New York State Great Lakes Wind Energy Feasibility Study: Evaluation of Site Conditions

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New York State Great Lakes Wind Energy Feasibility Study: Evaluation of Site Conditions

Final Report

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Abstract

The Great Lakes Wind Feasibility Study investigates the feasibility of adding wind generated renewable energy projects to the New York State waters of Lake Erie and Lake Ontario. The study examines myriad issues, including environmental, maritime, economic, and social implications of wind energy areas in these bodies of freshwater and the potential contributions of these projects to the State's renewable energy portfolio and decarbonization goals under the New York State Climate Act.

The study, which was prepared in response to the New York Public Service Commission Order Case 15-E-0302, presents research conducted over an 18-month period. Twelve technical reports were produced in describing the key investigations while the overall feasibility study presents a summary and synthesis of all twelve relevant topics. This technical report offers the data modeling and scientific research collected to support and ascertain Great Lakes Wind feasibility to New York State.

To further inform the study in 2021, NYSERDA conducted four public webinars and a dedicated public feedback session via webinar, to collect verbal and written comments. Continuous communication with stakeholders was available through greatlakeswind@nyserda.ny.gov NYSERDA's dedicated study email address. Additionally, NYSERDA and circulated print advertisements in the counties adjacent to both Lake Erie and Lake Ontario as to collect and incorporate stakeholder input to the various topics covered by the feasibility study.

Keywords

Great Lakes, offshore wind, bathymetry, wind resource, lake ice, currents, waves

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Acronyms and Abbreviations

AFDD	accumulated freezing degree days
FDD	freezing degree days
GLERL	Great Lakes Environmental Research Laboratory (NOAA)
MPa	megapascals
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NYSERDA	New York State Energy Research and Development Authority
R&D	research and development
WRF	Weather Research and Forecasting (model)
WIND Toolkit	Wind Integration National Dataset Toolkit

Executive Summary

This report assesses physical conditions relevant to wind turbine siting in NYS waters of Lakes Erie and Ontario. The National Renewable Energy Laboratory (NREL) performed new modeling to update the offshore wind energy resource assessment for the region. The modeled wind resource data indicate that the annual average wind speeds at a height of 100 m are very consistent across the lakes, with average winds up to 9.0 m/s in the eastern portion of Lake Ontario and part of Lake Erie. Additional physical site conditions were evaluated including ice climate, waves, currents, and bathymetry. The study did not find that any of the physical characteristics examined would present major obstacles to wind energy development, however many unique factors would need to be considered for design decisions and cost optimization.

1 Introduction

Site conditions were assessed in the New York State waters of Lakes Erie and Ontario to help determine the feasibility of existing wind technologies (fixed and floating wind turbines) as well as the readiness of future wind technologies in the Great Lakes. Physical constraints that were evaluated for this analysis included: bathymetry, wind resource, ice climate, waves, and currents. In most cases, existing literature and data sets were compiled and further analyzed to develop a complete picture for this study. In the case of wind resource, National Renewable Energy Laboratory (NREL) performed new modeling to update the offshore wind energy resource assessment for the New York Great Lakes, using a more robust twenty-one-year data set from 2000 through 2020 that includes uncertainty quantification. Additional siting considerations that may affect wind energy development in the Great Lakes are addressed in other parts of this study. The Great Lakes Wind Energy Feasibility Study: Physical Siting Analysis (NYSERDA 2022b) provides an accompanying analysis that evaluates geologic conditions that are important to siting wind turbines and associated energy infrastructure. The Great Lakes Wind Energy Feasibility Study: Visual Impacts (NYSERDA 2022i) study includes discussion of shipwrecks and other cultural heritage considerations. The Great Lakes Wind Energy Feasibility Study: State and Federal Permitting Roadmap (NYSERDA 2022j) examines environmental, multi-user, and visual impact considerations.

2 Evaluation of Site Conditions

2.1 Bathymetry

The water depth is a primary characteristic of the environment that any Great Lakes wind development would need to consider. It defines, in part, the technology that is suitable for a given location and can affect the suitability of vessels used. Depths that are less than 60 meters (m) are generally considered to be suitable for fixed-bottom wind turbines, while depths greater than 60 m may require floating technology. Lake Erie is characteristically shallow and almost exclusively less than 60 m deep. Lake Ontario is much deeper, and as a result, sites farther from shore are well over 100 m deep, indicating that floating technology should be considered.

Water depth influences other physical characteristics of the lakes such as wave height and temperature, as well as economic and technical factors for Great Lakes wind such as substructure type and installation costs. Detailed bathymetric data for the Great Lakes have been compiled by the National Oceanic and Atmospheric Administration (NOAA) from historic soundings and multibeam sonar surveys (National Geophysical Data Center, 1999a, 1999b). Bathymetry was mapped for both Lake Erie (Figure 1) and Lake Ontario (Figure 2).

Lake Erie consists of three basins: the eastern basin, central basin, and western basin, with depths increasing from east to west. The deepest portion of Lake Erie lies just west of New York waters; the maximum depth within State waters is between 50–60 m. Water depths throughout New York's Lake Erie area are suitable for fixed-bottom turbine foundations, which are considered suitable to ~60 m (Beiter et al., 2017). The lakeshore between Dunkirk and Buffalo has the shallowest depths in the State. Lake bottom slopes in Lake Erie are predominantly gradual inclines without significant steep sections.

Much of Lake Ontario is significantly deeper than Lake Erie, with only 30% of Lake Ontario waters within New York State boundaries less than 60 m deep (Figure 3). The lake consists of four basins, from west to east the Niagara, Mississauga, Rochester, and Kingston basins (Martini & Bowlby, 1991). The shallowest portion of Lake Ontario is the Kingston basin, which lies between the Duck-Galloo Ridge and the St. Lawrence River. The lake bottom drops steeply along the southern coast of the lake from Oswego westward.

Bathymetric contours are referenced to a standard low-water level datum for each lake. The actual water depth at any given point varies over time as the volume of water in the lake changes. Compared to coastal locations in the Atlantic or Pacific Oceans, the Great Lakes experience much greater variability in the mean water level (Gronewold et al., 2013). The annual mean water levels of both Lake Erie and Lake Ontario have historically varied within a range of approximately 2 m (U.S. Army Corps of Engineers, 2021). The lakes experience cyclical variations in water level due to annual precipitation and snowmelt patterns. Water levels are typically highest in the summer and lowest in the winter, with a difference of 54 cm between the highest and lowest monthly average levels on Lake Ontario and 35 cm on Lake Erie (U.S. Army Corps of Engineers, 2021).

Figure 1. Bathymetry of Lake Erie with Jurisdictional Boundaries by Country and United States

