6.3&6.4 LAKE-EFFECT LIGHTNING DURING THE ONTARIO WINTER LAKE-EFFECT SYSTEMS (OWLES) PROJECT

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1. INTRODUCTION

During the winter of 2013-14, scientists from eleven institutions gathered in upstate New York to conduct a first-of-its-kind field campaign on Lake Ontario-generated lake-effect snowstorms called the Ontario Winter Lake-effect Systems (OWLeS) Project. The University of Wyoming King Air (UWKA) aircraft, heavily instrumented for in-situ and remote sensing of the atmosphere, along with three Doppler on Wheels (DOW) radars, five (four mobile) rawinsonde systems, and the University of Alabama – Huntsville Mobile Integrated Profiling System (MIPS) were some of the key facilities used to study lake-effect storms. The key objectives were focused in three areas: structure and dynamics of long lake-axis-parallel (LLAP) storms, upwind and downwind causes and effects of lake-effect systems, and orographic influences on these storms.

Lake-effect storms occur when a continental polar (cP) air mass is modified via heat and moisture fluxes by a large body of water (in this case, the eastern lake shown in Fig. 1 – Lake Ontario). The surface-based convective cloud tops generally range between 1 and 4 km AGL and the storms form in bands parallel to the mean boundary layer wind direction approximately 10-25 km wide. For a more extensive review, please see Markowski and Richardson (2010; Section 4.5).

A major goal of this study was to determine under what conditions lake-effect snow clouds generate lightning. Previous studies have shown most lake-effect lightning associated with the Great Lakes occurs early in the cold season (November and December) and is confined to over or near the lake (Fig. 1). Lightning was reported (by humans and/or computer detection systems) during 5 OWLeS events: 11 Dec 2013, 18 Dec, 7 Jan 2014, 20 Jan, and 27 Jan. None of the reported lightning was over the lake!

The OWLeS project allowed for an in-depth analysis of the microphysics and storm kinematics of the electrified lake-effect snowstorms that were observed. For example, some key indicators of lightning initiation include: strong updraft speeds, significant supercooled liquid water amounts in the lake-effect clouds, mixed hydrometeor types (especially graupel), and significant depth of the -10 to -25°C layer in the cloud (Steiger et al. 2009 used this as the "charging layer").

2. DATA & METHODS

Two of the OWLeS events have been thoroughly investigated and compared: Intensive Observation Periods (IOPs) 5 (18 Dec 2013) and 7 (7 Jan 2014). The latter case was the most electrically active event observed during the field project, with a total of 24 lightning flashes detected by the Earth Networks Total Lightning Network (ENTLN; http://www.earthnetworks.com/products/totallightningnetwork.aspx) over a 4.5 hr period, as well as 15 mobile snow team observation reports of lightning and/or thunder. This was also the coldest and windiest event of the winter season with surface temperatures around -10°C and sustained 10-m winds around 50 kt. This event served as an ideal comparison to IOP 5, which featured warmer surface temperatures around 0°C, lighter winds, and plenty of graupel. Surprisingly, IOP 5 featured much less lightning than IOP 7, with only 5 lightning flashes being detected by the ENTLN and one human report of thunder. Both IOPs 5 and 7 featured no lightning over Lake Ontario, and instead occurred well inland over the Tug Hill Plateau region (Fig. 2 shows the location of the Tug).

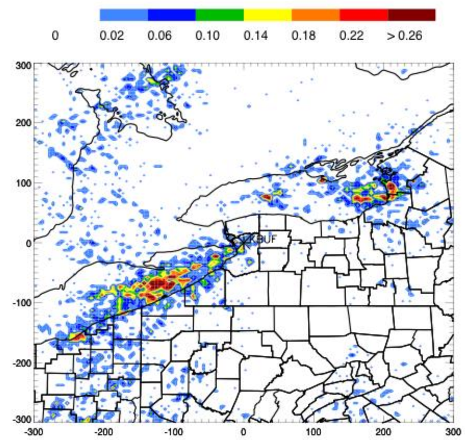

Figure 1. A climatology of cloud-to-ground lightning (flashes km^{-2}) associated with lake-effect storms using data from 1995-2007 reveals that the lightning normally occurs over or near the Eastern Great Lakes of Erie and Ontario (from Steiger et. al 2009).

