when the tangled clump of plants is subjected to currents. As the process of entanglement continues, holdfasts are pulled off the substratum (as shown in Fig. 3) or the stresses in intact stipes exceed their breaking stresses and they fail.

*Summary—Nereocystis* reportedly grow to lengths up to 40 m (Smith 1944) and are subjected to tensile forces by the buoyancy of their floats and to predominantly tensile drag forces by waves and tidal currents. Although the strength of *Nereocystis* is low relative to other biomaterials, the stipe can absorb as much energy before breaking as can wood or bone because of its high extensibility. We suggest that the high extensibility is allowed by the crossed helical array at 60° to the stipe axis of cellulose fibrils embedded in a visco-elastic gel matrix in the cell walls of the cortical tissue. The central position of the load-bearing inner cortical tissue in the stipe is consistent with tension-resisting, bend-permitting design principles (Wainwright et al. 1976) and places this important tissue as far as possible from abrasions and from nibbling urchins whose activities ultimately lead to kelp breakage.

A *Nereocystis* is an example of a structure that can withstand flowing water not by being rigid and strong, but rather by being flexible and extensible. If a body is easily bent and stretched, the form drag of the body in flowing water may be reduced (Wainwright and Koehl 1976), and the work that moving water must perform on the body to break it may be quite high.

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# Observed resultant circulation of Lake Ontario

*Abstract*—Vector-averaged current data from June–October 1972 suggest that Lake Ontario's resultant circulation during the stratified period consists of a dominant counterclockwise gyre together with a small clockwise gyre in the northwest portion of the lake. Current speeds are lowest in spring and have maximum vertical shear in early autumn. Spectra comparing summer and winter winds and currents show more high frequency energy in summer winds and currents and more low frequency energy in winter winds and currents.

One of the earliest studies of Lake Ontario currents was by Harrington (1895), who deduced a mean surface drift during the stratified period. He launched drift bottles from May–October in 1892, 1893, and 1894 and concluded that along the south shore the mean flow was to the east. Along the north shore the pattern was less clear; bottles launched in that region were also recovered on the south shore, often far to the eastern end of the lake.

Millar (1952) predicted Lake Ontario's circulation from ship intake temperatures recorded year-round from 1934–1946. He plotted the progression of the lake's surface temperature and found that the monthly mean isotherms were generally parallel with the isobaths. From these isotherm patterns, Millar concluded that the distribution of density must give rise, in both summer and winter, to a density current eastward near the south shore and westward near the north shore. Hence Harrington's north shore bottles would have gone counterclockwise around the whole lake to end up on the southeast shore.

Rodgers and Anderson (1963) added subsurface temperature data by using bathythermographs at 50 stations during 21 cruises from 1958–1961. They also concluded that if gradient currents existed, the mean thermal structure would imply a counterclockwise flow as summer progressed.

Whereas Harrington only measured surface currents, Casey et al. (1966) measured currents at several depths. Seventeen buoy stations were used to record both temperatures and currents from August 1964–November 1965. From their data, they drew a counterclockwise mean circulation pattern above the thermocline when the lake was stratified. Off Rochester, New York, however, part of the flow apparently left the south shore and headed north to avoid the full lake circuit. Currents below the thermocline (from both deep meters and seabed drifters) generally flowed in the same direction as those above. Mean temperature data from the buoy stations, supplemented by ship cruises, again showed the midlake cool water mound, with its upward bulging thermocline lasting from early spring into August.

Sweers (1969) reanalyzed Lake Ontario's thermal structure using temperatures recorded on ship cruises (9 in 1966, 11 in 1967) at 50 stations at 2-week intervals from June–October. Mean temperatures calculated from bathythermographs and towed thermistors once again showed midlake temperature minima consistent with a counterclockwise thermal circulation.

Hence both surface and subsurface temperature and current data from these earlier studies suggested a mean counterclockwise circulation in Lake Ontario during its stratified period. Against this background, the International Field Year for the Great Lakes (IFYGL) study of Lake Ontario was started in 1972 by Canada and the United States. Measurements were taken in a manner similar to Casey's, with buoy and tower stations operating throughout the lake from April 1972–March 1973.

The first available IFYGL data were from the coastal zone during the stratified season. Scott (1973) and Csanady and Scott (1974) showed that, within 10 km of shore, currents accelerated with the wind. When the wind slackened, however, the coastal current pattern appeared to drift slowly counterclockwise around the lake.

Next, the July deep-water current data were analyzed. Pickett and Richards (1975) found a one-cell counterclockwise resultant circulation, although data from several meters in the western portion of the lake did not seem to conform to this pattern.