Source National Geophysical Data Center, 1999a

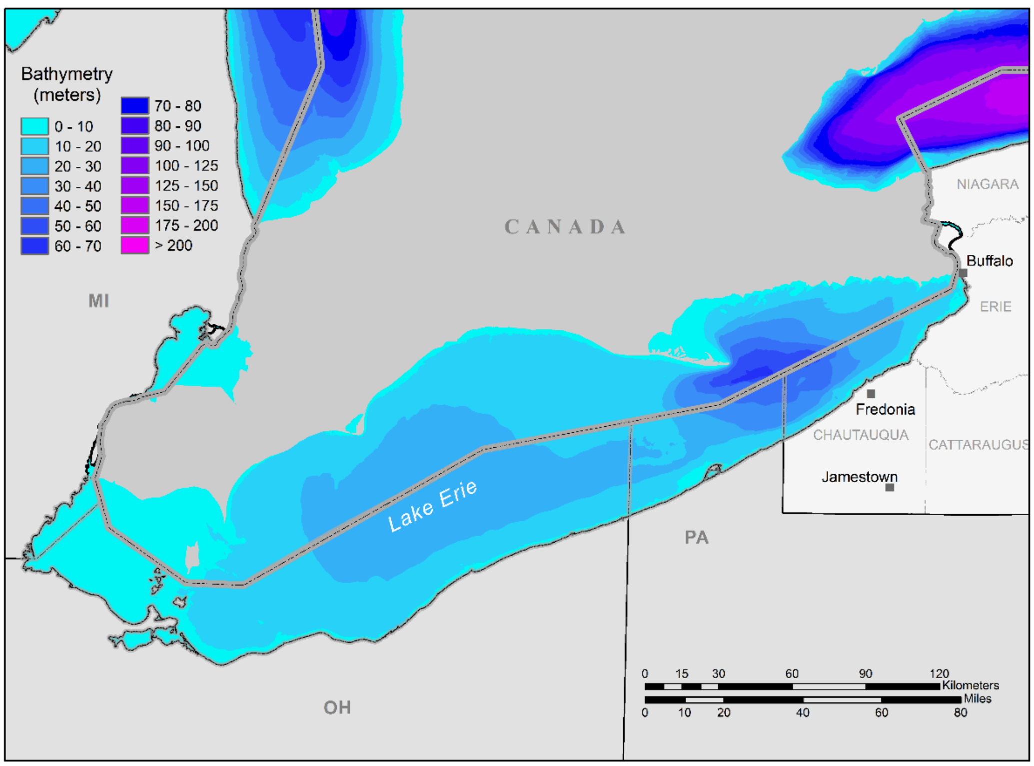


Figure 2. Bathymetry of Lake Ontario with Jurisdictional Boundaries by Country

Source: National Geophysical Data Center, 1999b

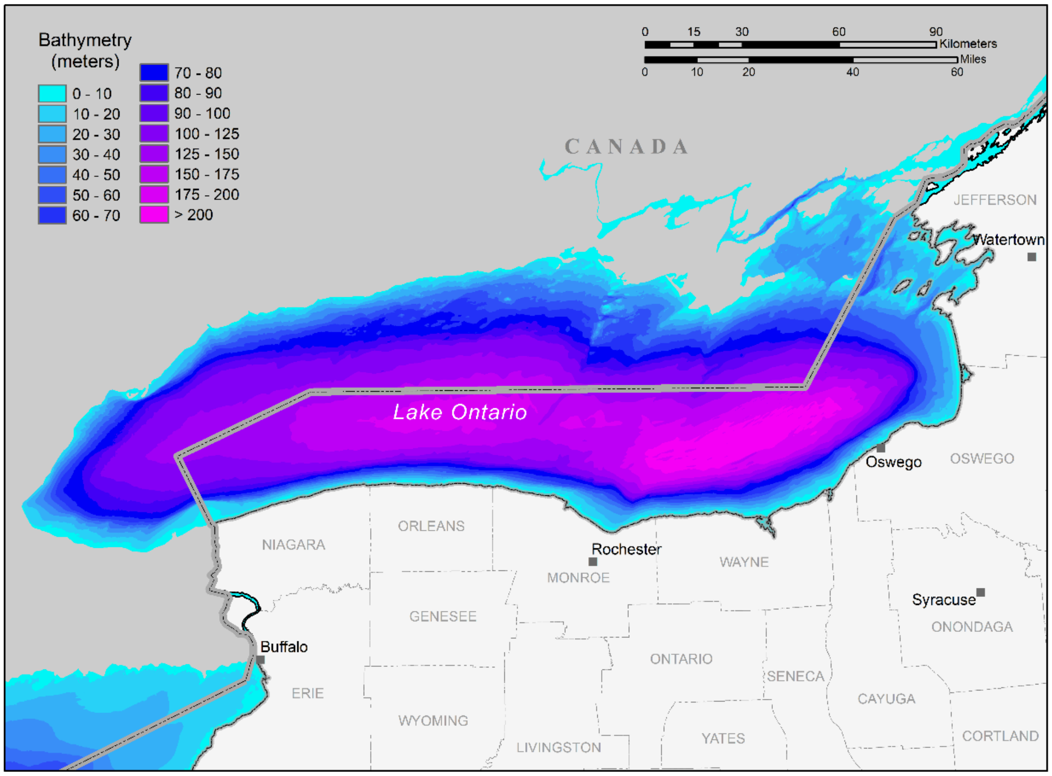
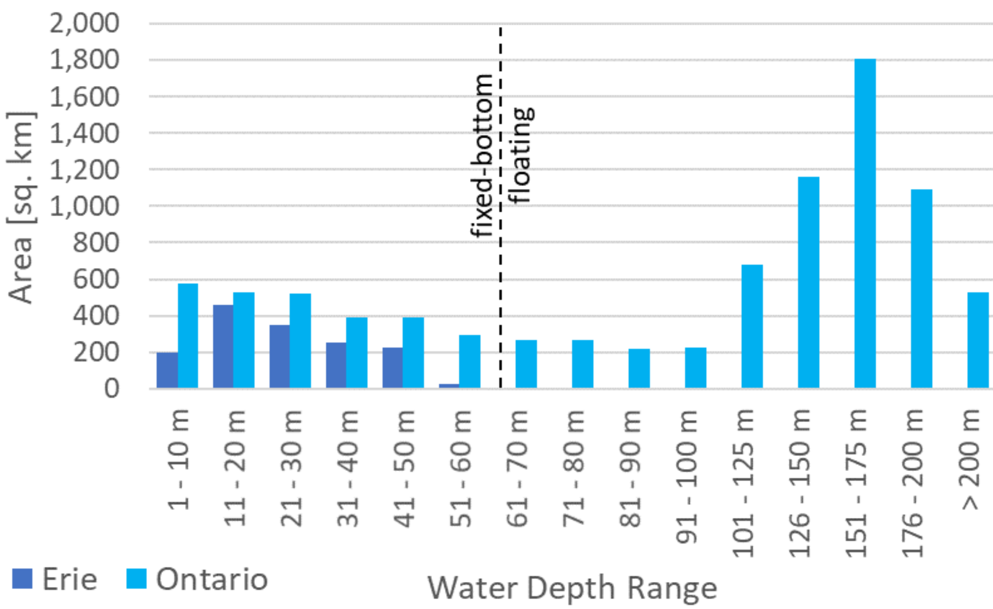


Figure 3. Distribution of Lake Surface Area by Water Depth

Note that bin ranges increase from 10 m to 25 m above 100 m depth.



2.2 Great Lakes Wind Resource

Wind resource assessments for Lake Ontario and Lake Erie presented in this section are based on new offshore wind resource data sets produced by NREL. These updated data sets replace NREL's previous Wind Integration National Dataset (WIND) Toolkit data (Draxl et al., 2014), which were produced in 2013 and have since been the basis for NREL's onshore and offshore wind resource assessments. Leveraging extensive research and development (R&D) advancements in numerical weather prediction modeling since 2013 (Optis et al., 2020) as well as higher computational capacity, the new data sets used in this study are more accurate than the WIND Toolkit for offshore wind resource characterization. The new data set also has more complete geographical coverage of the Great Lakes and includes a longer time period.

Wind resource data are produced using the Weather Research and Forecasting (WRF) model (Skamarock et al, 2019)—an open-source, community-based numerical weather prediction model maintained by the National Center for Atmospheric Research. A summary of the WRF model setup used for this Great Lakes wind resource assessment is provided in Table 1. Most notably, the wind resource assessment is based on a twenty-one-year time period—spanning from 2000 to 2020—and triples the previous seven-year time period used for the WIND Toolkit. Data are produced at 2-km spatial resolution with nine vertical model levels below 200 meters. Data are output at 5-minute time intervals. These data are hosted publicly through Amazon Web Services' Open Data Initiative and can be accessed for free through various means (NREL, 2021).

Table 1. WRF Model Setup used for Great Lakes Wind Resource Assessment

Feature	Specification
WRF Version	4.2.1
Spatial resolution	6 km (outer grid), 2 km (inner grid)
Vertical levels	61
Near-surface-level heights (meters)	12, 34, 52, 69, 86, 107, 134, 165, 200
Atmospheric forcing	ERA-5 reanalysis (Hersbach et al., 2020)
Lake temperature forcing	Operational Sea Temperature and Sea Ice Analysis (Donlon et al., 2012)
Planetary boundary layer scheme	Mellor-Yamada-Nakanishi-Niino (Nakanishi & Niino, 2009)
Land surface model	Noah (Ek et al., 2003)
Atmospheric nudging	Spectral nudging on 6km domain, applied every 6 hours
Microphysics	Ferrier (Ferrier et al., 2002)
Longwave radiation	Rapid Radiative Transfer Model
Shortwave radiation	Rapid Radiative Transfer Model
Topographic database	Global Multi-Resolution Terrain Elevation Data from the United States Geological Service and National Geospatial-Intelligence Agency
Land-use data	Moderate Resolution Imaging Spectroradiometer 30s (Justice et al., 2002)
Cumulus parameterization	Kain-Fritsch (Kain & Fritsch, 1993)

The mean 100-meter wind resource for Lake Ontario and Lake Erie based on the new twenty-one-year offshore data set was analyzed (Figure 4). Wind speed at 100 m was obtained by linearly interpolating model output at 86 and 107 m. For Lake Ontario, the annual average wind speeds are highest in the eastern half of the lake and peak at 8.5–9.0 m/s in a large portion of the lake. For Lake Erie, the eastern part of the lake has a similarly high wind resource, with wind speeds exceeding 9 m/s on average in a small part of the lake. The updated wind resource data are contrasted in Figure 5 against previous estimates from the WIND Toolkit (Draxl et al., 2014). The updated offshore data show a higher wind resource for Lake Erie and Ontario compared to that estimated from the WIND Toolkit. Increases in wind speed on Lake Erie range from about 0.8–1.6 m/s, and about 0.2–1.0 m/s over Lake Ontario.

Figure 4. Mean 100-Meter Wind Resource for Lake Ontario and New York State Portion of Lake Erie

