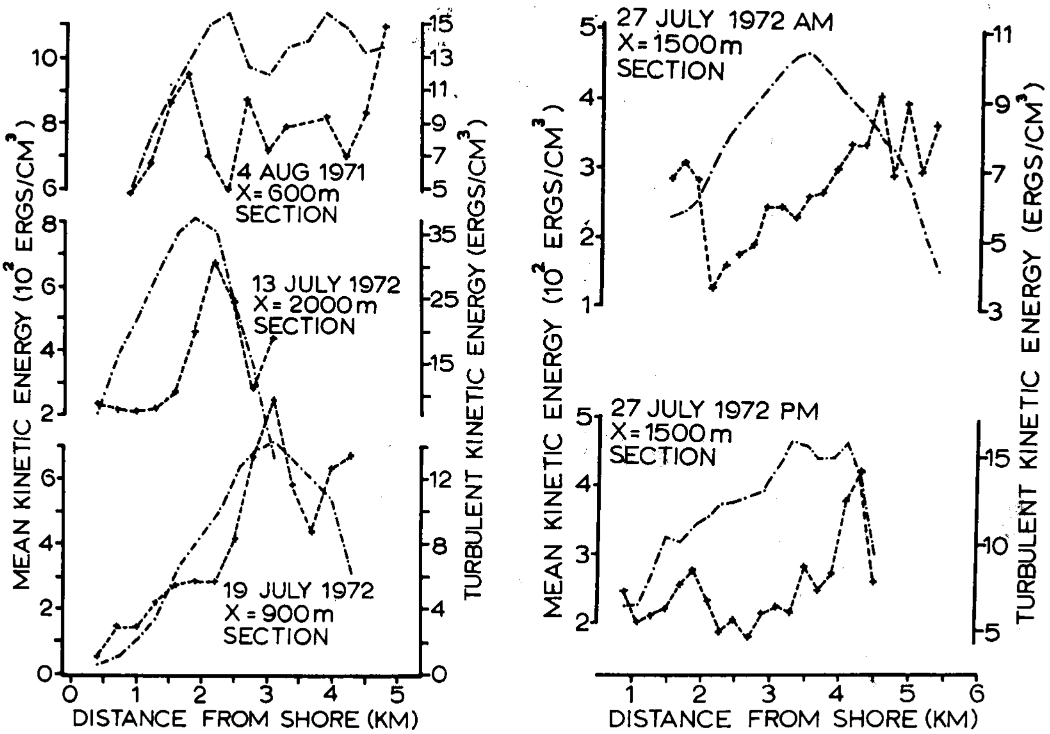

Fig. 6. Mean-flow kinetic energy $\varrho(\bar{u}^2+\bar{v}^2)/2$ and turbulent kinetic energy $\varrho(\overline{u'^2}+\overline{v'^2})/2$ across the Kewenaw Current. Dot-dash lines are mean-flow energy.

countercurrent existed on July 19, but not on July 13. Surface divergence dominates the current on 13 July, convergence on 19 July. Only highlights and "typical" data are presented below; the reader is referred to Yeske (1973) and Green & Yeske (1974) for other, similar data, and for more detail on that presented.

(*b*) *Mean flow*

Mean velocity profiles were calculated for several sections in each experiment. Representative profiles are shown in Fig. 4. The downstream changes in mean velocity average about 10% over the total longshore distance for which data are available. The thermal structure on July 19 is shown in Fig. 5, and is typical of that during the other epxeriments. No bathythermograph data were taken on July 13. Fig. 5 also shows the geostrophic velocity structure on July 19, arrived at using the usual dynamic height calculations (Ayers, 1956). The agreement between true surface speeds and geostrophic speeds is reasonably close. This correspondence holds on most of our spring-regime data, and seems to occur also in other of the Great Lakes (e.g., Scott et al., 1971).

