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Development of the Great Lakes Ice-circulation Model (GLIM): Application to Lake Erie in 2003–2004

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ABSTRACT

To simulate ice and water circulation in Lake Erie over a yearly cycle, a Great Lakes Ice-circulation Model (GLIM) was developed by applying a Coupled Ice-Ocean Model (CIOM) with a 2-km resolution grid. The hourly surface wind stress and thermodynamic forcings for input into the GLIM are derived from meteorological measurements interpolated onto the 2-km model grids. The seasonal cycles for ice concentration, thickness, velocity, and other variables are well reproduced in the 2003/04 ice season. Satellite measurements of ice cover were used to validate GLIM with a mean bias deviation (MBD) of 7.4%. The seasonal cycle for lake surface temperature is well reproduced in comparison to the satellite measurements with a MBD of 1.5%. Additional sensitivity experiments further confirm the important impacts of ice cover on lake water temperature and water level variations. Furthermore, a period including an extreme cooling (due to a cold air outbreak) and an extreme warming event in February 2004 was examined to test GLIM's response to rapidly-changing synoptic forcing.

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Introduction

Lake ice cover in the Great Lakes region can have an important impact on the regional weather and climate: two examples are lake-effect snow in winter and modulation of regional surface air temperature (SAT). Lake ice cover can also modify the lake circulation patterns and thermal structure because: 1) momentum transfer into the water column from wind stress drag is considerably greater over the water surface than over the ice surface; 2) the albedo over ice differs from that over water, and 3) heat and moisture exchange between the atmosphere and the lake water can differ significantly (as much as orders of magnitude different) with and without lake ice (Walter et al., 2006), thus leading to a striking difference in evaporation in wintertime due to strong cooling and wind mixing. Prediction of the lake's ice extent (i.e., ice cover) is crucial for predicting the lake's mixed layer, circulation, temperature, and water level, and thus for predicting primary and secondary productivity. In addition, the timing of ice melt, determined by SAT that is controlled by climate variability, will determine the timing of spring phytoplankton and zooplankton blooms (Vanderploeg et al., 1992). As a result, lake ice cover, although thin, is an important physical parameter for other ice-associated systems such as ecosystems and habitats for fisheries. This is in part because lake ice dynamics and thermodynamics significantly modify the water temperature, heat flux, mixing intensity, and water column stratification, which are important factors controlling phytoplankton blooms.

The Great Lakes are usually at least partially covered with ice from December to April. Initially, ice begins to form in shallow bays and then gradually grows offshore. Maximum ice extent is normally observed in late January to early February, when ice typically covers from 24% of Lake Ontario to 90% of Lake Erie (Assel et al., 1983). Naturally-formed ice thickness can vary from a few centimeters to a meter or more (Rondy, 1976). Ice decay and breakup usually begin in March as solar radiation increases, and the thinner ice can then be more easily broken up by the action of wind and waves. Recent observations of sensible and latent heat fluxes over Lake Erie (Gerbush et al., 2008) show a rapid decrease in flux magnitude as ice concentration approaches 100%.

The presence of ice cover also affects momentum transfer between the atmosphere and the water column, which determines waves and circulation patterns in a large lake. Momentum transfer is generally reduced by the presence of ice. Measurements of ice movement in Lake Erie using drifting buoys in winter 1984 show that wind is the

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major forcing to ice transport in the Great Lakes (Campbell et al., 1987). They reported that the mean observed speed of the buoys in ice is about 8 cm s^{-1}, half the mean speed observed in open water. An experiment to obtain under-ice currents in Lake Erie was conducted in 1979-80 (Saylor and Miller, 1983), but no specific analyses for the impact of ice on the lake circulation were made.

Lake Erie ice is first year ice, with ice thickness being typically a few centimeters to 1 m or more due to ice ridging or rafting caused by wind and waves. Synoptic weather patterns and cyclone passage (Lofgren and Bieniek, 2008) can significantly affect lake ice distribution. Thus, since the predictability of lake ice using statistical methods is poor due to the complexity of the climate patterns (Assel and Rodionov, 1998; Mysak et al., 1996; Wang et al., 2010) and highly dynamic regional weather patterns, numerical ice modeling is an important tool to help understand lake ice thermodynamic and dynamic features on synoptic time scales.

Wake and Rumer (1979, 1983); Rumer et al., 1981 developed a numerical model of ice transport in Lake Erie based on Hibler's (1979) dynamic–thermodynamic sea ice model, but no further progress has been made since then, perhaps due to a lack of resources and initiative. At present, there exists no viable ice model for use as a research and operational forecast tool in the Great Lakes, which is long overdue. However there have been some successful efforts in coupled ice-ocean modeling in many subpolar seas and bays, such as in Hudson Bay (Wang et al., 1994; Saucier and Dionne, 1998; Saucier et al., 2004), in the Gulf of St. Lawrence (Saucier et al., 2003), in the Baltic Sea (Meier, 2002a,b; Haapala, 2000; Haapala et al., 2001), and in the Labrador Sea (Yao et al., 2000; Tang, 2008). These areas are similar (except for salinity) to the Great Lakes because they do not have perennial ice cover.

