major features of the original response results. However, the new boundary condition has accentuated primary resonances and suppressed secondary ones, which facilitates analysis of the model response. The model is now less susceptible to feedback due to reflections from the outer boundaries.

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Observed and Predicted Great Lakes Winter Circulations

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ABSTRACT

Observed mean winter currents in Lakes Ontario and Huron are compared to predictions from a homogeneous, vertically integrated, steady-state model. If specific wind directions are selected to drive this model, the observed and predicted current patterns agree. The specific wind directions were chosen to maximize each lake's wind response. The agreement suggests that there is a mean wind-driven winter circulation in the Great Lakes, and that its pattern depends upon these specific wind directions. Based on these factors, winter circulations for Lakes Erie, Huron and Superior are predicted.

1. Introduction

Until 1972 there were no long-term observations of winter currents in the Great Lakes. There were, however, hypotheses about these currents. Surface cooling was expected to produce nearly isothermal water, so that with only weak density gradients, currents would be primarily wind-driven. Based on this hypothesis, numerous models were used to predict the wind-driven circulations of the Great Lakes. Both numerical (e.g., Gedney and Lick, 1970, 1972; Rao and Murty, 1970; Murty and Rao, 1970; Simons, 1971) and physical (e.g., Rumer and Robson, 1968) models were driven with a variety of winds. Even though these models predicted similar circulations when driven with similar winds, they could not be verified because of the lack of data.

By 1972 self-contained, automatic current meters with operational lives of over six months had been perfected. Instrumentation had improved to the point that circulation studies over a winter were possible. As a result, Canada and the United States cooperated on a Lake Ontario study using such instruments during winter 1972–73. Strings of meters were installed in November and retrieved in March. They operated continually, and the data from this study were reported by Pickett (1977).

Two years after this Lake Ontario study, the countries collaborated on another winter circulation study—this time on Lake Huron. Again automatic current meters were installed in autumn and retrieved in spring. Saylor and Miller (1979) reported the results of this 1974–75 winter study of Lake Huron.

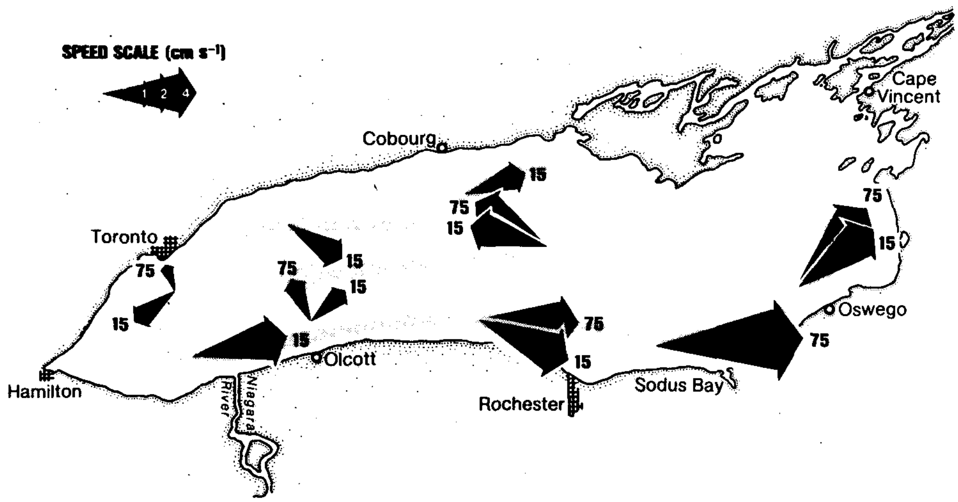

FIG. 1. Lake Ontario observed currents vector-averaged from November 1972 through March 1973 [depths in meters at arrow tips (from Pickett and Dossett, 1979)].

How well do the long-term observations from these two studies compare to the model predictions? This note points out a pattern in the observations, and shows that this pattern can be reproduced by a proper choice of wind directions in the models. On this basis, mean winter circulations patterns for the other Great Lakes are predicted.

2. Data

Fig. 1 shows the mean currents obtained in Lake Ontario during winter 1972–73. Speeds range from 1 to 10 cm s^{-1}, with an overall mean of 3 cm s^{-1}. Generally, mean speeds are higher near the southern shore. The shaded arrows, added to suggest an overall pattern, indicate net eastward flow off the northern and southern shores, with a return flow down the middle of the lake.