The mean current appears to be related to local water level variations connected with free oscillations of the entire Lake, with a time scale of several hours. In each of the July 1972 experiments, current speeds measured every ten minutes increase (decrease) in phase with increases (decreases) in the water level at Eagle Harbor. Water level data were not taken in August 1971.

(*c*) *Turbulence*

Typical cross-stream variations in turbulence intensity $I=\overline{u'^2}+\overline{v'^2}$ are shown in Fig. 6. There is a weak relation between general peaks in $\overline{u^2+v^2}$, and I (thus, between $\bar{u}$ and I) in each experiment. Other than this, and a general similarity of the distributions of I on the various sections in each experiment, the different experiments have little in common.

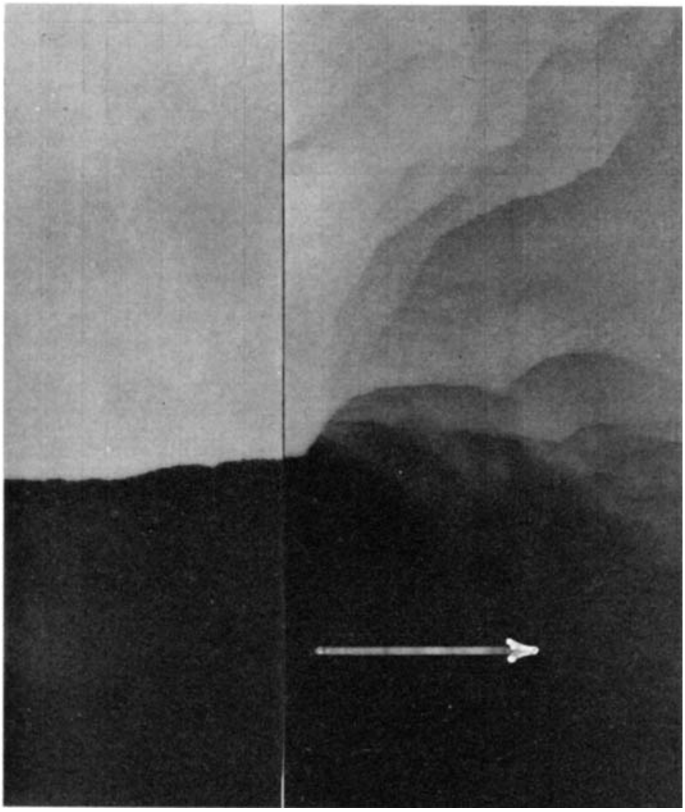

Fig. 7. An infrared line scan of the outer edge of the Keweenaw Current on 8 August, 1972, showing the sharp current boundary at the thermal bar and its downstream degeneration. The arrow denoting current direction is about 1 km long. Light tones denote colder (offshore) surface water, dark tons warmer (onshore) surface water. The maximum temperature difference is about 5°C. The vertical line comes from piecing together data from adjacent aircraft passes.

On July 13 and 19, I is quite well correlated with the mean downstream current speed. The term $\overline{u'^2}$ dominates I on July 13, but not on July 19. There is always a secondary maximum of I near the outer edge of the current on July 19, whereas this is usually absent on July 13.

This difference may well have been due to the presence of meanders along the sharp outer edge of the Current on July 19, with a space scale of about 1 km. These meanders seem to be associated with a frontal instability, and are most readily detected using airborne thermal scanning techniques (e.g., Scarpace & Green, 1973). An example of frontal instability and meander structure is shown in Fig. 7.

How much do meanders on the scale of the total Current width add to the velocity variations of the Current? Forty-eight airborne radiation thermometer surveys, together with several thermal scanner flights, in 1972 and 1973 (e.g., Fig. 7) indicate that these large meanders are quite rare, and probably not a major factor in the interaction between fluctuations and mean flow. Another crude estimate of the influence of an organized pattern of large meanders on I is the correlation between the mean cross-stream shear $\partial\bar{u}/\partial y$ and I. We find this correlation to be extremely weak, and conclude that, apart from instabilities on the order of one kilometer along the sharp outer edge, meanders are usually unimportant to the dynamics of the current.