Finally, we have analyzed all of the IFYGL summer current data. Our analysis confirmed the dominant counterclockwise resultant flow found or predicted by others, but we also found a small clockwise gyre in the northwestern portion of the lake.

The buoy and tower sensors were designed to sample every few minutes (6 min for the United States sensors, 10 min for the Canadian sensors) and to record surface winds within 1 m $s^{-1}$ and 5°, water temperatures within 0.2°C, and currents within 2 $cm^{-1}$ and 5°. Sensors operating <20% of the time were ignored, and current meters operating within 10 m of the surface (possible surface wave and buoy motion rectification) were not included.

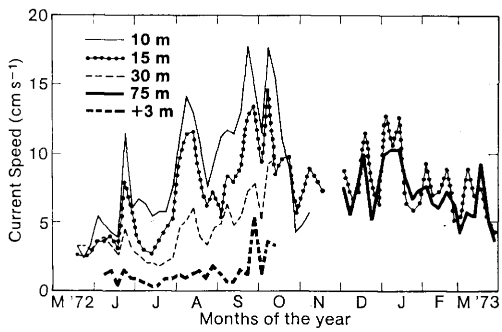



Fig. 1. Lake Ontario wind and current speeds averaged over 5-day intervals and all available sensors.

The remaining data were edited and averaged.

Both scalar and vector averages of currents were calculated. Speeds were scalar averaged over all sensors at the same depth, over 5 days, and then plotted for the entire year. Power spectra of wind and current components were also calculated for both the stratified (June 1972 through September 1972) and unstratified (November 1972 through March 1973) seasons. Finally, monthly and seasonally vector-averaged currents were computed and plotted for each sensor at each depth.

The 5-day averages of scalar current speeds for the 1972 field year are given in Fig. 1. Since these are averages over the whole lake and over 5 days, only large-scale, long lasting effects show up in the plot. One obvious feature of the figure is that in winter, when the lake is unstratified, currents appear to have similar speeds at all depths. In summer, when the lake is stratified, speeds decrease rapidly with depth. Turnover occurred at the end of October.

In addition to stratification effects, there is a gradual increase in current speeds at all levels from spring to fall. This increase is due partially to the greater wind speeds of autumn and partially to air–lake temperature differences. In spring the warm wind over the cool lake is less effective in driving currents.

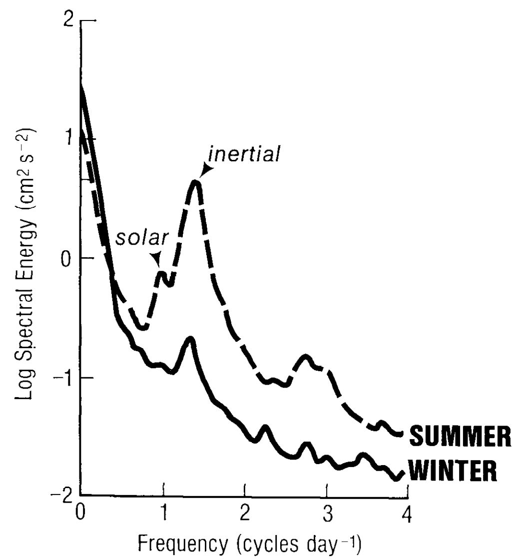



Fig. 2. Lake Ontario averaged current spectra at −15 m for east–west components in summer (June through October) and winter (November through May).

Still other differences between winter and summer currents can be seen in the sample power spectra in Fig. 2. These are averages of spectra from all stations of the east–west components of current speed at 15 m for the stratified and unstratified periods. Only the inertial, solar, and very low frequencies contain significant amounts of energy (modulation of the inertial generates the apparent energy at twice the inertial frequency). For all frequencies higher than 0.5 cy $d^{-1}$, summer currents contain almost an order of magnitude more energy than winter currents. The maximum difference is at the inertial frequency, where summer currents contain 25 times more energy. For frequencies shorter than 0.5 cy $d^{-1}$, winter currents contain more energy. Similar results were obtained for the north–south current components.