Fig. 2 shows similar mean currents recorded in Lake Huron during winter 1974–75. Speeds in this lake range from 1 to 7 cm s^{-1}, with the mean again being 3 cm s^{-1}. Higher speeds tend to occur nearer the western shore. Where currents were recorded at several depths, means at all depths are in about the same direction with about the same speed. Shaded arrows were again added to suggest an overall pattern. The net flow seems to be southward along the western shore with northward return flow near the middle of the lake.

3. Wind selection

a. Response diagrams

The simplest of the Great Lakes models referred to above are the linear, vertically integrated, steady-state models. Both lake bathymetry and the earth's rotation are incorporated in such homogeneous models. Wind climatologies around the Lakes (National Climatic Center, 1975), however, indicates the difficulty in simulating the mean winter circulations with a steady-state model. Since winds of any speed and from any direction can occur during a winter, how can a constant wind, steady-state model be used?

The answer to the above question hinges on the wind's effectiveness in generating currents. Since this effectiveness depends on wind speed squared (stress), the strongest winds, which blow primarily from the western quadrants in the Great Lakes region, ought to play the major role in determining any mean circulation.

Within these general western quadrants, the specific direction of a strong wind also is important in determining its effectiveness in generating currents. For a demonstration of this specific directionality, a kinetic energy calculation was added to a steady-state model. The model was then run with a unit wind stress from each point of the compass to calculate the lake's kinetic energy for each wind direction. This calculation was done for three idealized lakes and for the five Great Lakes. Next these energies were normalized for each lake by dividing by the maximum energy obtained for any wind direction over that lake. Finally, the results were plotted in polar diagrams (Fig. 3). These plots are analogous to antenna response diagrams used to show directions of maximum antenna gain. Maximum gain, in the case of a lake, would correspond to the wind direction that gives the strongest overall currents for a unit wind stress. Strong currents require long stretches of shallow water parallel to the wind.

FIG. 2. Lake Huron observed currents vector-averaged from November 1974 through March 1975 [depths in meters at arrow tips (data from Saylor and Miller, 1979)].

b. Idealized lakes

Results from three idealized lakes with paraboloidal bottoms are included in the box to the left in Fig. 3. In a circular lake (top diagram) any wind direction produces the same response. For an elliptical lake with an east-west axis four times longer than its north-south axis (middle of box), the relative response is reduced for winds parallel to the short axis. Finally, in a 20:1 channel-type lake (bottom of box) the cross-axis response falls to nearly zero. In the antenna analog, this long thin lake corresponds to a directional antenna.

The ideal lakes were also used to test if these response diagrams were sensitive to the bottom stress formulation used in steady-state models. Both the magnitude and the form of bottom stress were varied, but for any stress that produced currents in the observed range, the response diagrams were uneffected.

c. The Great Lakes

In comparison to these idealized lakes, Fig. 3 also shows that each of the Great Lakes has its own peculiar wind directional response. Lake Ontario's maximum response axis runs nearly east and west, Lake Huron's runs southeast and northwest; both Lake Erie's and Lake Superior's run east-northeast and west-southwest; and Lake Michigan's runs nearly north and south.

Each lake also has a unique minimum response.

In Lake Ontario, the response drops off similarly to the 4:1 ideal elliptical lake as the wind shifts from west to north. At the other extreme, Lake Superior, which is irregularly shaped, tends to have a strong response regardless of the wind direction (similar to a circular lake). Its response only decreases ~40% for a north-northwest wind. Lakes Huron, Erie and Michigan all have similar minimum responses, and their values fall between the extremes of Lakes Ontario and Superior.

4. Model circulations

Knowledge of both the general direction of the strongest winds and the specific direction of maximum response for each lake makes wind selection for a steady-state model easier. Since strong winds usually are from the western direction, the directional response plots indicate that strong west winds should determine Lake Ontario's mean wind-driven circulation, northwest winds should determine Lake Huron's circulation, and west by southwest winds should determine both Lake Erie's and Lake Superior's circulations. Either north or south winds could determine Lake Michigan's wind-driven circulation.