The third momentum flux $\overline{u'v'}$ was also

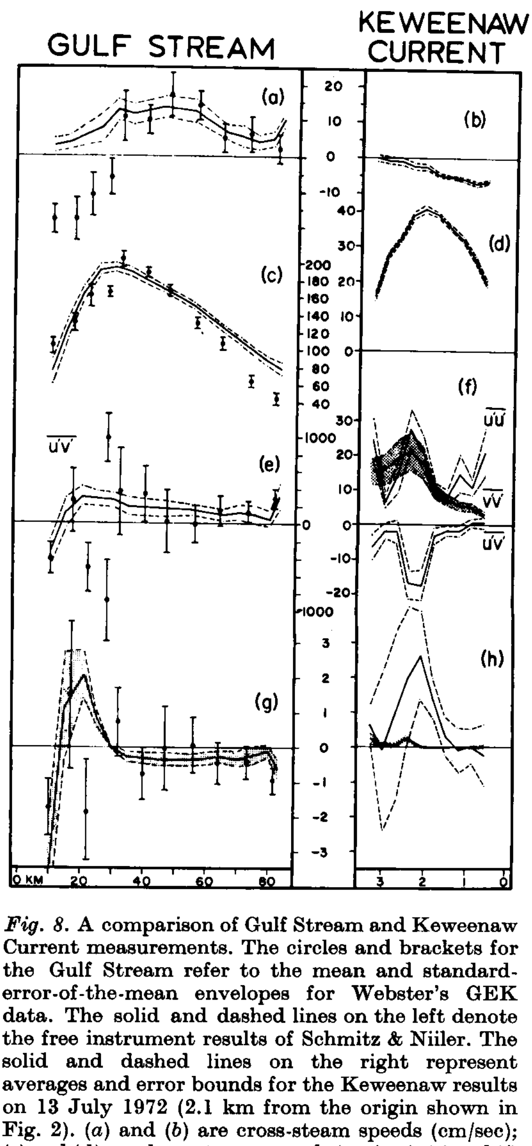

Fig. 8. A comparison of Gulf Stream and Keweenaw Current measurements. The circles and brackets for the Gulf Stream refer to the mean and standard-error-of-the-mean envelopes for Webster's GEK data. The solid and dashed lines on the left denote the free instrument results of Schmitz & Niiler. The solid and dashed lines on the right represent averages and error bounds for the Keweenaw results on 13 July 1972 (2.1 km from the origin shown in Fig. 2). (*a*) and (*b*) are cross-steam speeds (cm/sec); (*c*) and (*d*) are downstream speeds (cm/sec); (*e*) and (*f*) are momentum fluxes $\overline{u_i' u_j'}$ (cm²/sec²); (*g*) and (*h*) (shaded) are rates of kinetic energy transfer and error bounds ($\times 10^2$ ergs/cm³/sec) using $-\overline{u'v'}\,\partial\bar{u}/\partial y$. The unshaded solid and dashed lines in (*h*) depict the surface kinetic energy transfer from the mean flow, T, and the standard-error-of-the-mean envelope.

calculated in order to obtain the zonal kinetic energy transfers. It was normally quite small compared to $\overline{u'^2}$ and $\overline{v'^2}$.

(*d*) *Kinetic energy transfer*

The kinetic energy lost by the mean flow due to the action of the Reynolds stresses, T, was calculated in each zone. Webster used the estimate $W = -\varrho\overline{u'v'}\,\partial\bar{u}/\partial y$ for T, as discussed above. The full loss T involves four terms. Because the errors are rms additive (Berington, 1965), while the terms themselves cancel to some extent, the present results tend to be less significant statistically than those pertaining to the Gulf Stream. However, the larger amount of data in the present study compensates for this loss.

