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Ice thickness measurements in Lake Erie during the winter of 2010–2011

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ABSTRACT

Time series measurements of ice thicknesses were made at either 1 or 2 Hz at 6 locations in the western part of Lake Erie's central basin during the winter of 2010–2011. Ice was observed over approximately 80 days beginning in late December and continuing through mid-March. Deformation and ridging of ice occurred frequently and produced ice thicknesses of up to 10 m, and over 6 m at all stations. The measurements show considerable variability (up to several meters) between stations, even when the distance between them is <500 m. Comparison of the measurements to those generated by the National Ice Center show good agreement for undeformed thicknesses, but the Ice Center analyses do not account for increased thicknesses due to ice ridging. Several different measures of ice thickness (based on different averaging times and the parameter used to characterize the resulting distribution of thicknesses) are used to characterize the data, and the results can vary widely depending upon which measure is used. The best measure to use will depend upon the use for which the data is intended.

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Introduction

The presence of wide-spread ice cover on the Laurentian Great Lakes significantly influences lake-effect snow/storms (Notaro et al., 2013), regional weather, the hydrological cycle, water levels, water temperature (Wang et al., 2010), and the circulation of the lakes (Fujisaki-Manome et al., 2013). Knowledge of the growth and decay rates of ice are also needed for models of the thermal cycle of the lakes as well as for navigation and recreational purposes. Although the importance of ice measurements is well known, logistical difficulties make direct observations, particularly of ice thickness, quite rare. When these measurements are made, they are usually point measurements made with an ice auger. Titze and Austin (2016) reported observations of ice movement in Lake Superior during the winter of 2013–2014 and summarized previous work on ice in the Great Lakes. As they noted, "…literature addressing ice on the Laurentian Great Lakes focuses almost entirely on remotely sensed data … or modeling studies." Titze and Austin (2016) used acoustic current profilers to measure ice transport and reported ice thicknesses measured when the passage of ice keels changed the depth recorded by subsurface pressure sensors. At one station (where the pressure sensor was approximately 5 m below the surface), they report frequent thicknesses of 5–8 m, and one instance of a keel 11 m thick. At each of two other stations (where the pressure sensor was located about 13 m below the surface), they found at least one instance of keels >12 m thick. To our knowledge, these are the only *in situ* time series measurements of ice properties in the Laurentian Great Lakes.

Ice in the Great Lakes is seasonal ice. In most areas it is not frozen to the shoreline, and typically has thicknesses ranging from a few centimeters to one meter or more. Ice usually begins to form in the Great Lakes in December and January and reaches its maximum extent in February or early March (Wang et al., 2012). Ice cover can be very transitory, particularly in the mid-lake areas, where lake heat storage, air temperature, and wind can move, compact, and alter the concentration and thickness of the ice cover. There is also significant inter-annual variability (Bai et al., 2012). Leppäranta (2015) and Kirillin et al. (2012) reviewed the characteristics and behavior of ice in freshwater lakes, but most of the observations were made on lakes much smaller than the Laurentian Great Lakes.

Lake Erie is the smallest of the Great Lakes by volume, and is divided into three basins. Our measurements were made in the central basin of the lake, which is approximately 70–100 km wide and about 180 km long with a maximum depth of 25 m. This makes it a large, shallow lake according to the classification of Leppäranta (2015). The large size of the basin means that wind-generated waves can be significant mixing agents, while its shallow depth means that freezing occurs during most winters.

In Lake Erie, the spatial progression of ice formation is from the shallow west basin (maximum depth 10 m) in late December to the deeper central (maximum depth 25 m) and eastern (maximum depth 64 m) basins in January. In the central basin, new ice forms on the northern shore first. Lake Erie reaches its maximum ice cover by the end of January and retains this cover through February (Assel, 1990). While providing the greatest probability of extensive ice cover, this period also often features large variability in ice concentration (Assel, R.A. 2003, An electronic atlas of Great Lakes ice cover, *NOAA Great Lakes Ice Atlas*, NOAA

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Great Lakes Environmental Research Laboratory, Ann Arbor, MI., www.glerl.noaa.gov/data/ice/atlas, accessed December 8, 2017).

Analysis of ice cover and thickness in the Great Lakes is conducted jointly by the National Ice Center in the USA and the Canadian Ice Center. Satellite imagery is analyzed to determine the ice cover and combined with estimates of the ice thickness determined by a degree-day model. A chart is published at least once a week and more often when changes occur quickly.

This study documents *in situ* time series measurements of ice thickness made in the central basin of the lake during the winter of 2010–2011 as part of a joint NSF-NOAA program to measure and model ice growth and its effects in Lake Erie. The ice cover in Lake Erie during the winter of 2010–2011 was above average but not atypical; Assel et al. (2013) found that the maximum ice cover in Lake Erie in 2010–2011 was the 10th highest out of the 39 years between 1973 and 2011.