Using the above wind directions, a wind stress of 1 dyn cm^{-2}, and a bottom stress that produced current speeds comparable to those observed, the steady-state model was run for each of the Great Lakes. The predicted circulation patterns for each lake are shown in Fig. 4.

The model results for Lake Ontario driven by a west wind seem to agree with the observations (Fig. 1). In both the modeled and the observed results, clockwise circulation occurs in the northern half of the lake and counterclockwise circulation in the southern half. Stronger mean flow is predicted along the northern and southeastern shores. The strong northern shore flow is inshore of the observation sites, but strong flow (up to 10 cm s^{-1}) was recorded off the southeastern shore. In addition to matching the observed pattern, these same model results were also successful in predicting the movement of a pollutant in Lake Ontario (Pickett and Dossett, 1979).

In similar fashion, the model pattern for Lake Huron with a northwest wind seems to agree with the observations (Fig. 2). Counterclockwise circulation occupies most of the western part of the lake. The model also predicts clockwise circulation in the northern part of the main basin and

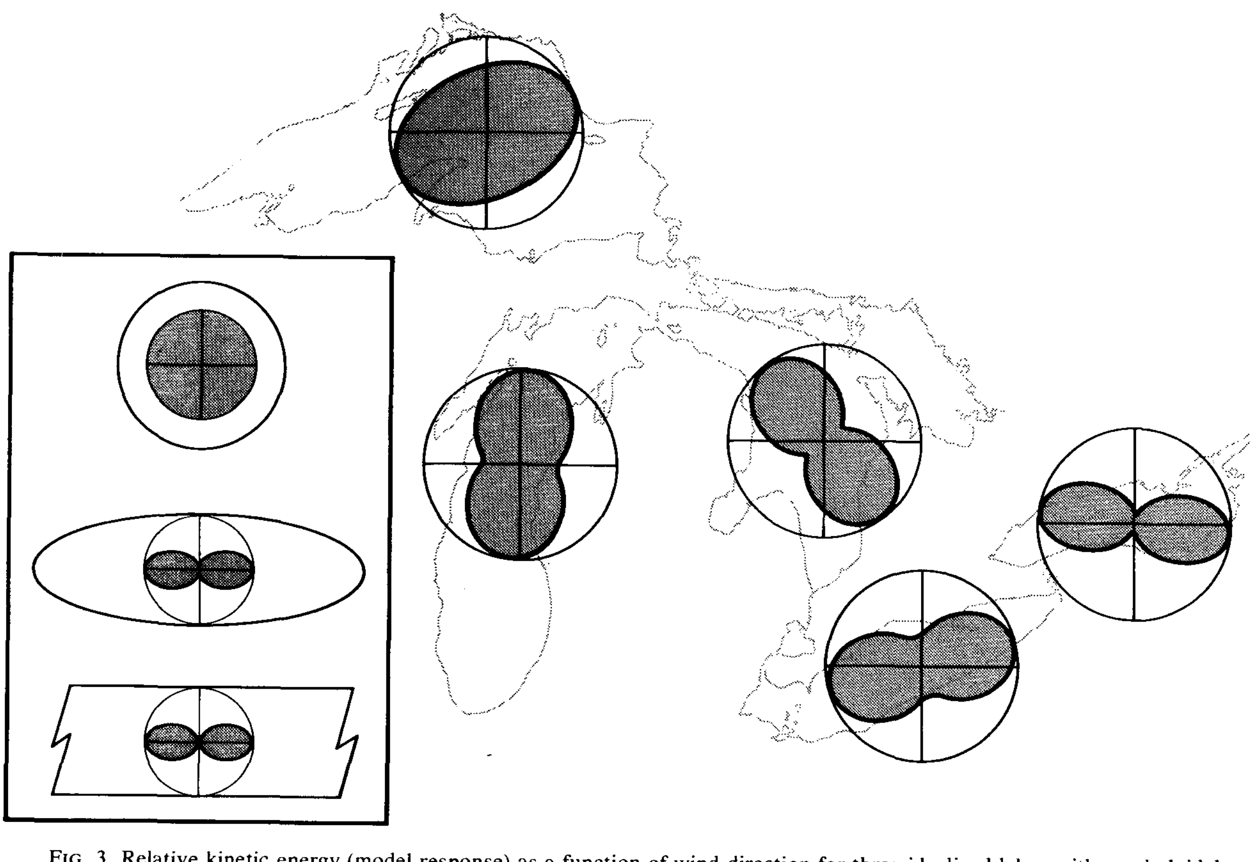

FIG. 3. Relative kinetic energy (model response) as a function of wind direction for three idealized lakes with paraboloidal bottoms and for the five Great Lakes.