For comparison, a typical result for the Keweenaw Current is plotted beside Gulf Stream kinetic energy transfer computations of both Webster (*loc. cit.*), and Schmitz & Niiler (1969) in Fig. 8. The statistical significance of the Keweenaw results shown is similar to that on other days, and on other sections on the same day. Although the Keweenaw data are somewhat more significant, the two sets of data are quite comparable. Note, however, that W is only a very small portion of T in the Keweenaw Current. This is generally true in all our data. The full transfer T in the Keweenaw Current is somewhat greater than the approximate transfer W in the Gulf Stream.

The zonal kinetic energy transfer results on 13 and 19 July are shown along with the mean flow in Figs. 9 and 10. Both days, the transfer pattern changes fairly regularly (bearing in mind the confidence limits, which are not indicated on the figures) in the downstream direction. No one section on a given day can be regarded as representative. The space scale of downstream change of significant features is on the order of a few hundred meters.

Examples of the computations leading to these results are given in Table 2. Downstream and cross-stream variations of zonal values of T are reasonably regular on both days. Of the four terms composing zonal values of T, $\varrho\bar{u}(\partial/\partial x)(\overline{u'^2})$ (term ① in eq. (2)) almost always dominates. The magnitudes of the sums of the four terms individually over all zones are in the ratio ①:②:③:④ = 1:0.12:0.05:0.04 (13 July) and 1:0.10:0.06:0.01 (19 July). Similar ratios of sums for the absolute values of the individual terms are 1:0.39:0.05:0.02 and 1:0.23:0.11:0.06. Term ④ is almost always negligible in zonal transfer. Terms ② and ③ are about the same size; ② is usually larger.

These statements are not generally true in the two or three zones nearest shore. Here, the effect of the coast on the surface flow may be significant through the action of either horizontal or vertical friction. This "frictional boundary layer" (FBL) is more apparent on July 13 than on July 19, probably due to the inshore countercurrent on July 19. We will adopt this terminology, bearing in mind that our suggestion of the dynamical significance of this region may be incorrect.

Those features of the individual terms which are dominant on either day but not both are given below. Bearing in mind the relatively broad confidence bounds, only those features common to all sections are noted.

July 13, 1972 was a day of large energy transfer. Here, ① is almost uniformly negative (i.e., acting to transfer surface kinetic energy to the mean flow), save for a consistent positive peak in the FBL. The negative extremum is always in the nearshore part of the cyclonic shear zone (CSZ), thus slightly offshore of the maximum current $\bar{u}$. This extremum tends to dominate ①, and thus T.

Term ② is usually negative. The only significant positive values are in the nearshore part of the CSZ. The absolute value of ② is only greater than that of ① in 9 of the 70 zones. Term ③ is almost always negative, and becomes extremely small in the lakeward part of the CSZ. There is a tendency for ③ to become positive in the FBL: the only significant positive values occur here. Term ④ is almost always negative, and hardly ever of significance to T.

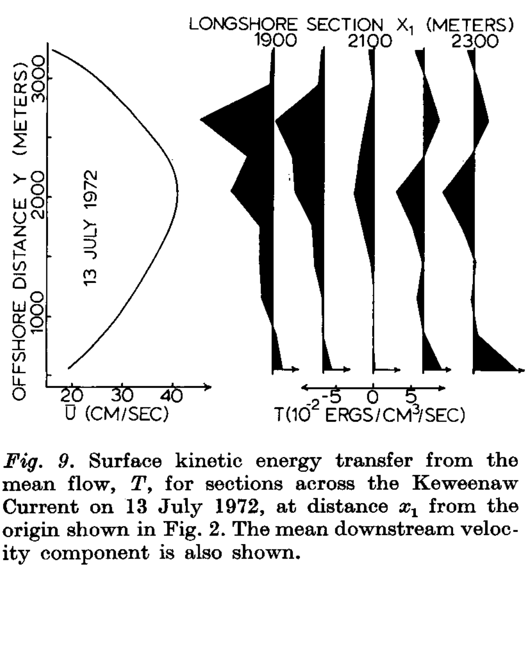

Fig. 9. Surface kinetic energy transfer from the mean flow, T, for sections across the Keweenaw Current on 13 July 1972, at distance x_1 from the origin shown in Fig. 2. The mean downstream velocity component is also shown.