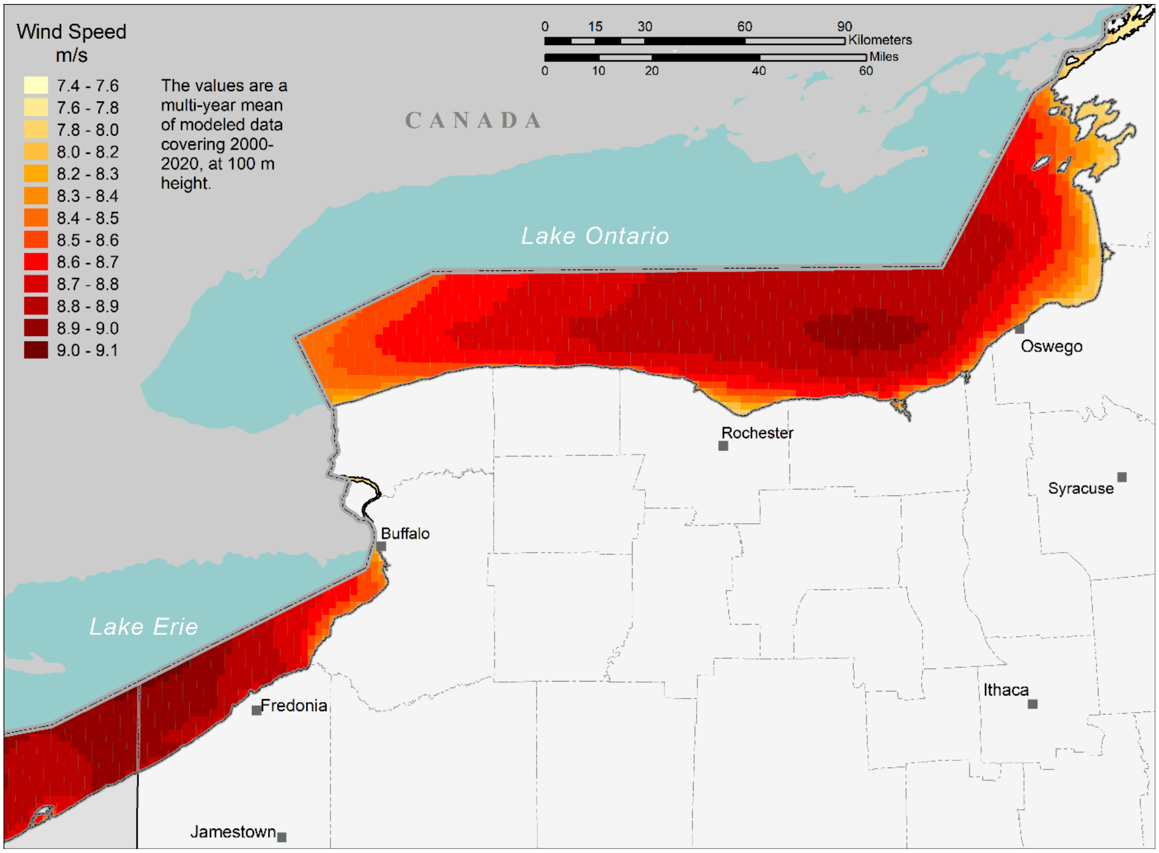
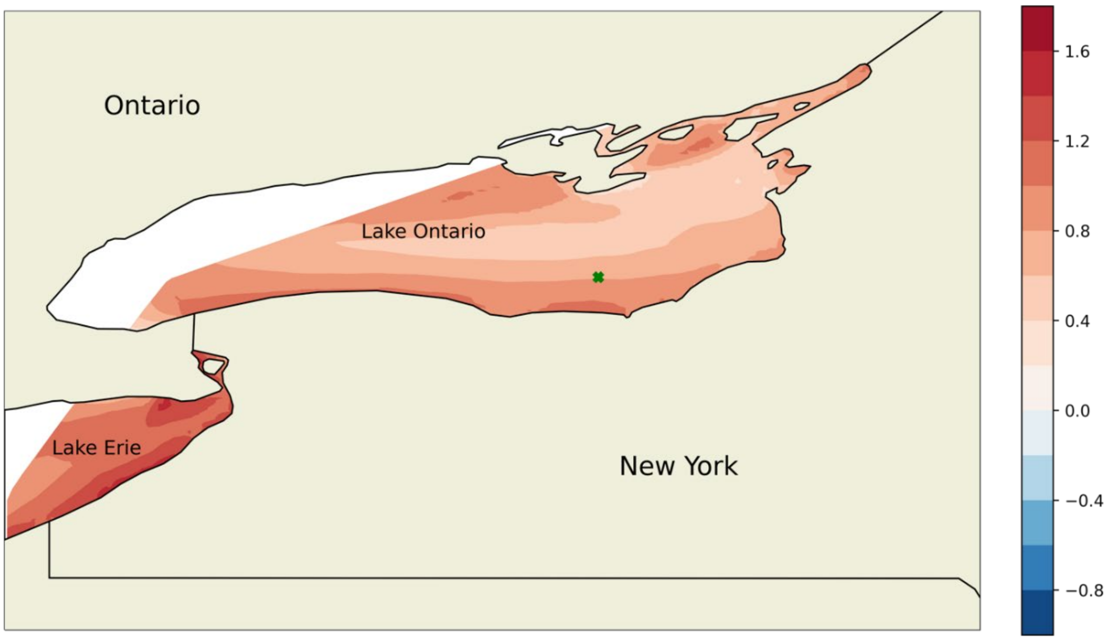


Figure 5. Difference in Mean 100-Mean Wind Speeds between the New Offshore Data Set and the WIND Toolkit

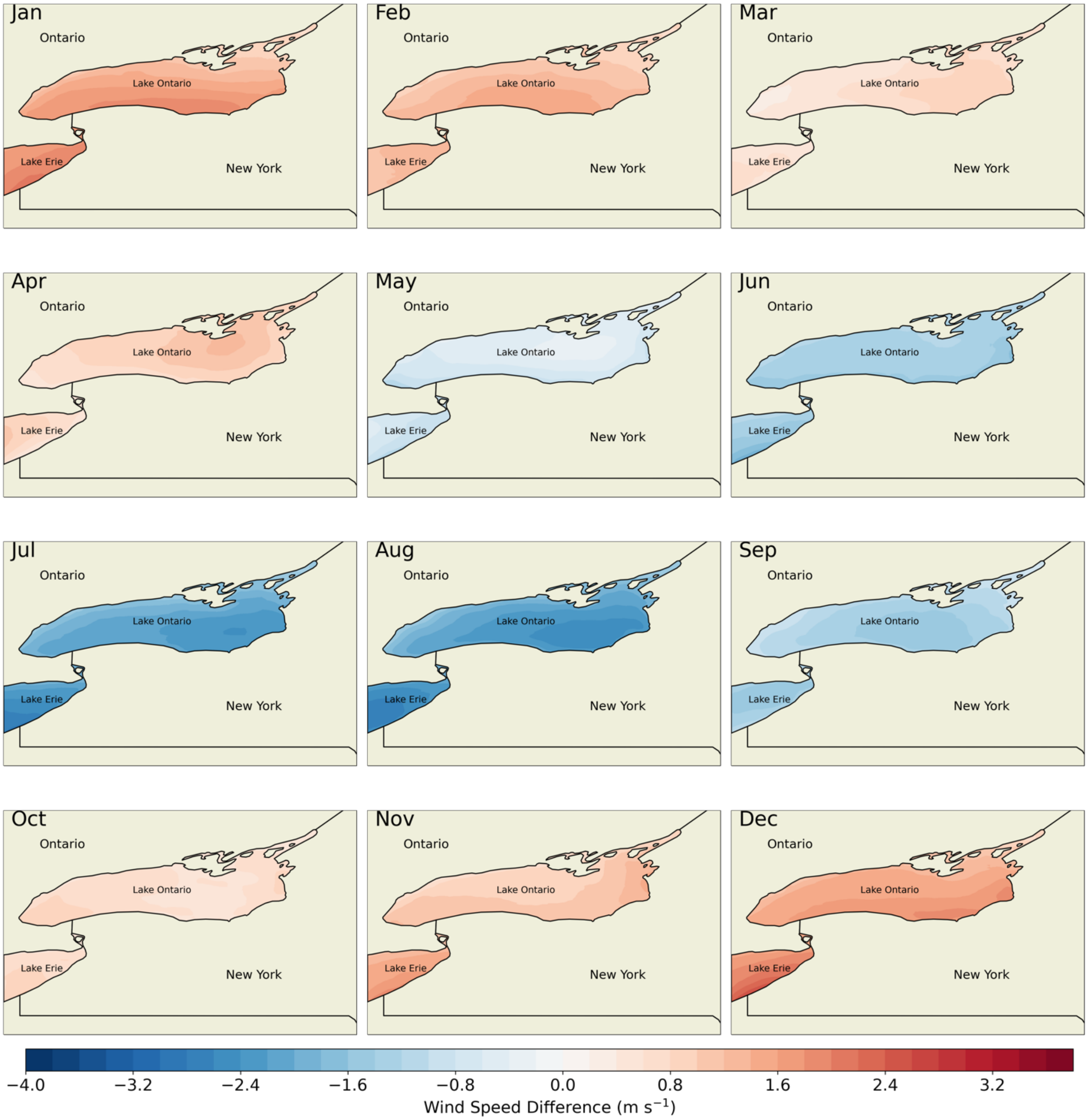
Positive (red) values indicate a higher resource in the new data set. Note that WIND Toolkit data is not available for portions of Lake Erie and Ontario in Canada (shown as white). The green marker denotes a sample location used in a later figure.



Monthly trends in the 100- meter winds are shown in Figure 6. The strong seasonal trend in the Great Lakes wind resource is evident here, with the strongest winds in winter (e.g., about 2 m/s above the annual average in December), and lowest in summer (e.g., about 3 m/s below the annual average in August).

Figure 6. Monthly Mean 100-Meter Wind Speed Differences from the Annual Mean

Red and blue values denote higher and lower monthly winds, respectively, relative to the annual mean.



Diurnal trends in the wind resource were analyzed for the region. Seasonal trends in the diurnal cycle are evident (Figure 7) for a sample location in Lake Ontario (see green cross in Figure 5), with much stronger diurnal amplitudes in the summer months compared to the winter months. These trends are assessed for the whole region in Figure 8, where we plot the amplitude in the mean diurnal cycle (i.e., the difference in the maximum and minimum in units of m/s) for each month. Again, there is a strong seasonal dependence on the diurnal cycle across both lakes, which is strongest in the summer and weakest in the winter months.

Great Lakes wind resources are on par with the mid-Atlantic regions where offshore wind energy development is proliferating. Annual average wind speeds close to 9 m/s in Lakes Erie and Ontario indicate that net capacity factors well over 40% would be achievable, and the seasonal characteristics indicate higher power levels during winter months.