Methods

Instrumented moorings were deployed at 7 locations in the central basin of Lake Erie in the fall of 2010 and retrieved in the spring of 2011 (Fig. 1). Details of the instruments deployed at each station are given in Table 1. Elevations in the table are in meters above bottom (mab). Different combinations of sensors were deployed on two separate moorings at each station. At stations 1–4, a SWIPS ice profiler manufactured by ASL Environmental Sciences and 4 to 6 Sea Bird 39 temperature sensors were mounted at either end of a 50 m ground line that was anchored with a concrete weight at both ends. A separate mooring contained either an RDI ADCP (at stations 1–3) or a Nortek AWAC current profiler. At stations 5–7 a bottom–resting tripod was deployed on one mooring, and the temperature sensors and either an RDI ADCP (at station 7) or a Nortek AWAC profiler were on the other. The tripods were instrumented with Sea Tech transmissometers and Paroscientific pressure sensors. Previous experience in Lake Erie in 1979–1980 showed that ice thicknesses could reach up to 10 m during the spring (G. Miller, personal communication), so all sensors were located at least 10 m below the water surface.

SWIPS ice profilers manufactured by ASL Environmental Sciences were deployed to measure ice thickness at stations 1–4. These profilers emit a single vertical acoustic beam at 546 kHz to measure the range to the bottom of any ice present. The instruments were mounted on a mooring 2–3 mab supported by subsurface floats. Between December 12 and May 1 the instruments were configured to make range measurements each second, and measurements of water pressure, water temperature, pitch, and roll every 10 s.

Acoustic current profilers were deployed at all 7 stations. At stations 1, 2, 3, and 7, upward looking RDI ADCPs were deployed at 0.5 mab. Currents were sampled in 1 m bins every 10 min. All the ADCPs also included RDI's ice-tracking software to track the velocity of any ice present. At stations 4, 5, and 6 upward-looking Nortek AWAC profilers were deployed at 0.5 mab. Currents were sampled in 1 m bins for 5 min every 30 min. These units also have a vertical acoustic beam to measure the range to the bottom of any ice present. Burst observations of the range, ice velocity, and pressure were made at 1 Hz for 1024 observations every hour. These stations are designated as stations 4a, 5a, and 6a in the remainder of this manuscript.

Hourly observations of air temperature, air pressure, wind speed, and wind direction were obtained from the National Weather Service Station located at Burke Airport located along Cleveland's lakefront. MODIS images of the ice cover in the lake were obtained from NOAA's CoastWatch program. Although cloud cover masks the lake surface for much of the observation period, clear images of the central basin were obtained about once per week.

The theory for calculating the ice thickness from the *in situ* observations is straight forward. Acoustic measurements of the range from the instrument to the bottom of the ice are subtracted from the total pressure measured by a pressure sensor to determine the thickness of the ice. This procedure does not distinguish between the contributions to the pressure measurement of ice and any snow present, and unless a separate measurement of the snow thickness and density is made, the two cannot be separated. In this study the effects of snow are probably small (D. Fissel, personal communication). Even if the effects of snow are neglected, the calculation is complicated since corrections for atmospheric pressure, instrument tilt (which affects range measurements), and changes in the speed of sound (which affects the range measurements and is affected by water temperature and salinity) all need to be included. For the SWIPS ice profilers the manufacturer has written a library of Matlab subroutines to aid in the processing; their use is documented in the IPS Processing Toolbox Users Guide (ASL Environmental Sciences, 2011). The process is an iterative one, and one of the keys is to identify periods when there is no ice cover and use those measurements to correct the other measurements. Fortunately, there were numerous such episodes at each station during the deployments described here. ASL Environmental Sciences states that the minimum ice thickness

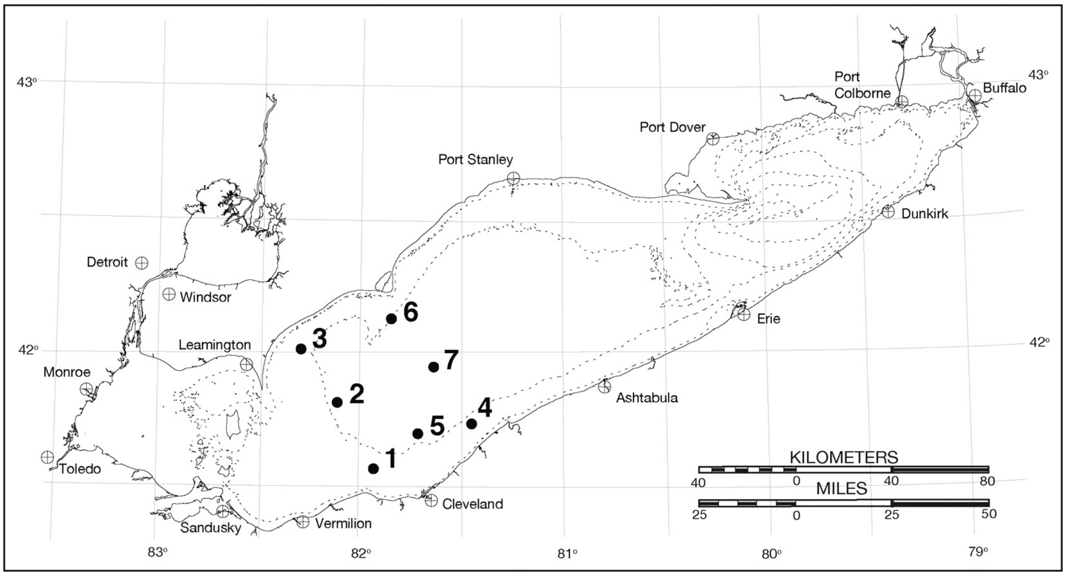

Fig. 1. Mooring locations. Dotted lines show bathymetry contours at 10 m intervals.

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