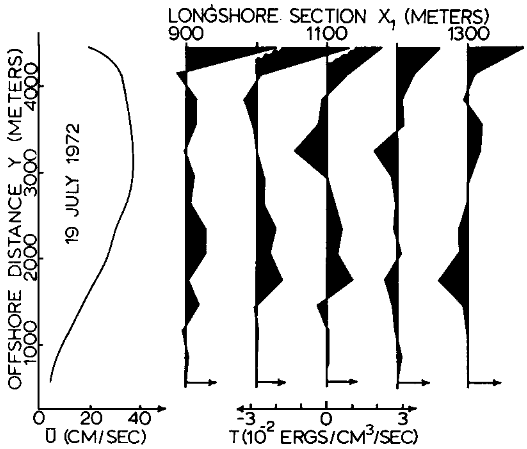

Fig. 10. Surface kinetic energy transfer from the mean flow, T, on 19 July 1972.

July 19, 1972 was a day of modest energy transfer. Term ① is generally small in the FBL (note that there was no inshore countercurrent on this day). It tends to be positive in the CSZ. There is no general sign in the anticyclonic shear zone (ACSZ). This term is always quite large and positive in the high-shear region which is the lakeward part of the CSZ. This contribution dominates ① and thus T over all sections, and forces net transfer of surface kinetic energy from the mean flow on this day. This phenomenon does not occur in 13 July.

Term ② is usually positive, but variations in sign seem uncorrelated with the cross-stream shear $\partial\bar{u}/\partial y$. The absolute value of ② tends to reach an extremum (of inconsistent sign) at the lakeward edge of the CSZ. It is small in the FBL. Term ③ has little pattern, although it tends to be negative. Term ④ is again negligible.

The data on the other days are not sufficiently complete to warrant detailed discussion. August 4, 1971 is also in the spring regime. However, the data only cover the central region of the Current. Terms ① and ② dominate T, and are generally about the same size. A large energy transfer usually occurs in the outer zone. The sign, however, is

Table 2. *Representative surface kinetic energy transfers for two experiments*

The zone width is 300 m. The number of interpolated velocities averaged over in a zone ranges between 13 and 20. All individual transfer terms are in units of 10^{-2} cm^2/sec^3. The net zonal transfers T and T' are in units of 10^{-2} erg/cm^3/sec