The Great Lakes Coastal Forecasting System (GLCFS) presently predicts lake water circulation, temperature, and surface waves (http://www.glerl/noaa.gov/GLCFS). Since it currently does not have a lake ice component, empirical methods have been used to keep the system running over the winter. Wave forecasts also must be modified, as ice cover dampens surface waves significantly during winter. Thus, it is inadequate to use only a circulation model to investigate hydrodynamics and thermodynamics when lake ice is present. The increasing need for predicting lake ice for navigation, weather forecasting, rescue efforts, and ecosystem studies motivated us to develop a coupled ice-circulation model.

The next section briefly describes the model, forcings, and data used to validate the model. The section of Simulation results presents physical explanations of lake ice dynamics and thermodynamics, and the model validation using satellite and in situ measurements, followed by the Summary and conclusions.

Description of GLIM, atmospheric forcings, and validation data

The GLIM is a combination of the Coupled Ice Ocean Model (CIOM) developed and applied to the Arctic Ocean and subpolar seas (Yao et al., 2000; Wang et al., 2002, 2003, 2005, 2009) and the Great Lakes version of the Princeton Ocean Model (POM, Schwab and Bedford, 1999; Beletsky and Schwab, 2001; Beletsky et al., 2003, 2006). The CIOM is based on a thermodynamic and a dynamic model with a viscous-plastic sea ice constitutive law (Hibler, 1979) and a multi-category ice thickness distribution function (Thorndike et al., 1975; Hibler, 1980) coupled to the Princeton Ocean Model. The coupling is governed by the boundary processes as discussed by Mellor and Kantha (1989).

The principal difference between the GLIM and the CIOM is the adaptation of heat and momentum flux submodels from the POM-based Great Lakes Coastal Forecasting System (Schwab and Bedford, 1999) so that during the ice-free season, the model is identical to the Great Lakes version of POM. Heat and momentum flux over the lake are calculated using a bulk aerodynamic approach using estimates of wind speed, air temperature, dew point, and cloud cover, which are interpolated to each grid point from hourly surface observations at a network of stations (Fig. 1) in and around the lake (Beletsky et al., 2003). Measurements are adjusted to a common 10 m anemometer height above the water surface using the profile method developed by Schwab (1978) and described more fully by Liu and Schwab (1987). The profile method employs the Charnock relation for increasing surface roughness with increasing wind speed and profile similarity theory presented by Businger et al. (1971) to describe the dependence of the profile on atmospheric stability.

Over open water, the profile theory is used at each grid square at each time step to estimate surface stress using the surface water temperature from the circulation model. This procedure provides estimates of bulk aerodynamic transfer coefficients for momentum and heat. Surface heat flux H is calculated by

$$H = H_{sr} + H_s + H_1 + H_{lr}, \tag{1}$$

where H_{sr} is the short-wave radiation from the sun, H_s is the sensible heat transfer, H_l is the latent heat transfer, and H_{lr} is the long-wave radiation. The heat flux procedure follows the methods described by McCormick and Meadows (1988) for mixed layer

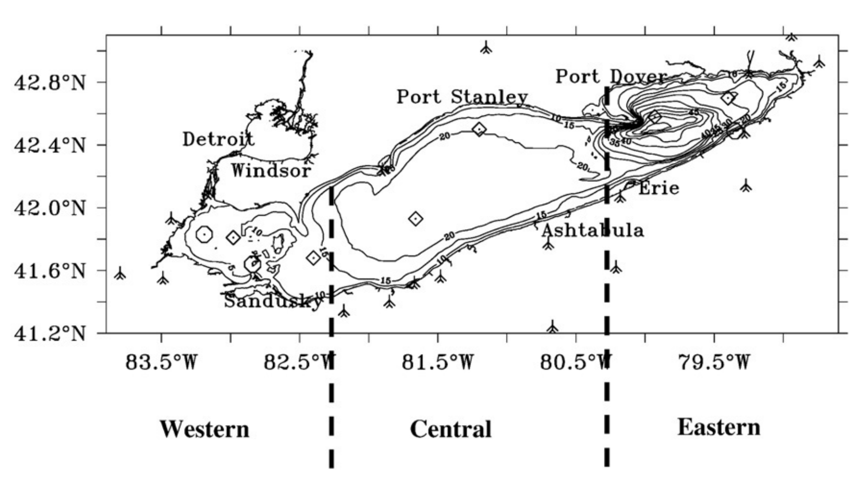

Fig. 1. Lake Erie bathymetry (depths are in meters) and the model domain with 2-km resolution. The meteorological forcing of the model is derived from the NDBC (National Data Buoy Center) buoys (◊), C-MAN (Coastal Marine Automatic Network) stations (O), and local airports. The vertical dashed lines (82.4 W and 80.4 W) divide Lake Erie into the western, central, and eastern basins.