Some of the above differences in current spectra are due to seasonal differences in the wind. The analogous winter and summer wind spectra are shown in Fig. 3. These plots are also averages of spectra at each station of the east–west components

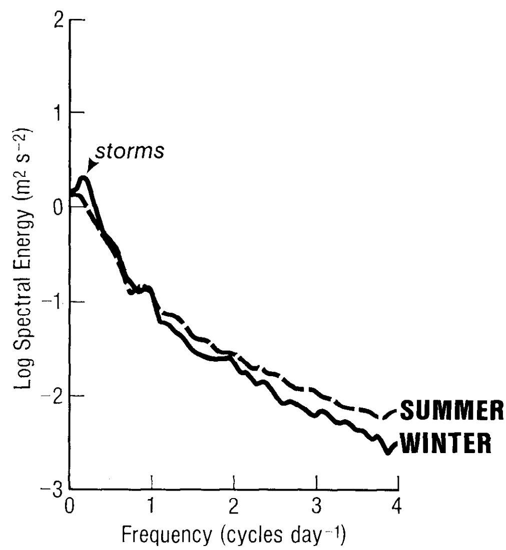



Fig. 3. As in Fig. 2, except wind spectra at surface.

of surface wind. They show more 4- to 8-day storm period energy in the winter wind and more high frequency energy in the summer wind.

The horizontal distribution of currents at all depths is presented in Fig. 4. These currents were vector averaged over the entire stratified season (as was done by Harrington and Casey et al.) because the monthly averages were all similar to each other and to the combined pattern. Part of the reason for this similarity is undoubtedly the similarity of the monthly summer winds, as shown in Table 1.

The current speeds in Fig. 4 are much lower than the scalar speeds in Fig. 1 because vector averaging removes gravity waves, inertial oscillations, and other nearly periodic disturbances. Only the steady or aperiodic background components remain.

In addition to the resultant currents themselves, stippled arrows have been added to Fig. 4 to show the general pattern. The pattern is counterclockwise except for a small clockwise gyre in the northwest portion of the lake. Also still evident is the tendency, noted by Casey et al., for part of the pattern to parallel the midlake rise by angling northward off Rochester, New York.

From both the summer and winter (Pickett 1976) data, the following pattern emerges. Off the south shore the resultant

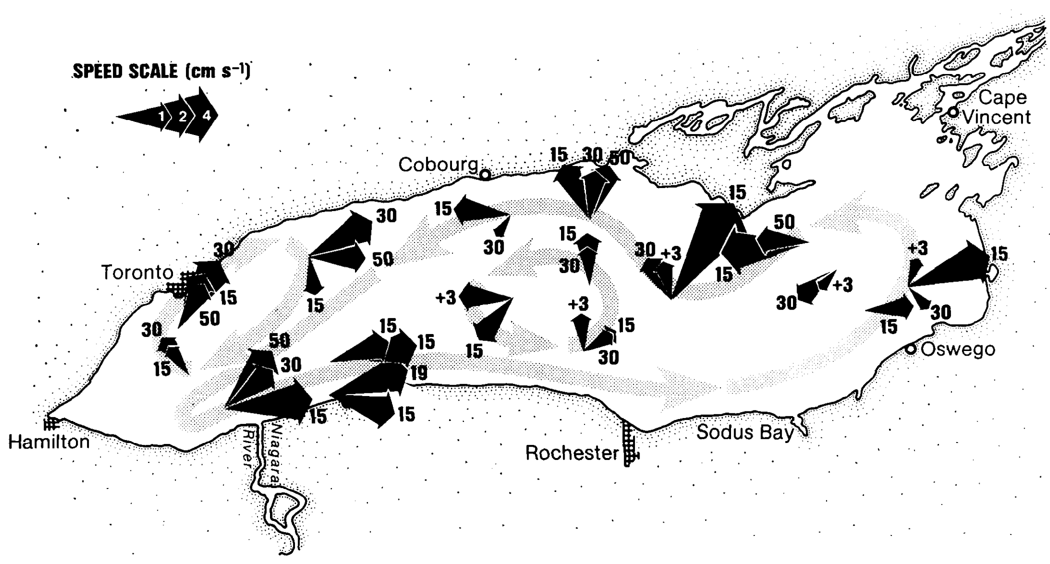
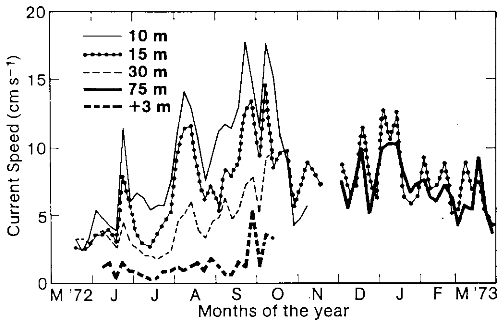



Fig. 4. Lake Ontario observed currents (depths in meters at arrow tips; +3 indicates 3 m off bottom) vector averaged from June through October 1972.