Figure 7. Mean Diurnal Wind Speeds at Sample Location in Lake Ontario

Green marker in Figure 5

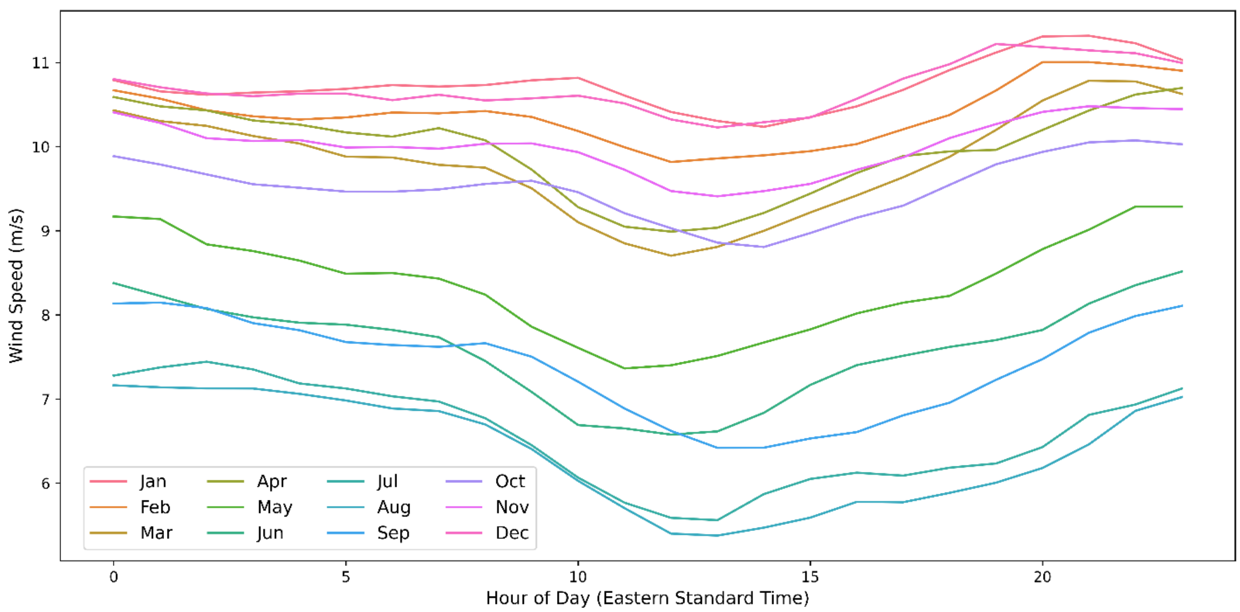
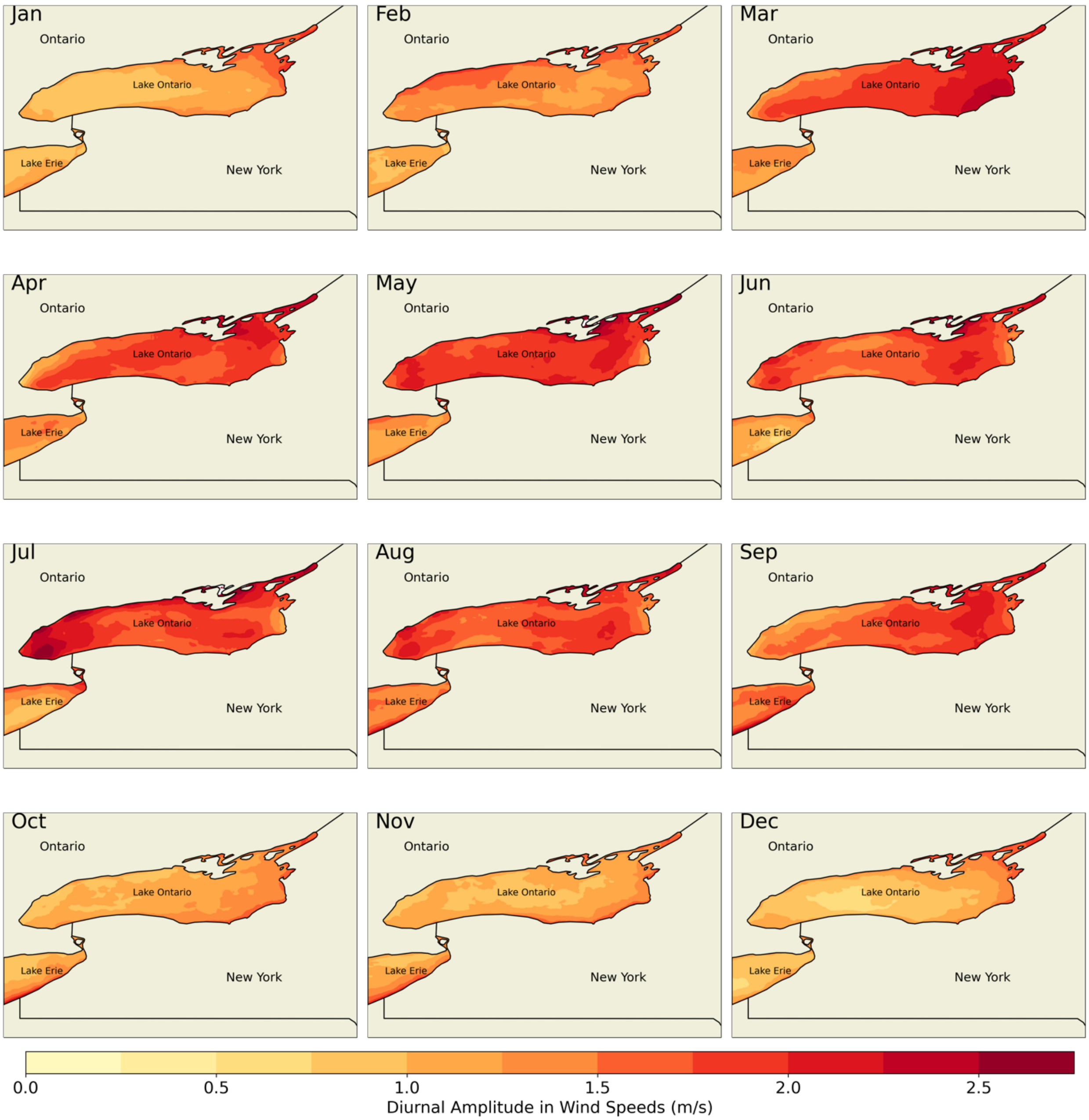


Figure 8. Amplitude of Mean Diurnal Wind Speeds for Each Month



2.3 Characterization of Ice Climate

The presence of ice on the surface of the lakes presents a significant design challenge which must be overcome for Great Lakes wind to be feasible. Wind turbines experience structural loading from the surface ice movement on the lake that must be resisted by the structure, similar to the aerodynamic and hydrodynamic forces imparted by the wind, waves, and currents. The problem of structural loading has been addressed in the offshore wind industry for fixed bottom substructures in other regions of the world.

In Lake Erie, the Icebreaker project proposed by LEEDCo off the city of Cleveland could potentially be the first Great Lakes wind project. However, there have not been any installations of floating wind turbines in oceans or lake ice climates. The presence of surface ice will likely limit the type of substructures that are possible in the lakes to types with slender profiles at the waterline which would better deflect ice floes and prevent jamming.

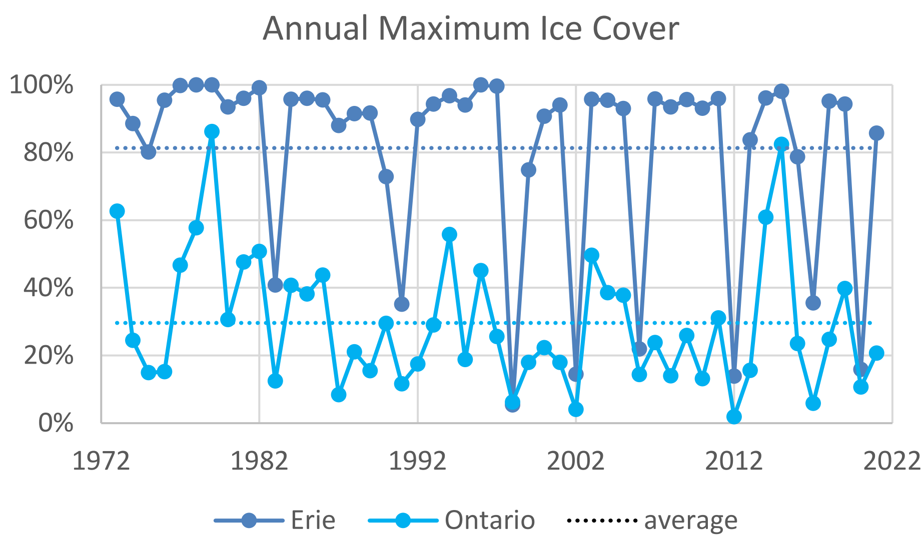
Freshwater ice on the Great Lakes differs in a few respects from the sea ice that is present at some locations where offshore wind turbines have been installed, primarily near Sweden and Finland in the Baltic Sea. Two important differences are the seasonality and salt content. Sea ice forms large floes that may persist for years, while ice in the Great Lakes melts completely each summer. Freshwater ice, including lake ice, forms at higher temperatures and is stronger than sea ice (Daly, 2016). The following sections review the available data and literature characterizing the ice climate on Lakes Erie and Ontario, noting areas where differences between lake ice and sea ice could impact wind turbine design or operation.

2.3.1 Annual Ice Cover Statistics for Lakes Erie and Ontario

Observations of ice cover on the Great Lakes are collected by the U.S. National Ice Center in cooperation with the Canadian Ice Service (U.S. National Ice Center, 2021). Ice coverage has been assessed from satellite imagery, in some cases supplemented by airborne observations, since 1973. Interannual statistics and analysis have been published periodically by NOAA's Great Lakes Environmental Research Laboratory (Wang et al., 2012, 2017). Annual maximum ice cover for Lakes Erie and Ontario were analyzed (Figure 9). There is a high degree of variation in the surface ice cover year-to-year, but some trends can be observed. Ice covers a large extent of Lake Erie in most years, which has an average annual maximum ice cover of 81% and exceeds that level in three out of four years. In contrast, Lake Ontario's average annual maximum ice cover is only 30% and remains below that level in three out of five years. Since 1973, the maximum ice cover has decreased by 0.53% per year on Lake Erie and 0.25% per year on Lake Ontario (Wang et al., 2017).