In addition of analyzing ENTLN data, the United States Precision Lightning Network (USPLN; http://www.uspln.com/capabilities.html) data were also examined. Both lightning networks provided us with spatial and temporal information for each lightning flash or strike detected. Note that the ENTLN detects both cloud-to-ground (CG) and intracloud (IC) lightning flashes while the USPLN detects individual CG and IC strokes. The ENTLN has a location accuracy of 100-300

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m, while that for the USPLN is 300-500m. Our goal in this study is not to compare the two networks, but rather to get a sense of how electrified IOPs 5 and 7 compared to each other. Data from both networks were also used to determine if a relationship between the detected lightning flashes or strokes and a nearby wind farm is evident. See section 6 for more information on our analysis related to the Maple Ridge Wind Farm located over the Tug Hill Plateau region, where most of the lightning occurred during both IOPs 5 and 7.

In addition to the lightning analysis, an in-depth evaluation of observed updraft speeds and reflectivity during both IOPs 5 and 7 was done. A total of three instruments were used to obtain these data, including the: Micro Rain Radars (MRRs), MIPS X-band Profiling Radar (XPR), and the UWKA Cloud Radar (please see http://catalog.eol.ucar.edu/owles for facility details). Note that there is no UWKA data available for IOP 5 as there was no flight conducted for this event; only these data for IOP 7 were analyzed. More importantly, keep in mind that data from the MIPS XPR were collected at Sandy Creek, NY, which is near the Lake Ontario shoreline about 50 km from where most of the lightning occurred for both IOPs 5 and 7. Nevertheless, these data still provide us with a good sense of the magnitudes of observed updrafts within these two lake-effect snowstorms, during the time period of lightning occurrence. Similarly, the UWKA data used to obtain maximum observed updraft speeds during IOP 7 was also >50 km from where most of the lightning occurred since we used a flight leg over Lake Ontario. This flight leg was flown approximately 2.5 hours after the last detected ENTLN flash, which provided us with the UWKA data closest to the time period of past lightning. The UWKA data closest in distance to past-detected lightning flashes or strokes was also analyzed, but by this time all lightning had ended about 4 hours prior. Fortunately, data from the four MRR transect locations (See Fig. 2) provided us with reflectivity and velocity time history plots for both events at points geographically close to where the lightning occurred, during the period of lightning.

Figure 2. The four MRR transect locations remained stationary throughout the OWLeS Project, starting along the lake shoreline at Sandy Island Beach about 75 m MSL and extending into the highest elevations of the Tug Hill Plateau at 530 m MSL. Courtesy Jim Steenburgh.

Two additional important parameters that can be associated with lightning initiation that were able to be analyzed included integrated liquid water and integrated water vapor amounts. These data were made available at 1-minute intervals during both IOPs 5 and 7 using the MIPS Microwave Profiling Radiometer (MPR). As mentioned before, it is necessary to be aware of the fact that all the MIPS data were collected at Sandy Creek, NY for both events; this is located approximately 50 km away from where most of the lightning occurred.

Lastly, we also analyzed the depth of the -10 to -25°C layer within the lake-effect snow clouds courtesy of the mobile rawinsonde (Vaisala, Inc. sondes) teams, which successfully launched several balloons at 3 hr intervals into the core of the lake-effect snow bands during both IOPs 5 and 7. Using RAOB software, these data were plotted onto a thermodynamic diagram (See Fig. 3). Fig. 3 shows a sounding launched within 10 minutes of an ENTLN flash detected about 35 km to the east of the launch site at Henderson Harbor, NY (See Fig. 3).