Inner boundary of zone y (km)	$\bar{u}$ (cm/sec)	① $\bar{u}\partial/\partial x(\overline{u'u'})$	② $\bar{u}\partial/\partial y(\overline{u'v'})$	③ $\bar{v}\partial/\partial y(\overline{v'v'})$	④ $\bar{v}\partial/\partial x(\overline{u'v'})$	Kinetic energy transfer from the mean flow, T	Kinetic energy transfer to the turbulence, T'
(*a*) July 13, 1972. Time interval: 1725–1807. Distance of section from origin: 1.9 km							
0.4	20.3 ± 0.6	1.77 ± .92	− .27 ± .13	− .01 ± .03	− .13 ± .10	1.36 ± .94	.08 ± .03
0.7	26.0 ± 0.8	0.49 ± .88	− .19 ± .10	− .01 ± .02	− .24 ± .16	0.05 ± .90	.07 ± .03
1.0	31.3 ± 1.0	− 1.22 ± 1.61	− .01 ± .18	− .05 ± .03	− .13 ± .16	− 1.41 ± 1.63	.10 ± .04
1.3	35.4 ± 0.9	− 1.52 ± 1.62	.04 ± .31	− .08 ± .05	− .07 ± .20	− 1.63 ± 1.66	.09 ± .05
1.6	39.8 ± 0.9	− .20 ± 1.55	− 1.37 ± .37	− .12 ± .05	.04 ± .28	− 1.65 ± 1.62	.09 ± .07
1.9	39.4 ± 1.4	− 3.78 ± 2.70	− 1.55 ± .60	− .03 ± .03	− .15 ± .16	− 5.51 ± 2.78	− .51 ± .06
2.2	38.0 ± 1.6	− 3.12 ± 5.08	.31 ± .87	.00 ± .00	.00 ± .03	− 3.43 ± 5.16	− 1.35 ± .19
2.5	34.6 ± 1.9	− 11.36 ± 9.00	1.81 ± .49	.00 ± .01	− 0.7 ± .21	− 9.62 ± 9.02	.42 ± .51
2.8	25.0 ± 0.9	− 1.57 ± 4.37	1.14 ± .56	.00 ± .02	.00 ± .03	− .44 ± 4.41	.02 ± .13
3.1	10.7 ± 1.1	.23 ± .92	− .24 ± .16	.00 ± .01	.00 ± .03	− .02 ± .94	− .56 ± .21
(*b*) July 19, 1972. Time interval: 0939–1011. Distance of section from origin: 1.3 km							
0.4	3.7 ± 0.3	.03 ± .01	.00 ± .01	− .01 ± .01	.03 ± .01	.05 ± .02	− .01 ± .00
0.7	6.7 ± 0.6	− .03 ± .10	.01 ± .01	− .00 ± .00	− .01 ± .05	− .03 ± .11	− .02 ± .01
1.0	11.6 ± 0.4	− .04 ± .14	.01 ± .03	.05 ± .02	− .01 ± .06	.02 ± .15	− .02 ± .01
1.3	15.2 ± 0.4	− .23 ± .30	− .11 ± .03	.03 ± .01	.13 ± .12	− .18 ± .33	.01 ± .02
1.6	20.8 ± 0.8	− .92 ± .92	− .09 ± .06	− .05 ± .01	− .11 ± .12	− 1.16 ± .93	.18 ± .04
1.9	27.6 ± 1.0	− .19 ± 1.50	.12 ± .07	− .02 ± .02	− .25 ± .11	− .34 ± 1.51	.04 ± .02
2.2	31.1 ± 1.0	− .28 ± 2.53	.15 ± .05	− .01 ± .01	− .20 ± .12	− .33 ± 2.53	.00 ± .01
2.5	35.4 ± 1.0	− .04 ± 2.68	.07 ± .08	− .02 ± .01	− .03 ± .06	− .01 ± 2.68	− .07 ± .02
2.8	38.1 ± 1.2	.11 ± 4.58	.11 ± .08	.03 ± .01	− .18 ± .13	.08 ± 4.58	− .06 ± .03
3.1	38.2 ± 1.2	.27 ± 4.57	.21 ± .13	.06 ± .02	− .04 ± .14	.50 ± 4.57	− .03 ± .02
3.4	36.6 ± 1.2	.59 ± 3.47	− .04 ± .09	− .02 ± .01	.01 ± .20	.53 ± 3.48	− .01 ± .04
3.7	34.3 ± 1.0	− .10 ± 2.24	.01 ± .14	− .02 ± .01	.00 ± .05	− .11 ± 2.24	.09 ± .02
4.0	32.3 ± 1.3	.42 ± 3.33	− .20 ± .09	− .01 ± .00	.04 ± .06	.25 ± 3.33	.37 ± .07
4.3	12.5 ± 2.3	2.44 ± 3.23	− .24 ± .09	.00 ± .00	− .01 ± .01	2.19 ± 3.23	2.06 ± .42

not consistent, and the zone one of relatively modest anticyclonic shear.

July 27, 1972 seems to have been in the period of transition between the spring and summer regimes. In the morning, term ① is positive, and completely dominates T, although the largest transfer is now in the ACSZ. In the afternoon, there is a substantial downwelling near shore, and $\bar{u}$, $\bar{v}$ are similar in size except in the outer zones. Largely because of this, no terms dominate T. Kinetic energy transfer is again large in the FBL, only now this adds energy to the mean flow. However, transfers near the maximum current dominate the net exchange.

