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References

Bolin, B., and W. Bischof. 1970. Variations of the carbon dioxide content of the atmosphere in the northern hemisphere. Tellus **22:** 431–442.

Broecker, W. S., Y. H. Li, and T.-H. Peng. 1971. Carbon dioxide—man's unseen artifact, p. 287–324. *In* D. W. Hood [ed.] Impingement of man on the oceans. Wiley-Interscience.

Culberson, C. H., and R. M. Pytkowicz. 1973. Ionization of water in seawater. Mar. Chem. **1:** 309–316.

Deffeyes, K. S. 1965. Carbonate equilibria. A graphic and algebraic approach. Limnol. Oceanogr. **10:** 412–426.

Fairhall, A. W. 1973. Accumulation of fossil CO_2 in the atmosphere and the sea. Nature (Lond). **245:** 20–23.

Hansson, I. 1973. A new set of acidity constants for carbonic and boric acids in sea water. Deep-Sea Res. **20:** 461–478.

Lyman, J. 1957. Buffer mechanism of sea water. Ph.D. thesis, Univ. Calif., Los Angeles. 196 p.

Machta, L. 1972. The role of the oceans and biosphere in the carbon dioxide cycle, p. 121–145. *In* D. Dyrssen and D. Jagner [eds.], The changing chemistry of the oceans. Almqvist and Wiksell.

Murray, C. N., and J. P. Riley. 1971. The solubility of gases in distilled water and in sea water. 4. Carbon dioxide. Deep-Sea Res. **18:** 533–541.

Pales, J. C., and C. D. Keeling. 1965. The concentration of atmospheric carbon dioxide in Hawaii. J. Geophys. Res. **70:** 6053–6076.

Park, P. K. 1969. Oceanic CO_2 system. An evaluation of ten methods of investigation. Limnol. Oceanogr. **14:** 179–186.

Whitfield, M. 1974. Accumulation of fossil CO_2 in the atmosphere and in the sea. Nature (Lond.) **247:** 523–525.

Zimen, K. E., and F. K. Altenhein. 1973*a*. The future burden of industrial CO_2 on the atmosphere and the oceans. Naturwissenschaften **60:** 198–199.

———, and ———. 1973*b*. The future burden of industrial CO_2 on the atmosphere and the oceans. Z. Naturforsch. **28a:** 1747–1753.

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Another explanation of the observed cyclonic circulation of large lakes

Abstract—The observed counterclockwise surface drift of large northern hemisphere lakes is explained by the variation of lake static stability caused by wind induced upwelling.

Emery and Csanady (1973) pointed out that many lakes and small seas in the northern hemisphere have counterclockwise surface circulations. Their explanation is that as warm surface water is advected to the right of the prevailing wind, increased wind drag over this warm water results in a cyclonic wind stress that drives a cyclonic surface flow. Wunsch (1973) proposed another explanation. He explained the cyclonic flow as the Lagrange drift induced by internal Kelvin waves. Both theories have merit; decreased turbulence over cold water is well established and the importance of nonlinear effects on Kelvin waves has been suspected for some time (Saylor 1970; Bennett 1973).

Here I propose a third mechanism and show it to be as important as Emery and Csanady's. This mechanism also invokes a prevailing wind to generate a cross-lake temperature gradient, but it explains a cyclonic surface circulation even for uniform wind stress.

At the upwelling shore, when the surface water moves offshore and is replaced

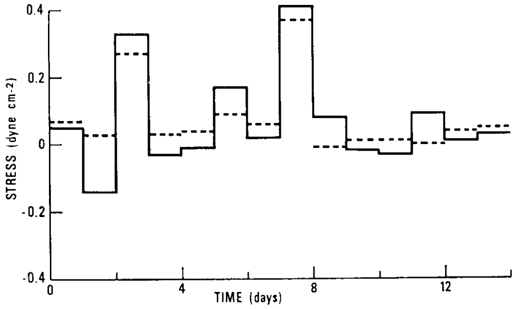

Fig. 1. Longshore component (solid line) and offshore component (dashed line) of wind stress.

by denser water, the static stability is lowered. This stability difference across the lake causes an asymmetry in surface current for two reasons. First, at the more stratified shore the wind influence is confined to the upper layer; stratification tends to suppress both large-scale vertical motion and downward turbulent transport of momentum. Second, once the flow is generated by the wind, decay is slower in stratified water because stratification insulates against bottom drag.

This work was done while I was an employee of the National Oceanic and Atmospheric Administration. My colleagues there, J. Ching, R. Pickett, and E. Aubert, contributed their aid and comments.

To compare the magnitude of this effect to that of Emery and Csanady's, two-dimensional "cross section" numerical model experiments similar to those in Bennett (1974) were run. Since longshore variations of current and temperature are neglected in this model the Wunsch theory could not be evaluated.

The bottom topography was parabolic with a maximum depth of 150 m and a shore depth of 15 m; the cross section width was 72 km. The computational mesh has 24 horizontal points and 12 vertical levels; the time step was 1 hr. Momentum advection was neglected, but advection of temperature is allowed. The initial condition was a motionless state with a basic temperature field consisting of a typical July temperature sounding for Lake Ontario with a linear north–south temperature gradient of 1°C per 24 km added to the upper 15 m. With no wind forcing, the initial imbalance causes a weak mean flow and an inertial oscillation which has a high degree of symmetry across the lake. It thus has no effect on the results. Throughout the experiments the temperature field undergoes a slow evolution due to wind mixing, surface heating, and vertical motion, but the surface temperature gradient is maintained.