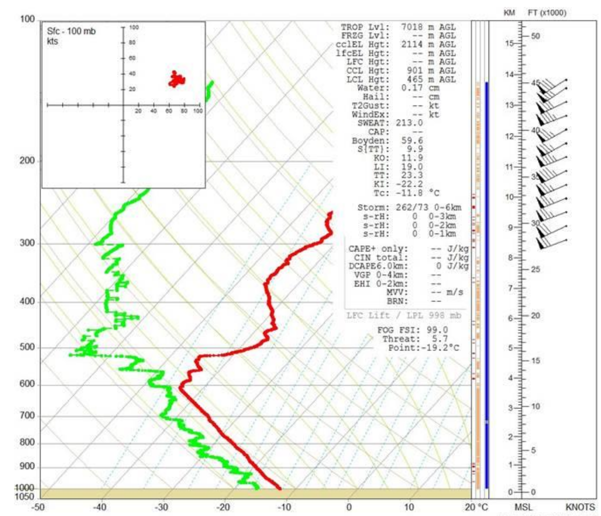

Figure 3. Observed sounding during IOP 7 at 1113 UTC.

3. SYNOPTIC OVERVIEW DURING IOPs 5 AND 7

A large amplitude, blocking upper-level ridge over western North America, with a downstream trough over eastern North America, dominated the synoptic pattern for most of the field project (see Figs. 4 and 5). This trough led to frequent intrusions of arctic air over and near Lake Ontario, sometimes originating from cross-polar flow. There was a total of 24 IOPs during the OWLeS field campaign, more than double what climatology suggested would occur!

The most prolific lightning event occurred on 7 Jan, when the Earth Networks Total Lightning Network (ENTLN) detected 24 flashes between 0630 and 1130 UTC. The 850 hPa temperatures were between -20 and -25°C, with strong west-southwest winds of near 50 kts (Fig. 6). The lake-effect band moved southward and the reflectivity gradient became very sharp along the northern band edge with many vortices embedded near the time of peak lightning activity (0630 – 0700 UTC). The in-cloud layer (defined where RH_{liquid} >= 80% and hence RH_{ice} near 100%) where temperatures were between -10 and -25°C (layer where mixed-phase microphysics and charge separation is possible/likely; Zajac and Weaver 2002) was 1750 m deep, but the -10°C level was below ground (i.e., very cold conditions; see Fig. 6). This begs the question: where is the cloud base in a lake-effect snowstorm when relative humidity with respect to ice is 100% from ground to cloud top?

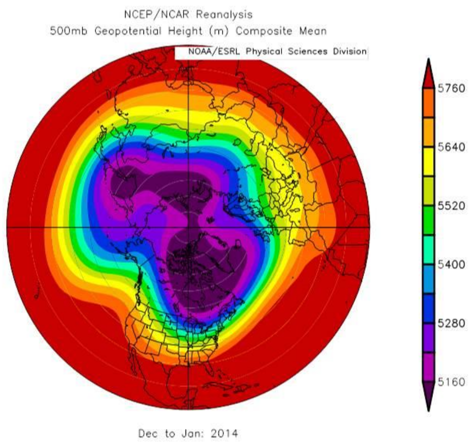

Figure 4. A reanalysis of mean 500 hPa geopotential heights (m) over North America from Dec 2013 to Jan 2014. Colder than average temperatures on the eastern half of North America and warmer than average temperatures on the western half were more than often the case during the OWLeS field campaign, setting the stage for an active lake-effect snow season!

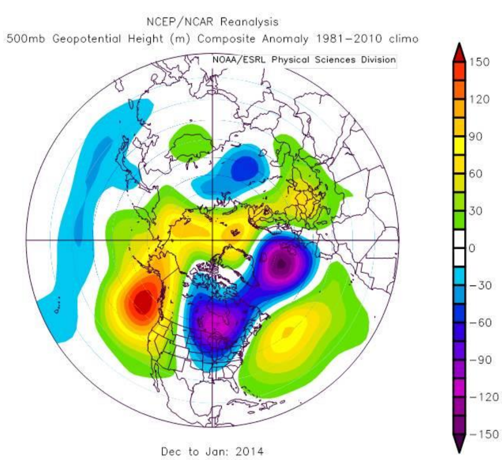

Figure 5. A reanalysis of mean 500 hPa anomalies (using 1981-2010 climatology of 500 hPa geopotential heights) over North America from Dec 2013 to Jan 2014. Notice the North Atlantic Oscillation (NAO) is not very negative.