The cross-stream average kinetic energy transfers $\hat{T}$ are found by summing T over a section and dividing by the number of zones. The results are shown in Table 3. These average transfers vary slowly in the downstream direction on all days—more slowly than the individual zonal transfers. A convenient measure of the efficiency of the average transfer is the transfer time $\tau = \varrho\widehat{(\bar{\mathbf{v}}\cdot\bar{\mathbf{v}})}/2\hat{T}$. For $\hat{T} > 0$, τ is a decay time: the time needed for the observed average transfer, if maintained at that rate, to bring the observed mean flow to zero. Negative values of $\hat{T}$ signify average energy transfers to the mean flow, and here τ can be regarded as a doubling time for mean-flow kinetic energy. In both cases, a small value of τ denotes a relatively efficient energy transfer.

These transfer times are also shown in Table 3. For comparison, Webster found

Table 3. *Surface kinetic energy transfers*

Date	Section distance from origin (km)	Cross-stream average kinetic energy of mean surface flow (ergs/cm^3)	Cross-stream average rate of surface kinetic energy transfer from mean flow, $\hat{T}$ (ergs/cm^3/sec)	Transfer time, τ (days)
4 August 1971	0.6	9.60×10^2	-25.2×10^{-4}	4.4
	0.9	9.65	−10.7	10.4
	1.2	9.75	11.2	−10.1
	1.5	9.91	31.9	−3.6
17 July 1972	1.9	4.52	−222.9	0.2
	2.0	4.53	−163.3	0.3
	2.1	4.68	−73.3	0.7
	2.2	4.83	−19.1	2.9
	2.3	4.86	15.3	−3.7
19 July 1972	0.9	3.31	45.2	−0.8
	1.0	3.32	45.2	−0.8
	1.1	3.20	24.6	−1.5
	1.2	3.12	8.1	−4.5
	1.3	3.02	10.3	−3.4
27 July 1972 AM	1.4	3.43	59.1	−0.7
	1.5	3.41	61.8	−0.6
27 July 1972 PM	1.5	2.75	−0.4	−78.5
	1.6	2.74	3.5	−9.1
	1.7	2.51	−13.2	2.2
	1.8	2.39	−25.1	1.1
	1.9	2.37	−8.1	3.4
	2.0	2.42	−6.3	4.4

doubling times which were usually on the order of 20 days in the Gulf Stream. Because the mean-flow kinetic energy does not vary widely between experiments, an overall measure has some significance. There are altogether 108 doubling days, and 39 decay days, so that transfer of energy from the mean flow seems to dominate. However, when $\hat{T}$ is small, τ is quite large and can bias results based on such a small sample. If the 1.5 km section on 27 July PM is deleted, there are only 30 doubling days. Now the overall picture suggested by our limited data must be regarded as inconclusive: transfers from the mean flow may very well be offset by opposite transfers at other times. Over the duration of the spring regime, the net energy transfer may be quite small.

Energy transfers also show a tendency to cancel in the along-current direction on individual days. This suggests that the principal contribution of the Reynolds stresses may be the downstream redistribution of mean-flow kinetic energy. The significant variation of T across most sections also implies mainly a redistribution, rather than a net transfer, of kinetic energy.