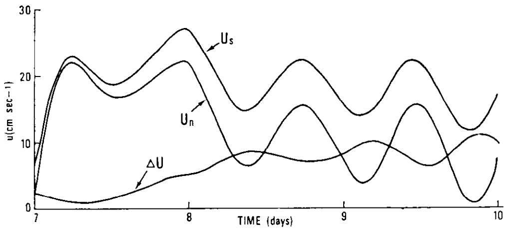

Fig. 2. Longshore current at 3 km from the north (u_n) and south (u_s) shores and the difference between them ($\Delta u = u_s - u_n$).

The eddy diffusivity was computed by the method of Sundaram and Rehm (1973). The same mixing coefficient was used for momentum but the bottom stress was computed from the quadratic law, using a drag coefficient of 0.002.

To evaluate the asymmetry in the mean flow due to uniform winds, I ran the model for 14 days using the wind stress given in Fig. 1. This was estimated from provisional data collected from 8–21 July 1972

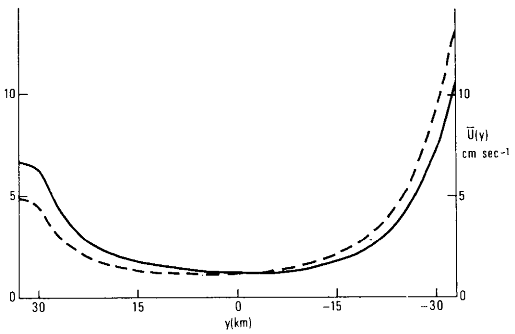

Fig. 3. Mean surface current for 14 days for uniform time dependent winds (solid line) and for uniform winds plus a time independent curl (dashed line).

as part of the International Field Year for the Great Lakes. The mean wind stress is from the southwest at about 0.1 dyne cm^{-2}.

Figure 2 shows the longshore component of the surface current at 3 km from each shore and the difference between the two for a 3-day period beginning with the 8th day. As expected, the difference increases both during the relatively strong winds on the 8th day and during the decay stage on the 9th and 10th days.

The mean longshore component of the surface current for the 14-day period for the case of uniform winds is the solid line in Fig. 3. Although it is toward the east even in the center of the lake, the flow at the southern (warm) shore is 4 cm sec^{-1} stronger than at the northern shore.

To compare this result with the Emery-Csanady theory I ran the model again adding a constant curl to the wind stress given in Fig. 1. This added 0.018 dyne cm^{-2} to the south shore and subtracted the same from the north shore for each day. This difference of 0.036 dyne cm^{-2} is consistent with Emery and Csanady's estimate of a difference of 0.5 dyne cm^{-2} acting for 8 hr if we assume that such a wind impulse occurs every 5 days. The mean longshore current for this case is given by the dashed line in Fig. 3. The addition of the wind stress curl to the uniform winds increases the cross-lake surface current difference from 4 to 8 cm sec^{-1}. Thus, both the variation of lake static stability and the variation of surface stress across the lake have comparable effect on surface circulation and complement one another.

If one includes the classical explanations of cyclonic circulation, the tendency for river inflows to be deflected to the right by the Coriolis force and the geostrophic circulation during spring and fall when the shore zones respond faster to thermal forcing, there are now five possible explanations. I am now attempting to evaluate the relative importance of them for Lake Ontario using a three-dimensional numerical model.

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References

BENNETT, J. R. 1973. A theory of large-amplitude Kelvin waves. J. Phys. Oceanogr. **3:** 57–60.

———. 1974. On the dynamics of wind-driven lake currents. J. Phys. Oceanogr. **4:** 400–414.

EMERY, K. O., AND G. T. CSANADY. 1973. Surface circulation of lakes and nearly land-locked seas. Proc. Natl. Acad. Sci. U.S. **70:** 93–97.

SAYLOR, J. H. 1970. Non-linear resonances between Kelvin waves in Lake Michigan. Proc. 13th Conf. Great Lakes Res., Int. Assoc. Great Lakes Res. **1970:** 508–527.

SUNDARAM, T. R., AND R. G. REHM. 1973. The seasonal thermal structure of deep temperate lakes. Tellus **25:** 157–167.

WUNSCH, C. 1973. On the mean drift in large lakes. Limnol. Oceanogr. **18:** 793–795.

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Morphometric control of variation in annual heat budgets

Abstract—The extent of variation in annual heat budget of 23 European, North American, and Australian lakes tends to be related to lake volume and mean depth.

In a 3-year study of the comparative limnology of Lakes Purrumbete, Bullenmerri and Gnotuk, near Camperdown, in western Victoria, Australia (Timms 1973), mean heat budgets were not only related to mean depth and area, as expected (Gorham 1964), but the extent of annual fluctuations was also morphometrically controlled. This latter relationship may be widely applicable and more reliable than the observation that lakes in continental climates tend to have more constant heat budgets than those in oceanic climates (Hutchinson 1957).