This event also featured a very deep boundary layer (for winter) with tops near 550 hPa (4.4 km MSL). Lake-induced CAPE values (calculated using NAM model soundings via the BUFKIT computer program; http://www.erh.noaa.gov/buf/bufkit/bufkit.html) were greater than 2100 J kg^{-1} and the lake-induced equilibrium level was 5.2 km!

In contrast, the 18 Dec event was much warmer and climatologically a more favorable time for lake-effect lightning (per Steiger et al. 2009). Five lightning flashes occurred between 2130 and 2230 UTC. 850 hPa temperatures were near -10°C and winds at this level were westerly at 35 kt. Surface temperatures were near 0°C. The in-cloud layer conducive to charging was 1970 m deep and the boundary layer top was 675 hPa (3.1 km MSL; see Fig. 7). It is also important to note the band structure on 18 Dec was quite broken in radar reflectivity imagery ("convective"; not shown) while it was more solid during the 7 Jan case.

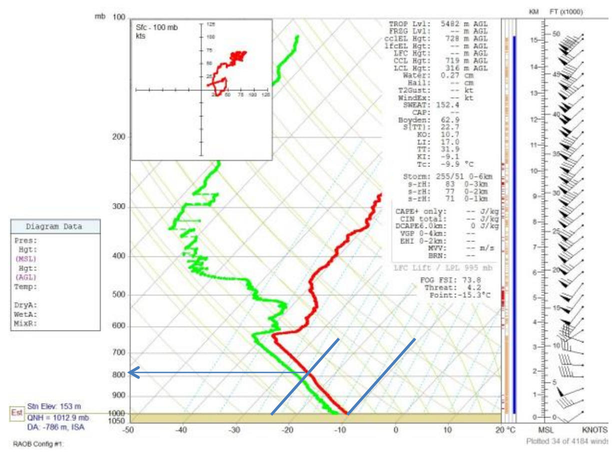

Figure 6. Sounding launched by SUNY Oswego team within lake-effect snow band at Henderson Harbor, NY at 0513 UTC 7 Jan 2014 (1 hr before lightning). The blue lines highlight the area where -25°C <= T <= -10°C.

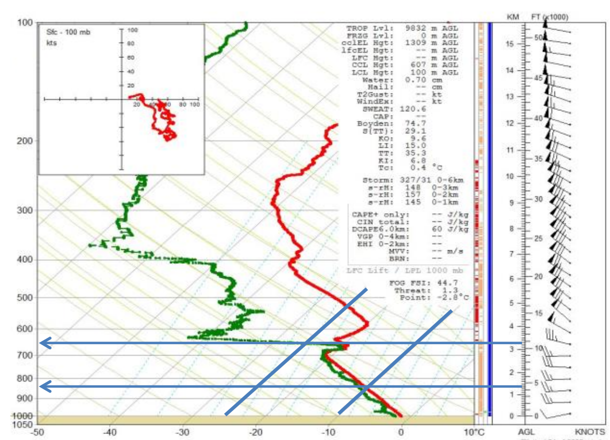

Figure 7. Same as Fig. 6, except for 2007 UTC 18 Dec 2013, Ellisburg, NY and 1.5 hrs before lightning occurrence.

An analysis of lightning associated with convective snowfall in the Hokuriku District of Japan suggests that cold environments are less favorable for lightning occurrence, as no lightning flashes were observed when the altitude of the -10°C isotherm was below 1.4 km (Michimoto 1993). Most parameters were suggestive the 18 Dec 2013 event should be more conducive to lightning (-10°C level 1.3 km AGL vs. below ground in 7 Jan, deeper -10 to -25°C layer); yet the 7 Jan 2014 event had many more flashes (5 times more). Granted, the 7 Jan event had a deeper boundary layer and more LI-CAPE, but observations showed the maximum updraft speeds were similar in both events (see Table 1 and sections 4 and 5).