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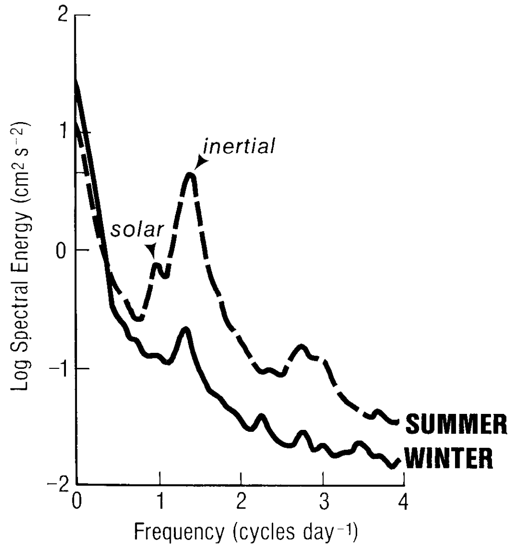


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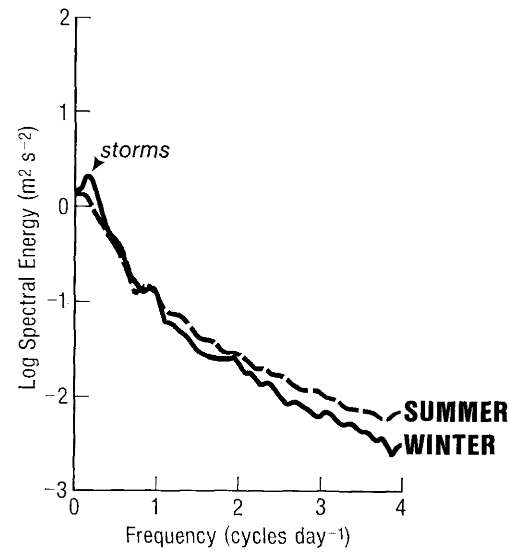


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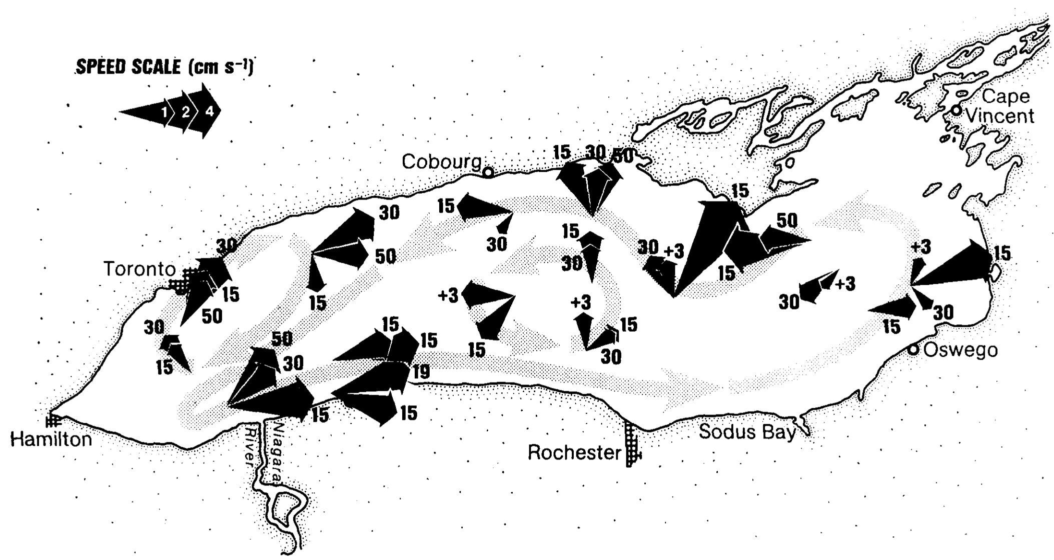


Fig. 4. Lake Ontario observed currents (depths in meters at arrow tips; +3 indicates 3 m off bottom) vector averaged from June through October 1972.