Figure 9. Annual Maximum Ice Cover on Lakes Erie and Ontario

Source: NOAA-GLERL, 2021



Total accumulated ice cover—which accounts for the number of days of ice cover per year as well as the fraction of the surface area—has a median value of 27% on Lake Erie and 6% on Lake Ontario (U.S. National Ice Center, 2021) (Figure 10). Ice cover is not uniformly distributed, with shallower areas tending to form ice sooner (Figure 11). Ice typically begins to form in December and lasts until April or May (Figure 10), with peak ice cover occurring around the second week of February on Lake Erie and the third week of February on Lake Ontario (U.S. National Ice Center, 2021). The end of the ice season in the spring tends to be later at the eastern ends of the lakes because floating ice is pushed eastward by the prevailing winds (Assel, 1999). In Lake Ontario, the shallow waters north of Stony Island have the longest duration of ice cover. The Buffalo area experiences the longest ice cover duration on Lake Erie.

Figure 10. Daily Ice Coverage Percentages on Lake Erie (left) and Lake Ontario (right), 1973–2021

Maximum (red, 1978: Erie and 1979: Ontario) and minimum (blue, 1998: Erie and 2012: Ontario) ice cover years are highlighted for each lake.

Source: NOAA-GLERL, 2021

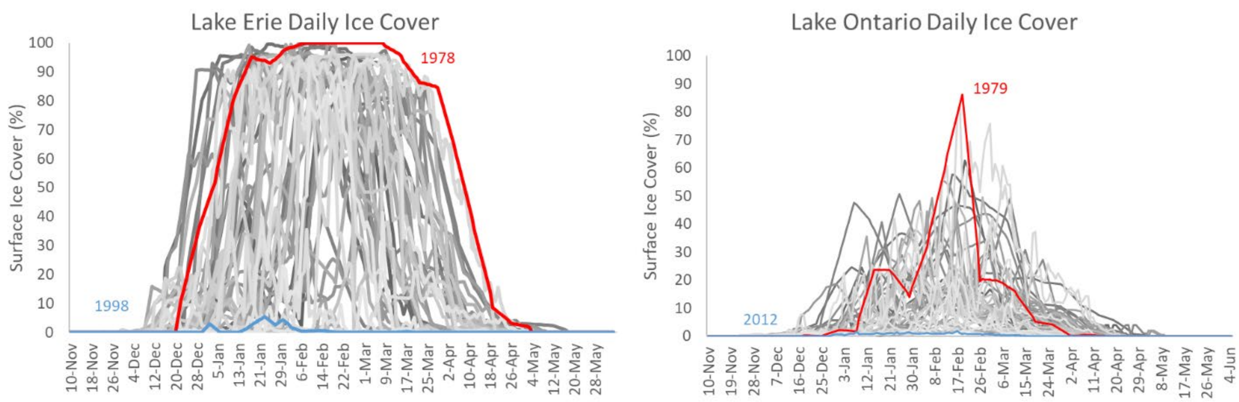
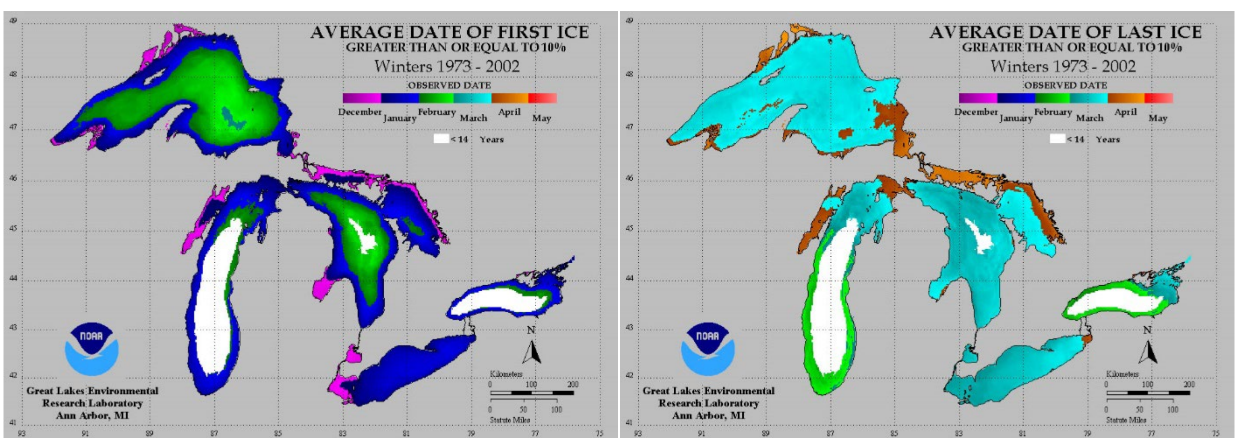


Figure 11. Average Dates of First (left) and Last (right) Ice Cover of at Least 10% Concentration, 1973–2002

Note that white regions indicate the area is not usually ice covered (<14 out of 30 years).

Source: Assel, 2002



2.3.2 Ice Thickness

2.3.2.1 Level Ice

The rate of formation of ice on the surface of a lake depends on the ambient temperatures of the air and water. The thickness of a sheet of level ice (i.e., an ice sheet formed by freezing at the water's surface, rather than by snow accumulation or collisions) grows during the period when the air and water temperatures are at or below freezing. Weather stations around the Great Lakes record freezing degree days (FDD), which are calculated from the average daily temperature and can be reported in units of degrees Celsius or Fahrenheit. The accumulated freezing degree days (AFDD) for a given location is the sum of the difference between the average temperature and freezing throughout an ice season, neglecting any periods where the temperature is above freezing. Measurements of AFDD have been shown to explain around 80% of the variability in ice thickness on the Great Lakes, with snow cover and water temperature history contributing additional variability (Hewer & Gough, 2019). The U.S. National Ice Center publishes estimates of ice thickness based on satellite observations and a freezing degree day model twice weekly during each ice season (U.S. National Ice Center, 2021).

The National Ice Center ice thickness estimates were found to be in good agreement with acoustic measurements of level ice thickness in Lake Erie during the 2010–2011 ice season (Hawley et al., 2018). Direct measurements of ice thickness on Lake Erie from 1965–1977 were used to develop the following equation relating ice thickness, η, with AFDD (Daly, 2016):

$$\eta = 2.39\sqrt{AFDD - 43.4}$$

Average values of AFDD measured at weather stations along the coast of Lake Erie in New York State during a 41-year period (1973–2013) range from 285°C-days in Dunkirk to 418°C-days in Buffalo. The corresponding ice thicknesses for these AFDD values are 37 cm and 46 cm, respectively, assuming steady growth without melting. The maximum surface-ice thickness with a 50-year return period (i.e., a 2% chance of exceedance in any given year) was estimated at 65–70 cm (Daly, 2016).

Ice thickness on Lake Ontario has been the subject of less study than on Lake Erie. The mechanism for surface ice formation is the same on both lakes, but the relationship between AFDD and ice thickness differs due to the deeper water in Lake Ontario, which requires the air temperature to remain below freezing for a longer period to lower the water temperature enough for ice to form. Observations from 1965–1977 recorded maximum ice thicknesses between 40–50 cm (Sleator, 1995).

2.3.2.2 Dynamics of Freshwater Ice

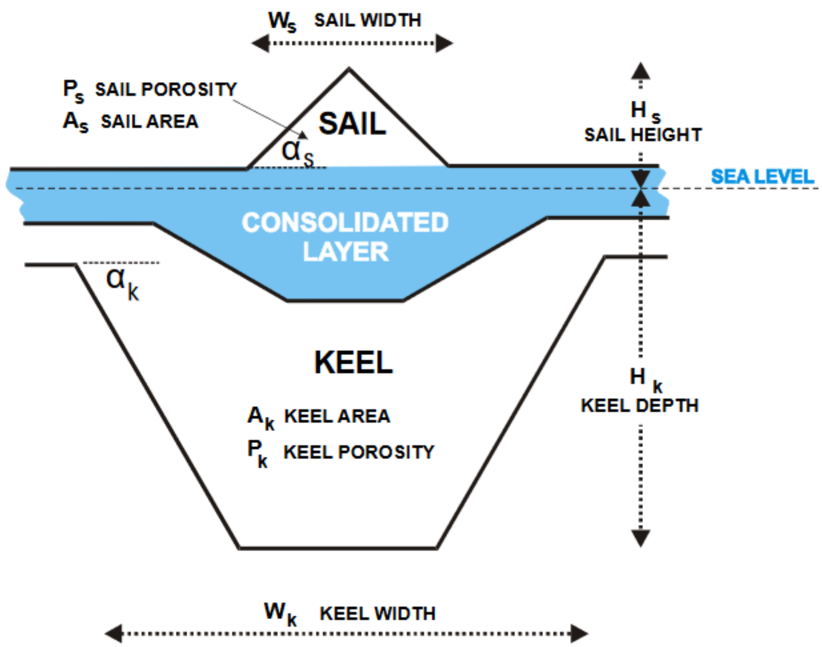
Surface ice sheets interact with wind turbines and other structures in the water when they collide. The force transmitted by such collisions depends on the velocity of the ice sheet and its flexural strength, which is its ability to withstand bending. Freshwater ice is approximately three times stronger than sea ice and can deliver a larger impact before buckling. The flexural strength of an individual ice sheet depends on factors including thickness, temperature, and ice grain structure, with typical values on the order of 2 MPa (Timco and Frederking, 1982). The velocity of a traveling ice sheet is influenced by currents within the water as well as by the speed of the wind above the ice. The ratio of the ice velocity to the wind velocity is described by the Nansen number Na, which depends on the densities of the air and water. Titze and Austin (2016) derive a value of $Na = 0.036$ for the Great Lakes, which is supported by their observations of ice movement on Lake Superior in which ice was found to travel at 4.3% of the wind speed. Average ice velocities in Lake Erie may be slower (approximately 2% of the wind speed) because large portions of the ice can become “landfast” or fixed to shore due to the greater extent of ice coverage (Wang, 2010). The direction of ice movement also follows the wind, with an offset of approximately 20° clockwise from the wind direction (Titze and Austin, 2016; Wang, 2010).