4. AN ANALYSIS OF LIGHTNING DURING IOP 5: ASSOCIATED STORM KINEMATICS AND MICROPHYSICS

IOP 5, which occurred on 18 Dec 2013 from approximately 1600 to 0000 UTC 19 Dec, was the second most electrically active lake-effect snowstorm observed during the OWLeS field project. Although the USPLN detected no lightning at all during this event, the ENTLN detected a total of 3 CG and 2 IC flashes all having negative polarity (See Fig. 8). The ENTLN detected its first and last lightning flashes during IOP 5 at 2148 and 2220 UTC, respectively.

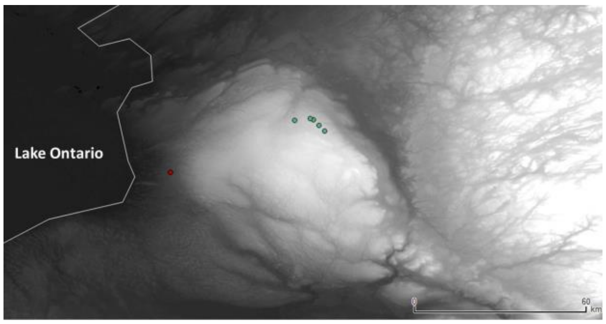

Figure 8. The dark green dots denote the location of detected ENTLN flashes during IOP 5. The red dot denotes a human report of thunder by the MIPS team located at Sandy Creek, NY. The lightning data are overlaid onto topographical data, with whiter colors being the highest elevations (near 500 m MSL) and dark grays being the lowest (near 75 m MSL). The elevated Tug Hill Plateau region to the east of Lake Ontario is well depicted.

The red dot in Fig. 8 also denotes the location of the MIPS team during IOP 5. Although the MIPS was about 50 km away from the detected lightning flashes, the XPR data can be used to analyze observed updraft speeds during the time period of lightning. A maximum observed updraft speed during the entire event occurred 19 minutes after the last detected ENTLN flash with a magnitude of approximately 8 m s^{-1}.

MRR transect data were analyzed as another source of observed updraft speeds. Not only did all of these transects collect data in the lake-effect snow band during the time period of lightning, but two of these transects also provided data very close in proximity to the lightning, particularly the Upper Plateau (UP) MRR transect location (See Fig. 9).

Notice the "cellular" convective nature of this event in Fig. 9, with updraft speeds greater than 5 m s^{-1} being observed rather frequently. Updraft speeds are surprisingly the weakest where most of the lightning occurred over the UP region.

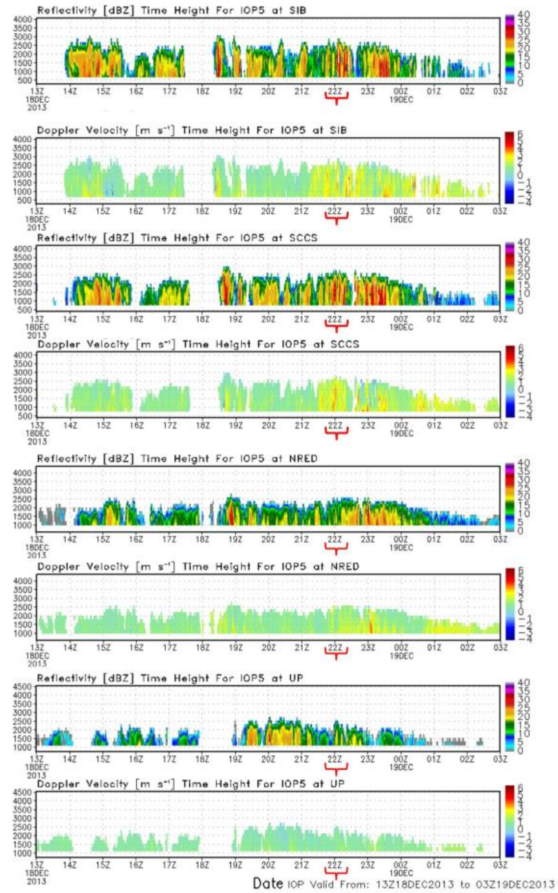

Figure 9. Reflectivity time-height and their corresponding Doppler velocity plots are shown for each of the four MRR transect locations, beginning with the westernmost location at Sandy Island Beach (SIB) and ending with the UP location. The red brackets denote the time period of lightning.