Table 1. Monthly summer winds.

| | Vector-averaged direction (from) | Scalar speed (m $s^{-1}$) | Resultant speed (m $s^{-1}$) |
|---|---|---|---|
| Jun | W | 4 | 1 |
| Jul | W | 3 | 2 |
| Aug | SW | 4 | 1 |
| Sep | W | 4 | 1 |
| Oct | W | 5 | 2 |

flow is to the east both in winter and in summer. The vector-averaged speeds in winter are about 5 cm $s^{-1}$ and in summer about 2 cm $s^{-1}$. Off the north shore the pattern is more complicated. In summer, the eastern two-thirds of the north shore has a resultant flow pattern to the west at about 2 cm $s^{-1}$, while the western third has a resultant flow to the east at about the same speed. Where these two patterns meet, they turn southwest. In winter, with more variable winds and very little possibility of a thermal current, the northwestern clockwise gyre seems to expand and contract from month to month. At one extreme the clockwise gyre covers the northern half of the lake, at the other extreme it disappears. When the clockwise gyre is large, resultant currents off the north shore are in the same direction as those off the south shore, and the return flow is to the west down the middle of the lake. When the clockwise gyre disappears, there is only one large counterclockwise gyre pattern.

Most of the differences in energy between summer and winter currents can be attributed to the differences between summer and winter winds. The mean wind stress in summer was less, and there were fewer strong storms. As a result, summer currents contained less low frequency energy. But summer winds contained more high frequency energy which, coupled with stratification to reduce damping, would account for the greater energy in higher frequency currents in summer.

As mentioned above, earlier investigators deduced that Lake Ontario had a single-gyre counterclockwise resultant circulation during its stratified period. But what is the role of the wind in such a circulation pattern? Emery and Csanady (1973), Wunsch (1973), and Bennett (1975) all offered explanations of how the wind could support a one-cell counterclockwise pattern. They argued that a variable wind drag coefficient, Kelvin wave drift, or the effect of uneven stratification could produce a wind-driven circulation in agreement with earlier observations.

In addition to the one-gyre mechanism, however, there could also be a barotropic two-gyre response of Lake Ontario to the wind such as that predicted by Rao and Murty (1970). Since the prevailing wind is from the west or southwest all summer, the resulting steady state current pattern would consist of a clockwise cell in the northern half of the lake and a counterclockwise cell in the southern half.

A combination of the above mechanisms probably accounts for the IFYGL observations of Lake Ontario's resultant circulation during the stratified season. The mean wind may tend to generate two counterrotating gyres, while variations in the wind and possibly thermal mechanisms tend to generate one counterclockwise gyre. The net result would be two counterrotating gyres with a diminished clockwise cell and an enlarged counterclockwise cell. The relative size of these two gyres would vary with the relative strength of the one- and two-gyre mechanisms.

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# The thermal structure of the Dead Sea

*Abstract*—The thermal structure of the Dead Sea was measured with a sensitive probe ($2 \times 10^{-3}$°C accuracy). It displays a horizontal uniformity below a depth of about 100 m. An adiabatic temperature distribution was found from the bottom (335 m) to a depth of 185 m.

The Dead Sea is a graben located in the Jordan rift zone. It is 80 km long, highly saline, its surface is about –400 m MSL, and it reaches a maximum depth of 335 m. Its average width is about 14 km. The sea is divided into a deep north basin and a shallow south basin whose depth is only a few meters. Along most of its length the graben is bordered by fault scarps.

Neev and Emery (1967) were the first to measure the thermal structure throughout the depth of the lake in a systematic manner using calibrated instruments. They used a reversing thermometer for depths >250 m with an accuracy of 0.1°C and a bathythermograph for depths between the surface and 250 m with an accuracy of 1.0°C and a sensitivity of 0.1°C. They also reported earlier temperature measurements.

In October 1975 a thermal survey was made of the water-covered portions of the Jordan rift zone: Lake Kinneret, Dead Sea, and Gulf of Eilat. The mean value of the heat flow data determined for the Dead Sea is 0.7 $\mu$cal cm$^{-2}$ s$^{-1}$. The most reliable measurements are those of stations 1, 14, 15, 16, and 17 in the north part of the Dead Sea (Fig. 1) (Ben-Avraham et al. 1977). Their average value is 0.9 $\mu$cal cm$^{-2}$ s$^{-1}$. This value is comparable with nearby continental values obtained by measurement of the heat flow in abandoned wells (Eckstein 1975). The continental average value is 1 $\mu$cal cm$^{-2}$ s$^{-1}$.

A heat flow probe was used to measure the heat flux from the sediment as well as the water temperature. It can measure temperatures to a relative accuracy of 0.002° C; Hänel (1970) gives a detailed description of the instrument. This enabled us to resolve the fine thermal structure of the water body as a by-product of the heat flow survey.

The thermal profile (Fig. 1) shows a horizontal uniformity below a depth of about 100 m. It includes all the water temperature data (Table 1). Measurements at different stations in the north basin as far apart as 40 km fall on a line with a very small deviation for any given depth, except for station 19, where we had some instrumental difficulties. In the top 100 m there