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A study of Lake Erie seiche and low frequency water level fluctuations in the presence of surface ice

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ABSTRACT

Coastal storms can initiate periodic low-frequency fluctuations of water level particularly in enclosed bodies of water. Such oscillations, known as seiches, can potentially result in an unexpected rise in water level leading to coastal flooding in low lying areas. Low frequency water level motions are also believed to contribute to long-term erosion of coasts. In this paper, low frequency motions of Lake Erie water levels are, analytically and numerically, studied for ice-free and ice-covered lake conditions. For the analytical study, first, a spectral analysis is performed on long-term hourly water level data collected over a 40-year period (1975–2015) at various water levels measuring stations around the lake. The frequencies of the lake's seiching modes are determined and the spatial variations of the energy corresponding to the low frequency fluctuations of the lake are investigated. Secondly, the seasonal variations of the seiching motions as well as the effects of surface ice on the low frequency oscillations of the lake level are assessed by analyzing the spectra and cross-spectra of the hourly water level data at various stations during winter and summer for ice-covered and ice-free conditions. The spatial variations of the spectral energy, phase lag and coherence for the low frequency motions are quantified for the winter and summer data. The lake's low frequency water level variations for a short-term extreme event, *i.e.* storm, are studied numerically. A historical winter storm taking place under ice-covered lake conditions is simulated using a coupled storm surge and spectral wave model (ADCIRC-SWAN). The model is forced by wind and pressure fields under a hypothetical ice-free conditions. The spectra of the low frequency motions for the simulated and measured lake level time-series are then compared. The spectral analysis of the Lake Erie long-term hourly water level data reveals distinct energy concentrations at the frequencies of approximately 1.7, 2.6, 4.1 and 5.8 cycle/day (CPD) which correspond to the first four modes of seiching oscillations. The energy corresponding to the low frequency motions is found to be at its highest level near Toledo, in the western basin, and lowest in Fairport, located at the nodal point for the first mode. The comparisons of the summer and winter spectra show that surface ice can suppress the low frequency oscillations. In general, the spectra of the lake levels during the summer are more peaked at the seiching modes than those of the winters when the lake is ice-covered. For the low frequency oscillations of the lake level following a short-term extreme event, higher energy levels are associated with the ice-free lake condition. This energy level is higher at the eastern and western ends of the lake, consistent with the findings for the winter and summer lake level oscillations. In general, the effect of surface ice on low frequency fluctuations of the lake is more pronounced in the western basin where typically more extensive surface ice is present during winters.

1. Introduction

Lake Erie is the fourth largest in surface area, smallest in volume and shallowest lake among the Great Lakes. The length and width of the lake are about 400 km and 90 km, respectively. Lake Erie is on average 24 m deep with a maximum depth of 63 m. The lake is comprised of three basins: western, central and eastern. The western basin is the smallest and shallowest. The eastern basin is the deepest and the central basin is the largest in area. Due to its shallow depth, the lake warms and freezes quickly during the summer and winter, respectively (Environmental Protection Agency Great Lakes Atlas). Fig. 1 shows the bathymetry of Lake Erie where the depth is based on the long-term mean lake level of 174.0 m (NAVD88) as the datum.

Lake Erie's seiches have been the subject of several early studies *e.g.*, (Palmer and Izatt, 1972; Dingman and Bedford, 1984). Attempts have been made to identify the frequencies corresponding to the first few modes of the free oscillations based on limited lake level data for ice-free lake conditions. Those analyses showed that the low frequency

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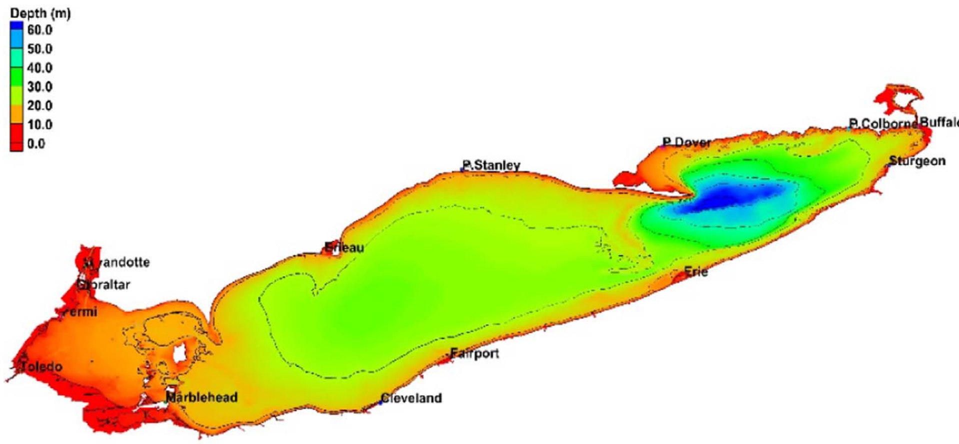

Fig. 1. Lake Erie Bathymetry.

oscillations of water levels were more energetic during winters than summers but less concentrated at the frequencies related to the first and second seiching modes. The relationship between meteorological forcing and water level oscillations in Lake Erie was studied using wind and water level data collected from a network of stations during the summer. Using the standard harmonic analysis, the tidal amplitude and phase of lunar semidiurnal tide were determined. The studies revealed that a counterclockwise rotation of high water level corresponding to diurnal and lower order seiches took place in the lake (Henry, 1902; Garriott, 1903; Mortimer, 1987; Platzman and Rao, 1964; Platzman, 1966; Irish and Platzman, 1962; Hamblin, 1987; Kite, 1992a, 1992b).