IOP 5 also featured significant amounts of integrated liquid water (ILW) and water vapor when compared to IOP 7. The MIPS MPR data revealed a maximum ILW value of 1.95 mm during IOP 5, which was measured just minutes after all lightning activity had ended about 50 km from the MIPS site. (Please see Table 1 for a summary of all the main observations related to lightning that were analyzed during IOPs 5 and 7.)

5. AN ANALYSIS OF LIGHTNING DURING IOP 7: ASSOCIATED STORM KINEMATICS AND MICROPHYSICS

IOP 7, which occurred on 7 Jan 2014 from approximately 0000 UTC to 2230 UTC, was the most prolific lake-effect snow storm observed during the OWLeS field project with the most lightning detected. The ENTLN detected a total of 17 CG and 7 IC flashes, all having negative polarity except for 1 CG flash and 2 IC flashes. The ENTLN detected its first and last lightning flashes at 0633 and 1121 UTC, respectively. The USPLN detected a total of 30 individual lightning strokes during IOP 7 (See Fig. 10).

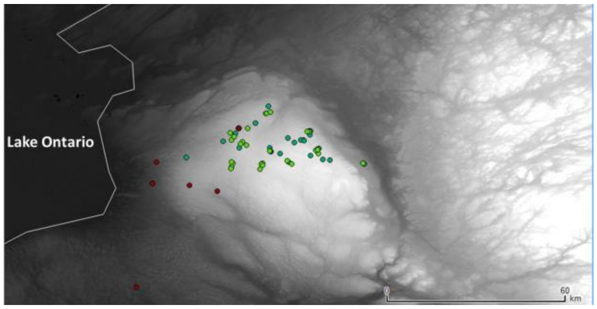

Figure 10. The dark green dots denote the location of detected ENTLN flashes during IOP 7. The lighter green dots denote the location of detected USPLN strokes. The red dots denote human reports of lightning and/or thunder by several mobile snow teams. The lightning data are overlaid onto topographical data, with whites being the highest elevations and dark grays being the lowest.

The MIPS XPR velocity data reveal a couple of maximum updraft speeds >=6 m s^{-1} during the time period of lightning, although these data were collected at Sandy Creek, NY, about 50 km to the west of where most of the lightning occurred.

Updraft speeds are generally less than 5 m s^{-1} and are also observed less frequently than in IOP 5 according to Fig. 11 (MRR data). Once again updrafts are the weakest where most of the lightning occurred over the UP region.

IOP 7 featured small amounts of integrated liquid water and water vapor when compared to IOP 5. The MIPS MPR data revealed a maximum ILW value of 0.25 mm during IOP 7, which was measured during the time period of lightning, although the lightning occurred about 50 km away (see Table 1).

6. A POSSIBLE CONNECTION TO WIND FARMS?

Past research has already shown relationships between lightning and wind turbines. Multi-MW wind turbines are tall structures with a higher probability of being struck by typical negative cloud-to-ground lightning than their surroundings (Rachidi et al. 2008). Towers and natural objects rising more than 100 m above their surroundings are exposed to strong local electric fields under thunderclouds, which increases their tendency to initiate an upward propagating leader itself (Berger 1967). A rotating wind turbine tends to have a higher chance of initiating an upward leader than a static tower of similar height (Wang et al. 2008), and also has a larger attractive radius than the expected one for a stationary tower (Wilson et al. 2013). Due to the blades of a wind turbine rotating at fast speeds, the blade tips avoid the accumulation of self-produced space charge (ionized air). The speed of the blade tip needs to be greater than the drift velocity of small ions produced by corona in order to escape the space charge. Therefore, the blades are exposed to stronger local electric fields than static objects (Montanyà et al. 2014).