2.3.2.3 Ice Ridges and Lakebed Ice Scour

Ice ridges are formed by collisions between surface ice sheets or between surface ice and solid objects. Along the edge where the collision occurs, one layer of ice is pushed under the other along with smaller pieces of ice rubble that break off during the collision. Repeated collisions can form very long, tall ridges that are much thicker than the surrounding surface ice. The upper portion of the ridge is called the sail, while the portion below the water is the keel (Figure 12). The portion of the ridge that exerts the strongest force on offshore structures is the consolidated layer, which forms when layers of rubble freeze together in a solid mass (Timco et al., 2000). Ice in the remaining area of the keel and sail is more loosely agglomerated than in the consolidated layer.

Figure 12. Idealized Geometry of an Ice Ridge.

Source: Reproduced from (Timco et al., 2000)



There has been relatively little collection of data related to ice ridges in the Great Lakes. Direct access to the ice ridges is challenging, and satellite imagery does not provide sail height or keel depth. Two recent measurement campaigns in Lake Superior and Lake Erie used acoustic sensors mounted on the lake bottom to determine ice thickness (Hawley et al., 2018; Titze and Austin, 2016). The Lake Erie data was collected in the central basin during the winter of 2010–2011, which had a fairly typical annual maximum ice cover of approximately 96%. Level ice thicknesses varied from 0.10 to 0.25 m during the measurement period, with ridge thicknesses between 1 to 2 m occurring frequently. Maximum ice thicknesses of up to 10 m were observed for briefer periods. Similar results were obtained for Lake Superior during the heavy ice winter of 2013–2014, with the deepest measured keel depth exceeding 11 m.

Maximum keel depths are limited by the buckling strength of surface ice, which depends on the ice sheet thickness. Daly et al. (2016) proposed the following relationship for maximum keel depth H_K as a function of ice sheet thickness η:

$$H_K = 34.4\sqrt{\eta}$$

This equation gives a maximum keel depth of nearly 29 m for the 50-year extreme value of 70 cm surface ice thickness found for Lake Erie in the "Level ice" section above. In shallower locations, keel depth is also limited by the water depth. Evidence of scouring on the bed of Lake Erie indicates that ice keels can dig channels up to 2 m deep, although the age of the visible scours has not been determined (Daly, 2016).

The degree to which ice ridges may impact structures is still highly uncertain due to the lack of site-specific data with actual quantification of ice ridges in terms of the loads they would impart. Using best industry practices, wind turbine substructures should be feasible in these ice climates studied in the New York Great Lakes, but further verification of these extreme conditions may be necessary.

2.3.3 Blade Icing

Ice can accumulate on wind turbine blades when temperatures are close to or below freezing and there is moisture in the air from precipitation, fog, or droplets sprayed from the lake surface. The accumulation of ice on blades compromises their aerodynamics and adds weight, leading to a reduction in power output and possibly to a temporary shutdown of the turbine. Ice that falls or is thrown from a blade poses a potential safety hazard to wind plant technicians or to people in boats nearby. Standard wind turbines are designed to operate in temperatures down to -10°C (14°F), but most turbine manufacturers produce cold climate-adapted models and more than 127 gigawatts of wind capacity have been installed in cold climate regions (Bredesen et al., 2017).

The Wind Power Icing Atlas (Rissanen and Lehtomaki, 2016) identifies the Erie and Ontario lakeshores as IEA Ice Class 1 locations, which indicates that blade icing is expected to occur less than 1.5% of the year and cause less than 0.5% loss of gross annual energy production. Additional analysis by the same researchers (Rissanen & Lehtomaki, 2015) highlights the importance of height above ground level in determining the likelihood of icing and suggests that turbines with a hub height of 150 m could experience icing up to 3% of the year in the Great Lakes region. Turbines in the Great Lakes would also be exposed to spray from wind and waves. This additional moisture could increase the potential for ice formation in freezing temperatures; however, surface ice cover can block spray when it is present. Site-specific measurements of moisture and temperature up to tip height would be needed to provide a more accurate assessment of the likely impact of blade icing on energy production.

In general, blade icing should be taken into account during the design but would not pose an insurmountable challenge for engineering or cost if turbines were to be sited in the Great Lakes.

2.4 Waves and Currents

The waves and currents that are characteristic of the Great Lakes are generally smaller than what is commonly found in the Atlantic Ocean, outside of the fall storm season when waves on the Great Lakes reach similar heights as waves on the Atlantic Coast. As such, these external conditions do not pose a major design challenge for technology that may be deployed in the Great Lakes.

The NOAA National Data Buoy Center in the United States and the Meteorological Service of Canada collect data from buoys deployed in the Great Lakes and weather stations along the shore (Environment Canada, 2019; NOAA, 2021). Several identifiers in Figure 13 show the locations of stations and buoys located in Lake Ontario Lake Ontario and eastern Lake Erie. Additional details are provided for four selected buoys in the Great Lakes and two Atlantic locations close to New York State in Table 2. Wind speed, wind direction, atmospheric pressure, and temperature data are collected at all locations, while wave height, period, and direction are only measured at buoys. The majority of wave data are collected during the warmer months of the year as the buoys are removed from the water in November or December and returned to service in April or May. Prior to 2004, some data were collected over winter months by Canadian buoys in Lake Ontario. Ice cover can suppress wave formation in the winter, but areas of open water will still develop wind-driven waves.

Figure 13. Buoy and Weather Station Locations on Lakes Erie and Ontario

Station identifiers (45xxx) are listed for selected buoys, with an inset image of buoy number 45012.

Source: (NOAA, 2021)