Lake Erie hydrodynamics, in the presence of surface ice, were studied based on current velocity data collected on the northern shore of the lake during two different time periods. The first period was once the lake became fully ice-covered, and the second period was two months after the first data measurement when the lake was still fully ice-covered. The current velocity variation during the first period, the formation period, appeared to be similar to that of ice-free lake spectra as the density spectra were peaked at the frequencies corresponding to the free-oscillation modes. The maximum current velocities measured during the second period were significantly less than those of the ice-free condition. There was no distinct energy concentration at any frequency in the density spectra of the current velocity for the second period (Palmer and Izatt, 1972).

Lake Erie's response to an extreme event with a partially ice-covered surface was quantitatively studied by analyzing the spectra of the lake level fluctuations. The study suggested that the surface ice could suppress the lake level oscillations, particularly, at the first mode of free oscillations. The only dominant low frequency oscillation mode, not greatly affected by the ice cover, was found to be that of the tide (Dingman and Bedford, 1984).

In this paper, the Lake Erie low frequency motions are studied using the spectral analysis of hourly lake levels at three different time scales, long-term, intermediate term or seasonal (winter/summer), and short-term (storm). For the long-term study, the hourly water level data for a 40-year period (1975–2015) are analyzed spectrally. For the intermediate term, data for time spans of four months are selected and spectrally analyzed for both the winter and summer for three different years with varying surface ice conditions. For the short-term event, a historical winter storm with partially ice-covered lake condition is selected for numerical modeling using a coupled storm surge (Advanced Circulation Model, ADCIRC) and spectral wave, (Simulating WAves Nearshore, SWAN) model (see Section 2.3). The model is forced by wind and pressure fields for an 8-day period under a hypothetical ice-free condition. The spectra of the low frequency motions for the simulated (ice-free lake) and measured (ice-covered) lake levels are compared.

2. Method

The Great Lakes storm record shows that storms are more likely to occur between November and March (US Army Corps of Engineers, 2012). Due to its shallow depth and because the direction of predominant wind is along the lake's longitudinal axis, following a major storm, Lake Erie water level exhibits low frequency oscillations, known as seiches. A seiche in 1844 was reported as "one of the greatest disasters in Buffalo's recorded history". It reportedly "occurred without warning, breaching the 4.5-m seawall, flooding the waterfront, and drowning at least 78 people" (Buffalo Architecture and History). In 2008, flooding near Buffalo was the result of a powerful storm that created up to 5 m high waves and a storm surge of about 3 m (National Oceanic and Atmospheric Administration (NOAA)). The post-storm periodic fluctuations of hydrodynamic characteristics of a shallow lake such as Lake Erie are believed to enhance bottom shear stress and intensify turbulence which could, in turn, influence sediment resuspension and transport in the lake (Dusini, 2005; Dusini et al., 2009; Matisoff and Carson, 2014; Lick et al., 1994). The variations of the lake's water levels were found to be responsible for resuspension of contaminated sediments deposited throughout Lake Erie, especially in the western basin (Painter et al., 2001; Marvin et al., 2002). Such phenomenon can degrade water quality, adversely affecting both human and ecosystem health. Moreover, given that the main rivers connected to Lake Erie, *e.g.*, Detroit and Niagara Rivers, are nearly flat, the low frequency fluctuation of Lake Erie water level can propagate into the rivers affecting the hydrodynamics and sedimentation processes in them and other connected streams (Gailani et al., 1996; Inamdar, 2014; Williams, 2004; Singer et al., 2008).

The Lake Erie surface ice can, also, hinder waves from reaching the coasts, especially those near the shoreline, *i.e.* shore-fast ice. Hence, the surface ice could reduce the risk of flooding and erosion.

2.1. *Water level data*

Lake Erie's water levels have been monitored for 150 years. The hourly water level data have been collected at several US stations operated by National Oceanic and Atmospheric Agency (NOAA) (National Oceanic and Atmospheric Administration NOAA) as well as at a number of Canadian stations operated by the Department of Fisheries and Oceans (Fisheries and Oceans Canada). The hourly data at the NOAA stations have been collected since 1975.

2.1.1. *Ice Cover*

The Great Lakes historical ice data show that the Annual Maximum