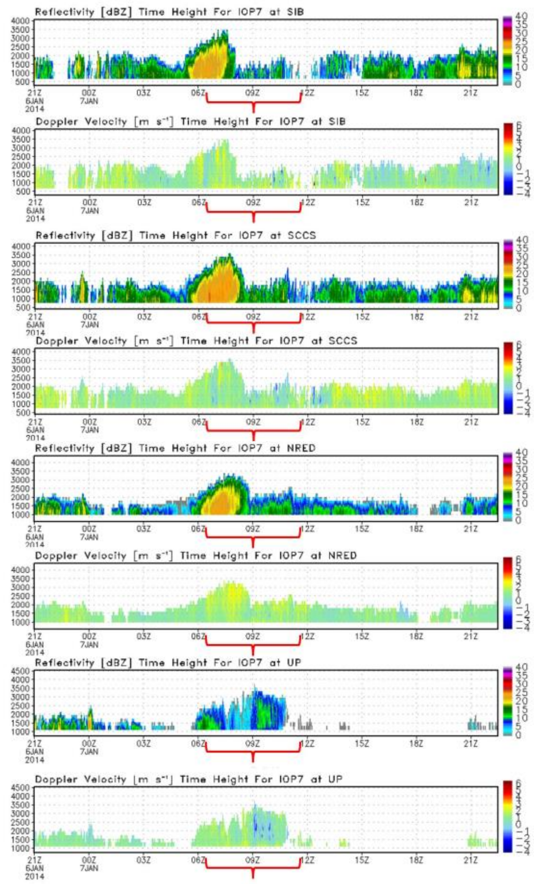

Figure 11. Same as Fig. 9.

After close inspection of ENTLN and USPLN data overlaid onto Google Earth imagery, a significant trend in the location of detected lightning flashes or strokes was observed. Many of these detected lightning flashes/strokes were located within a few hundred meters of a nearby wind turbine at the Maple Ridge Wind Farm. Located over the Tug Hill region, each wind tower is 79 m tall, with a rotor blade length of 40 m. The total height is 119 m for each tower. Each blade weighs 7 metric tons and is made from a wood interior coated with fiberglass. The rotor blade speed is 14 RPM (revolutions per minute), which translates to 1200 RPM's at the generator. The blade will produce electricity when the wind is blowing at about 8-10 mph and will shut down when the wind is higher than 42 mph (http://www.adirondackstughill.com/windpower.php).

Using the Google Earth "Ruler" Tool, we could easily determine the exact distance between detected lightning flashes/strokes and the nearest wind turbine (See Figure 12). If this distance was less than the upper limit of the corresponding lightning network's location accuracy, then it was considered a distinct possibility that the detected lightning flash/stroke came in direct contact with a wind turbine. Please note that this method was only conducted for detected lightning flashes/strokes that were within 6 km of a nearby wind turbine, as it is difficult to find the nearest turbine for lightning that occurred far away from the Maple Ridge

Wind Farm. After this method was completed for both IOPs 5 and 7 using both ENTLN and USPLN data, we were able to calculate some basic statistics to see how significant the relationship was between the lightning that occurred and nearby wind turbines (See Table 1). A significant fraction of lightning flashes (10-25%) were located within a few hundred meters of a turbine tower.

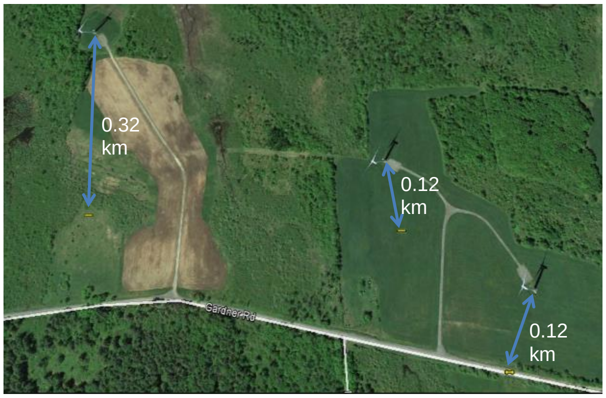

Figure 12. Google Earth image showing turbines and ENTLN-detected flashes. The Ruler tool was used to calculate the distance of the nearest flash to the turbine base.