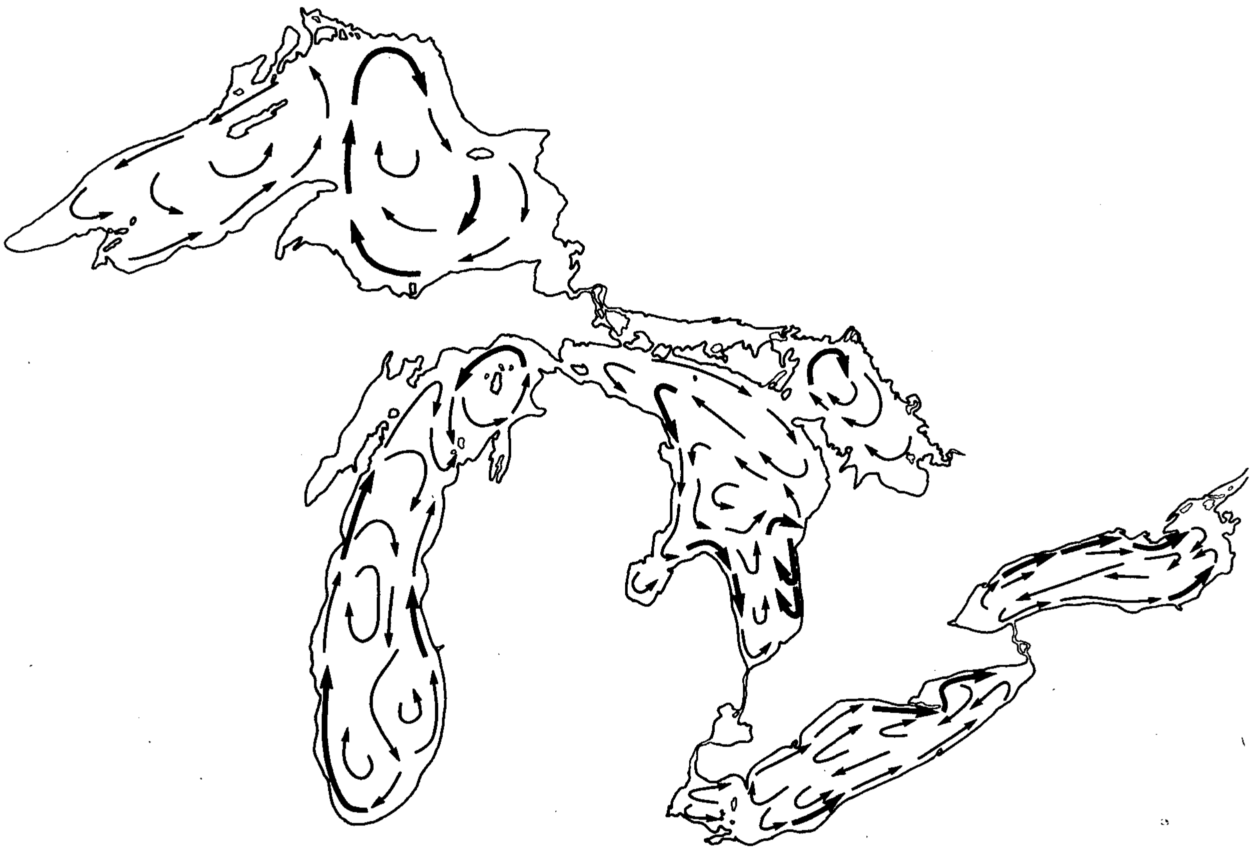

FIG. 4. Winter circulation patterns predicted for the Great Lakes by a steady state model with a 1 dyn cm^{-2} wind stress along the axis of maximum response. (Thicker arrows represent the stronger resultant currents of $\sim$10 cm s^{-1}.)

in Georgian Bay. Strong net southerly flow is predicted close to both the eastern and western shores of the southern basin. The observations confirm strong southward flow along the western shore, but apparently there were no observations close enough to the southeastern shore to confirm southward flow there.