Although mean-flow energetics were the primary emphasis of this work, the turbulence energy balance is also of some interest. The term analogous to T which measures the gain of surface kinetic energy by the turbulence due to the action of the Reynolds stresses is (Hinze, 1959)

$$T' = -\varrho\left\{\overline{u'u'}\frac{\partial \bar{u}}{\partial x} + \overline{u'v'}\frac{\partial \bar{u}}{\partial y} + \overline{u'v'}\frac{\partial \bar{v}}{\partial x} + \overline{v'v'}\frac{\partial \bar{v}}{\partial y}\right\}$$

We calculated zonal values of T' for some representative sections. The term $\overline{u'u'}(\partial\bar{u}/\partial x)$ seems to dominate T'. Along the July 13 and July 19 sections shown in Table 2, T' is

Table 4. *Turbulence and mean-flow transfer times*

Positive values denote energy transfers to the turbulence or mean flow

Date, section	Mean-flow transfer time (h)	Turbulence transfer time (h)
13 July 1972 1.9 km from origin	5	−0.9
19 July 1972 1.3 km from origin	−82	3

usually much smaller than T. However, because the turbulent kinetic energy I is much smaller than that of the mean flow, the turbulent transfer time $\hat{I}/\hat{T}'$ is small compared to its mean-flow counterpart (Table 4). That is, the Reynolds-stress interactions are more important to the turbulence than to the mean flow. On both days, an energy transfer from one flow component is accompanied by a transfer to the other component, as expected.

(e) *The relation of average surface kinetic energy transfer to the resultant wind*

The direction of the mean-flow surface kinetic energy transfer appears to depend to some extent upon the wind field. Net transfers to the mean flow occur on July 13 and July 27 (PM), both late afternoon experiments, The eight-hour resultant winds just before these experiments were 10° and 21° from the y (i.e., cross-stream) axis. A net transfer from the mean flow occurred in the other three experiments described above (all morning experiments). Here the eight-hour resultant wind directions were 47°, 62°, and 89° from the y axis. The reason for this apparent relation between wind direction and energy transfer is not known. There seems to be no relation between resultant wind speed and rate of transfer.

VI. Summary

The kinetic energy transfer from the surface mean flow of the Keweenaw Current due to the action of the Reynolds stresses has been estimated using an aerial photogrammetric technique. Transfers are about the same size as those calculated by others for the Gulf Stream. However, the term $\bar{u}\partial/\partial x(\overline{u'^2})$ dominates the total transfer T; the term $\overline{u'v'}\,\partial\bar{u}/\partial y$, which was used in the Gulf Stream calculations to estimate T, is an order of magnitude smaller. If this relation also holds in the Gulf Stream, the energy transfer is larger than previously thought.

A large contribution to T often occurs at the sharp outer edge of the current, located at the thermal bar. This contribution seems to be associated with meanders of the outer edge, due in turn to a frontal instability mechanism.

The transfers calculated at points both along and across the current suggest that the horizontal Reynolds stresses act mainly to redistribute mean-flow kinetic energy in the long-current direction. Although there are fairly large gains or losses of energy at certain points over any section across the current, they persist only relatively short distances downstream, and can change sign in a few hundred meters. The resultant wind directions over the eight hours preceding the experiments are correlated with the direction of overall energy transfer. Transfers from the mean flow occur in conjunction with long-current winds, transfers to the mean flow in conjunction with cross-current winds. Reynolds-stress transfers to the turbulent kinetic energy are smaller than those from the mean flow, but seem quite important to the turbulent kinetic energy balance.

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ГОРИЗОНТАЛЬНЫЙ ТУРБУЛЕНТНЫЙ ПЕРЕНОС ЭНЕРГИИ, СВЯЗАННЫЙ С ПРИБРЕЖНЫМ ТЕЧЕНИЕМ В ВЕЛИКИХ ОЗЕРАХ

С помощью самолетной фотограмметрической техники несколько раз летом 1971 и 1972 гг. измерялась мелкомасштабная структура течения Кивиноу. Вычисляется перенос кинетической энергии от среднего потока, производимый напряжениями Рейнольдса. Потоки энергии имеют место как к самому течению, так и от него, и они составляют значительную часть средней кинетической энергии. Результаты расчетов показывают, что такие переносы проявляются, главным образом, в перераспределении энергии вдоль течения. Направление переноса энергии может быть связано с направлением ветра: ветры вдоль течения приводят к переносу энергии от среднего течения, ветры, дующие поперек течения, вызывают перенос энергии к течению.