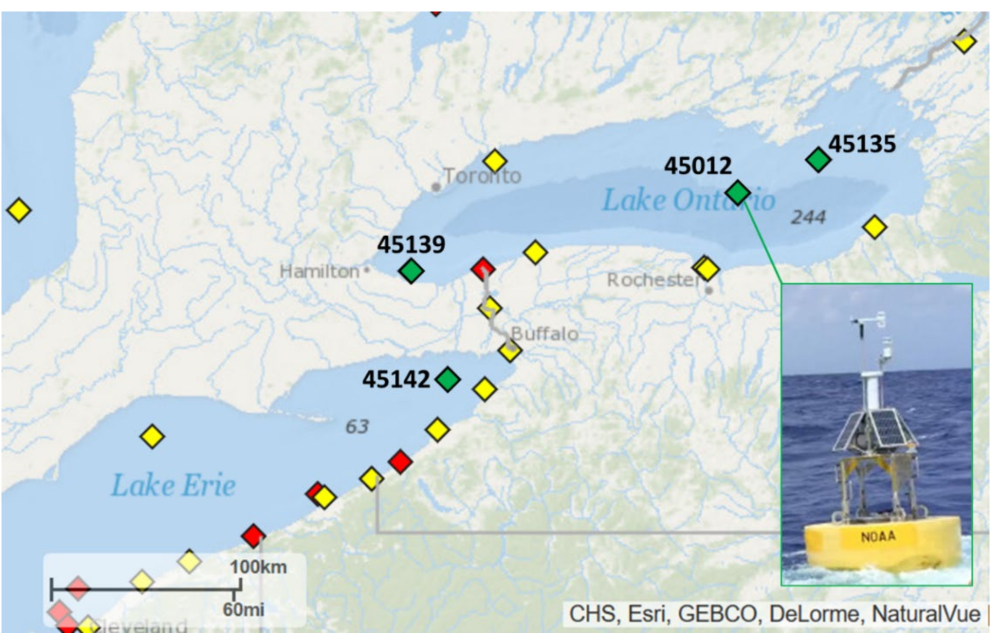


Table 2. Buoy Locations, Water Depth, and Period of Record

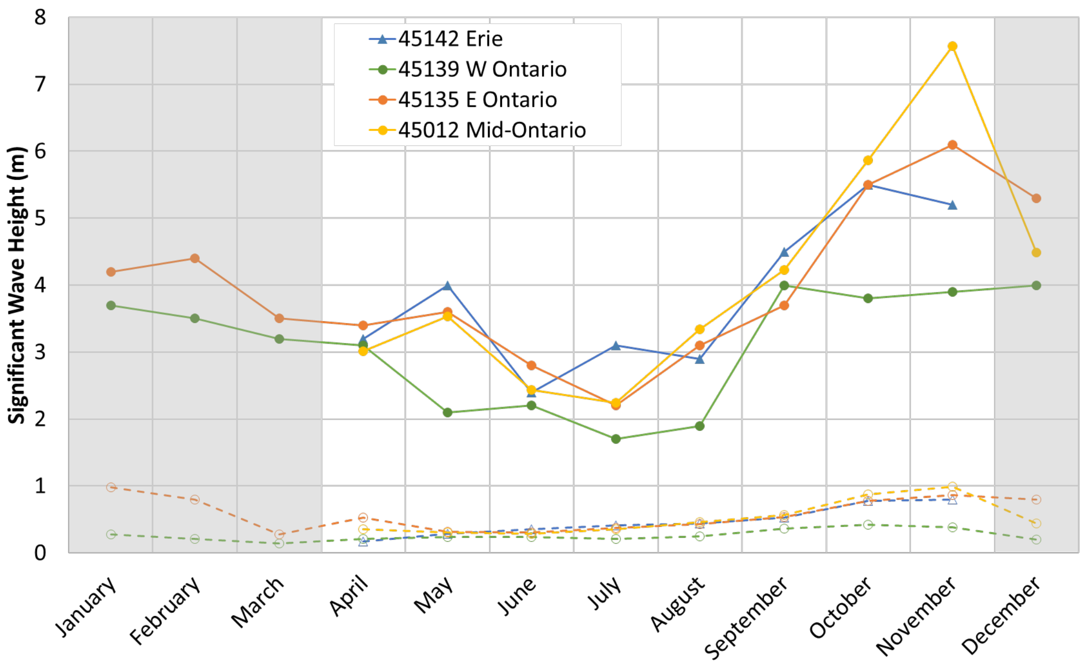
Buoy ID	Name	Latitude	Longitude	Depth	Begin Date	# Records (through 5/12/21)
45142	Port Colborne	42.74	-79.29	27 m	1994	148,591
45139	West Lake Ontario	43.26	-79.55	35 m	1991	127,093
45012	East Lake Ontario	43.62	-77.40	143 m	2002	93,529
45135	Prince Edward Point	43.79	-76.87	68 m	1991	102,395
44025	Long Island	40.25	-73.16	36 m	1991	142,270
44091	Barnegat, NJ	39.77	-73.77	26 m	2014	112,103

Monthly maximum and average significant wave heights were calculated based on buoy measurements during the warmer months (Figure 9). The maximum height of an individual wave can reach twice the significant wave height, which is defined as the average height from trough to crest of the largest third of observed wave heights in a given period. Average significant wave heights range from 0.2 to 0.9 m (8 in. to 3 ft.), while the maximum significant wave height is 7.6 m (25 ft). Both average and maximum wave heights are lower in the summer and higher in the fall, corresponding to seasonal variations in the wind speeds that drive wave formation. With prevailing winds from the west or west-southwest, waves in the eastern portions of the lakes typically have a longer fetch (distance that wind has traveled over open water) and are larger than waves at the western ends of the lakes. Comparison of the wave heights at buoy #45139 with other buoys in the area illustrates this effect (Figure 14).

Figure 14. Significant Wave Heights Recorded by Selected Great Lakes Buoys

Buoy IDs correspond to the locations in Figure 13. Solid lines/filled symbols indicate monthly maximum wave heights, and dashed lines/open symbols indicate monthly mean wave heights. Buoys were removed from the lakes from December to March in most years and there are only 25% as many observations per month in the period shaded in gray compared with the warmer months.

Source: Environment Canada, 2019; NOAA, 2021



Significant wave heights on Lakes Erie and Ontario are lower than at ocean sites where offshore wind plants have been installed. For example, in the North Sea, monthly average significant wave heights are between 1–2.5 m (Fraunhofer IWES, 2021). Annual maximum significant wave heights in offshore wind lease areas on the U.S. East Coast range from 211 m (Barthelmie et al., 2021). Significant wave heights from buoys close to offshore wind lease areas in the New York Bight (Figure 15) were analyzed for comparison to Great Lakes conditions (Figure 16). Mean significant wave heights are higher throughout the year at the Atlantic sites than in the Great Lakes; however, the maximum significant wave heights are very similar in both regions during the fall months. During the remainder of the year, maximum significant wave heights are higher in the Atlantic. The mean significant wave height during the summer months in the Great Lakes are less than half those in the Atlantic. In comparison with ocean sites, waves have less space in which to develop, which leads to slower-moving, steeper waves (Boyce et al., 1989).

Figure 15. Buoy and Weather Station Locations on the Atlantic Coast near New York State

Station identifiers (44xxx) are listed for selected buoys, with an inset image of buoy #44025.

Source: NOAA, 2021

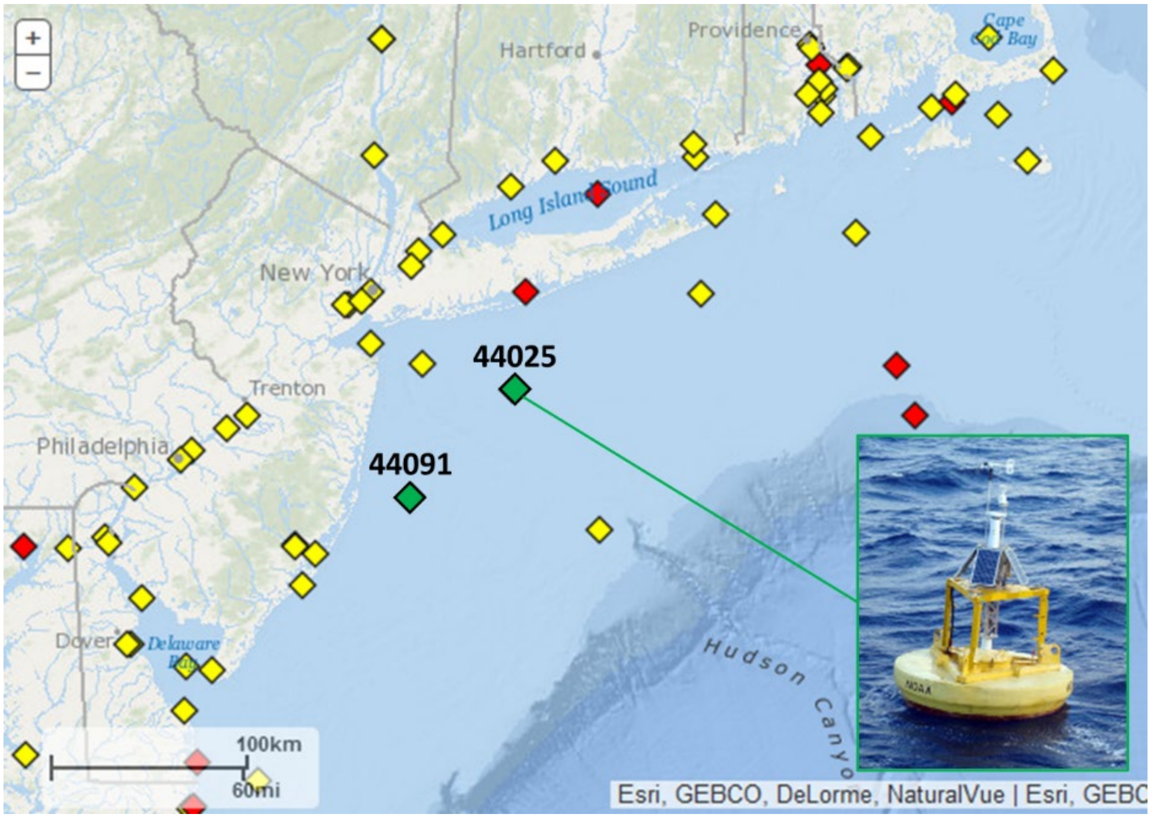
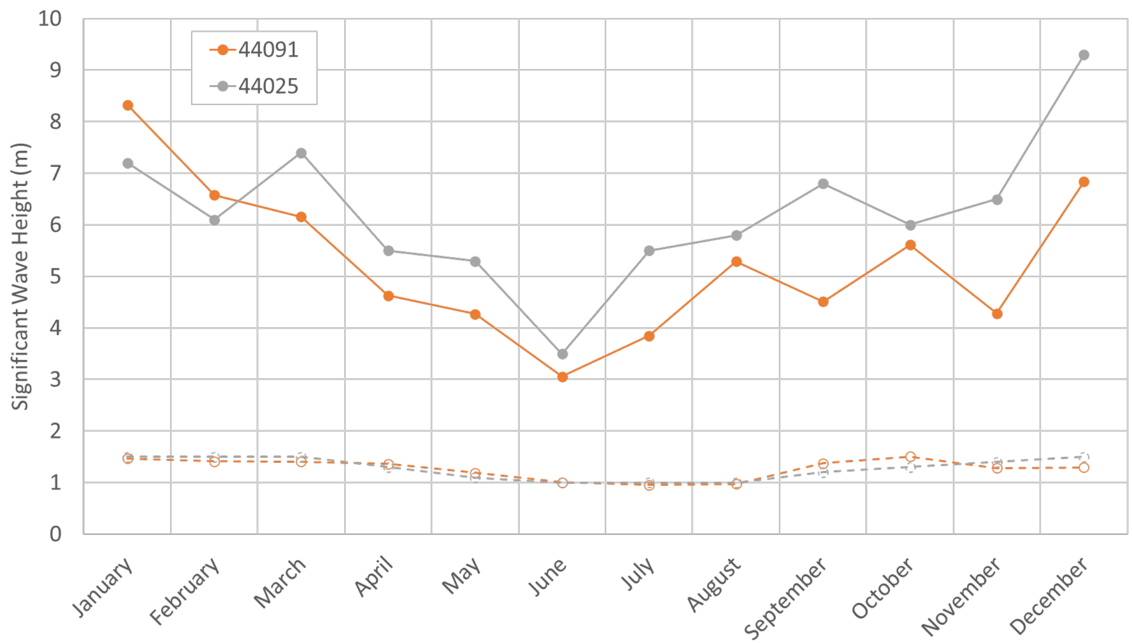


Figure 16. Significant Wave Heights Recorded by selected Atlantic Coast Buoys.