For the rest of the Great Lakes, these model winter circulation patterns are speculative. For Lake Erie, with its west-southwest wind, the pattern is similar to that of Lake Ontario, with clockwise flow in the north and counterclockwise flow in the south. Coastal flows are parallel to the shores, with westward return flow down the middle of the lake. Larger mean flows are predicted off the northeastern shore and in a smaller region off the southwestern shore.

Lake Superior has a strong current response for almost any wind direction, but for the optimum west-southwest wind the pattern consists of two gyres, counterclockwise in the west and clockwise in the east. In general, there is relatively strong northward flow in the central region of the lake where the two gyres meet.

Lake Michigan's circulation is peculiar. Since the axis of maximum response is north-south and thereby outside the region of strongest winds, the wind-driven circulation in this lake is probably more variable. As a result, Lake Michigan should have smaller winter mean currents than the other lakes. For winds with strong components from the south, the model shows net flow northward along both shores, with a weaker return flow meandering southward down the middle of the lake. The opposite circulation would occur for winds with strong components from the north. However, the circulation due to winds from the south was chosen for Fig. 4 for two reasons. First, the maximum wind response of the lake is shifted slightly west of due south. Thus, a southwest wind should generate larger currents than a northwest one. Second, wind climatologies indicate an excess of southerly over northerly winds around Lake Michigan.

5. Summary

Judging from Figs. 1, 2 and 4, the observed mean winter circulations patterns in Lakes Ontario and Huron seem to agree with a steady-state, homogeneous model driven with a wind from the direction of maximum wind response. The circulation patterns shown in Fig. 4, for Lakes Erie, Michigan and Superior, however, are unverified.

Lake Erie's pattern is similar to Lake Ontario's, and agrees with earlier predictions with steady-state models (Murty and Rao, 1970; Gedney and Lick, 1972). Attempts were also made by those authors to compare their homogeneous model results to data. Unfortunately, only summer data were available (when the Lakes are not homogeneous), but the models did show some agreement. Such agreement would suggest that the wind-driven patterns in Fig. 4 may even show up in mean summer circulations.

Another special problem in Lake Erie is ice. This lake has more ice than the other Great Lakes, and usually freezes over sometime during winter. During periods of ice cover, the wind's effectiveness in driving currents will be reduced, so that Lake Erie's winter currents might be smaller than expected.

The predicted circulation pattern for Lake Superior also generally agrees with previous modeling work. Even though Murty and Rao (1970) used a wind with horizontal shear and Lien and Hoopes (1978) used a west wind, both predicted counterclockwise flow in the western end. Lien and Hoopes also verified their numerical model with a scaled physical model. Nevertheless, the irregular bathymetry of this lake may result in a circulation of greater complexity than simple coarse-grid models can produce. The test will come when its winter circulation is finally observed. Unfortunately, an extensive, and thus expensive, current network will be required.

Lake Michigan is a special case. The cross-wind response axis suggests that the circulation pattern could constantly be reversing, depending on whether a stronger wind component comes from north or south of west. This reversing would yield small mean currents. As stated above, the cumulative impact of all winter storm winds should favor the pattern in Fig. 4 but the validation of this prediction also awaits a winter current study.

This note has shown that observed mean winter currents in Lakes Ontario and Huron have patterns similar to those of a homogeneous, steady-state model driven with winds along each lake's maximum response axis. Are such similarities fortuitous? Is there a mean wind-driven lake circulation (in the same sense that there is a mean wind-driven ocean circulation) that is constantly being perturbed by wind shifts? Since only two of the Great Lakes have been observed so far, the answers to these questions are still unclear. But the pattern and symmetry of the mean winter currents in Lakes Ontario and Huron suggest more than just a collection of random residual currents.

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NOTES AND CORRESPONDENCE

Comments on the "Spatial Variability of Coastal Surface Water Temperature during Upwelling"—P. Y. DESCHAMPS AND R. FROUIN, Laboratoire d'Optique Atmosphérique, Universite de de Lille, Villeneuve d'Ascq, France, AND L. WALD, Laboratoire d'Océanographie Physique, Muséum National d'Histoire Naturelle, Paris, France.

Reply—F. L. SCARPCACE AND T. GREEN, Marine Studies Center, University of Wisconsin, Madison.