7. DISCUSSION & CONCLUSIONS

The findings of our research are of particular interest because they refute previous lightning research hypotheses in some ways. Past studies lean towards IOP 5 having more favorable meteorological conditions for lightning to occur when compared to IOP 7 (see Steiger et al. 2009). Although both IOPs 5 and 7 had maximum observed updraft speeds around 8 m s^{-1}, IOP 5 had more frequent stronger updraft speeds over land when compared to IOP 7. In addition, IOP 5 had much greater integrated liquid water (ILW) amounts when compared to IOP 7. The depth of the -10 to -25°C layer in the cloud was very similar for both IOPs 5 and 7, with the main difference being that the -10°C isotherm was at or below the ground during IOP 7 as it was a much colder event (See Table 1). Lastly, climatology shows that most lake-effect lightning occurs over or near the Great Lakes (Steiger et al.); this was not the case for IOPs 5 and 7 as all of the lightning occurred well inland (> 30 km) over the Tug Hill region.

According to NAM data over Lake Ontario, IOP 7 had much greater lake-induced CAPE values than IOP 5 (2000 J kg^{-1} vs. 300 J kg^{-1}), yet IOP 7 generally had weaker average updraft speeds than IOP 5. One hypothesis for this inconsistency is that IOP 7 was a much windier event than IOP 5, and these strong winds blowing horizontally over the lake surface may disrupt vertical motions, hence limiting maximum updraft speeds. The fact that IOP 7 had much lower ILW values than IOP 5 was expected, as IOP 7 was a much colder event. Many questions still remain as to why IOP 7 had more lightning than IOP 5, as well as how much wind turbines are related to the lightning events.

8. ACKNOWLEDGEMENTS

First we would like to acknowledge the NSF grant AGS 1258894, NCAR EOL. We wish to thank Dr. Robert Ballentine of the SUNY Oswego meteorology faculty for his insight into a possible connection between lightning occurrences during IOPs 5 and 7 and the nearby Maple Ridge Wind Farm. Also, our gratitude is given to Dr. Jim Steenburgh, one of the lead researchers during the OWLeS Project, for his work in preparing Fig. 2. The same is given to Justin Minder, an OWLeS participant from the University of Albany, for supplying us with the MRR transect time-height plots of reflectivity and velocity during IOPs 5 and 7. We would also like to thank Leandro Macedo, a student researcher from Brazil that took part in the OWLeS field campaign, for helping us prepare Figs. 8 and 10. Kudos to all of the OWLeS participants for their hard work and dedication in collecting so much relevant data to work with!

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	IOP 7 (7 Jan 2014)	IOP 5 (18 Dec 2013)
Max observed updraft speed	8 m/s	8 m/s
Max observed vertically integrated liquid water	0.24 mm	1.95 mm
Max observed vertically integrated water vapor	2.2 mm	7.1 mm
Min height of cloud base	0.1 km	0.2 km
Max height of cloud top	~3.5 km MSL	~3.0 km MSL
Predominant hydrometeor type	Dendrites	Graupel
Depth of -10 to -25°C layer (in cloud)	1.6 – 2.0 km (from surface up)	1.4 – 2.0 km (from about 1 km AGL up)
# ENTLN lightning flashes	24	5
# USPLN lightning strikes	30	0
% ENTLN flashes within 300m of a wind turbine	25%	40% (NOTE: all 5 flashes are within 500m of turbine)
% USPLN strikes within 500m of a wind turbine	10%	No strikes detected
ENTLN mean/med distance to nearest wind turbine	0.49/0.32 km	0.32/0.32 km
USPLN mean/med distance	0.50/0.49 km	No strikes detected

Table 1. A summary of all the parameters examined for both IOPs 5 and 7.