(Buoy IDs correspond to the locations in Figure 15.) Solid lines/filled symbols indicate monthly maximum wave heights, and dashed lines/open symbols indicate monthly mean wave heights.

Source: NOAA, 2021



A wave phenomenon known as "seiche" can occur on confined bodies of water such as the Great Lakes. Seiches are standing waves that form when water is driven to one end of the lake by wind or atmospheric pressure changes. When the water reaches the shore, waves are reflected back across the lake, where they interact to form large peaks and troughs. The largest amplitude of the seiches occur at the shallow ends of the lake and can reach a height of approximately 6 m on Lake Erie. The seiche effect is less pronounced on Lake Ontario, where seiches are typically less than 0.5 m (Boyce et al., 1989). The most extreme storm surge and seiche events typically occur between September and December (Farhadzadeh et al., 2017).

2.4.1 Currents

Currents in the Great Lakes can be driven by the wind or by temperature differences within the lakes. During the winter, water temperatures do not vary significantly when depth and currents are primarily wind driven, while in the summer, surface heating produces differences in density that give rise to thermally driven currents in addition to the wind driven currents (Bai et al., 2013). Seasonal mean current patterns are shown for Lakes Erie and Ontario (Figures 17–18). The dominant pattern of wind driven currents is a double gyre, in which water along the shoreline flows in the direction of the wind parallel to the shore, and the current in the center flows opposite the wind direction, maintaining equilibrium across the lake. Thermally-driven currents in the summer tend to form a single gyre rotating counterclockwise (Boyce et al., 1989). Currents tend to be stronger in the winter months and weaker during the summer (Table 3). Summertime currents are limited to the upper layers of the lakes due to thermal stratification. In the winter there is a greater extent of vertical mixing, and currents penetrate more deeply below the surface (Bai et al., 2013).

Table 3. Seasonal and Annual Depth-Averaged Mean Currents (Bai et al., 2013)

	Erie	Ontario
Winter	0.026 m/s	0.022 m/s
Summer	0.019 m/s	0.016 m/s
Annual	0.023 m/s	0.019 m/s

Figure 17. Seasonal Mean Circulation in Lake Erie

Source: Image Reproduced from Bai et al., 2013

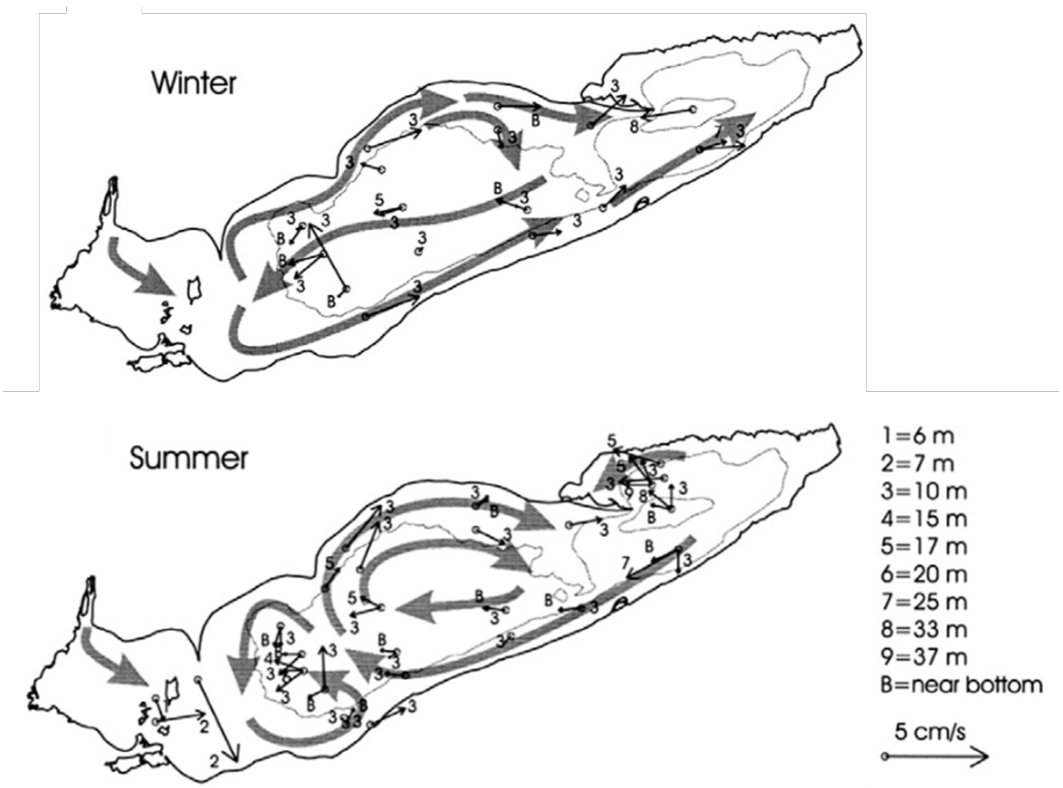
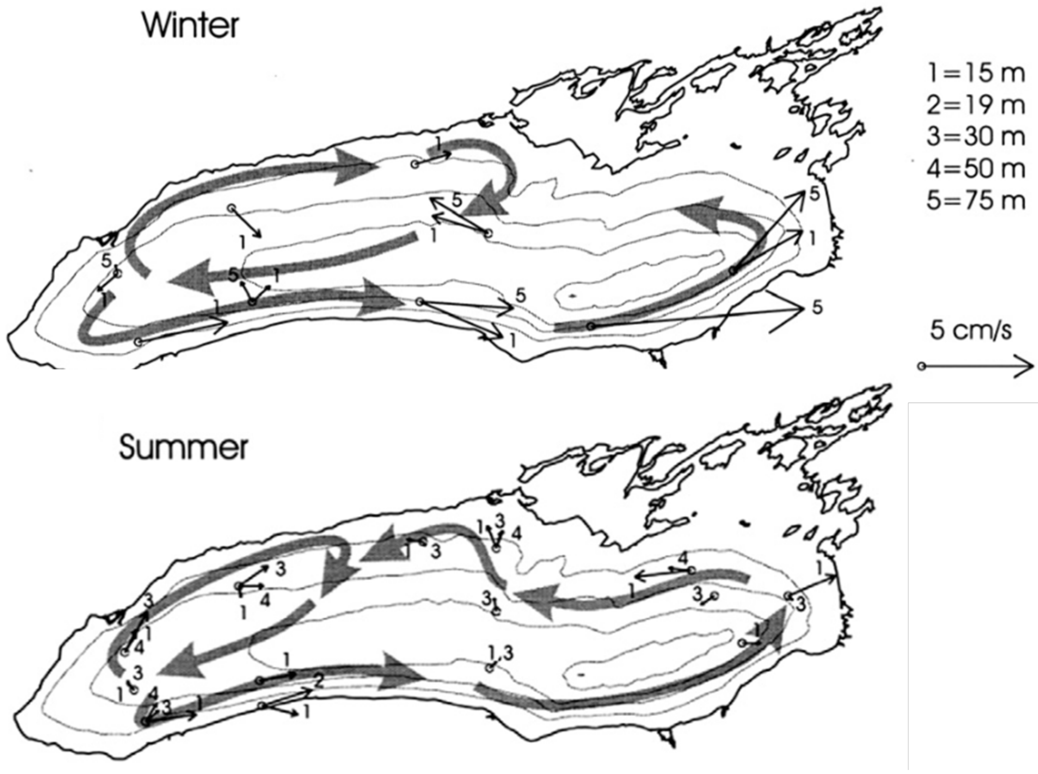


Figure 18. Seasonal Mean Circulation in Lake Ontario

Source: Reproduced from Bai et al., 2013



2.5 Conclusions

Physical conditions relevant to wind turbine siting in New York State waters of Lakes Erie and Ontario were assessed. In the case of wind resource, NREL performed new modeling to update the offshore wind energy resource assessment for the region, using a more robust twenty-one-year data set from 2000 through 2020. For Lake Ontario, the modeled wind resource indicates that annual average wind speeds at a height of 100 m are highest in the eastern half of the lake and peak at 8.5–9.0 m/s in a large portion of the lake. For Lake Erie, the eastern part of the lake has a similarly high-wind resource, with wind speeds exceeding 9 m/s on average in a small part of the lake.

Ice formation will affect wind turbines on the Great Lakes in the form of ice accumulation on turbine blades as well as ice cover on the lake surface. Lake Erie experiences significant ice cover in most years, with an average annual maximum ice cover of 81%. Level ice cover on Lake Erie can grow to tens of centimeters thick, and collisions can form ice ridges that may be several meters in height. However, the degree to which ice ridges may impact structures is still highly uncertain due to the lack of site-specific data with actual quantification of ice ridge loads. Wind turbine substructures should be feasible in these Great Lakes ice climates, but further verification of these extreme conditions may be necessary. The extent of ice cover on Lake Ontario is much less, with an average annual maximum of 30%. Ice cover can suppress wave formation in the winter, but autumn storms can produce wave heights comparable to those observed on the Atlantic coast. In general, blade icing should be taken into account during the offshore wind turbine design but would not pose an insurmountable challenge for engineering or cost if turbines were to be sited in the Great Lakes.

Wave heights in the spring and summer are relatively low and would be unlikely to impede vessel operations in support of wind energy deployment. Currents are also relatively slow, particularly during the summer months. None of the physical characteristics examined here present major obstacles to wind energy development, although they may impact design decisions (refer to Great Lakes Wind Energy Feasibility Study: Substructure Recommendations) (NYSERDA 2022e) and cost (Great Lakes Wind Energy Feasibility Study: Cost Analysis) (NYSERDA 2022g). Any wind energy development would require detailed, site-specific analysis to assess its technical and economic feasibility.

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