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Contribution of Lake-Effect Snow to the Catskill Mountains Snowpack

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ABSTRACT

Meltwater from snow that falls in the Catskill Mountains in southern New York contributes to reservoirs that supply drinking water to approximately nine million people in New York City. Using the NOAA National Ice Center's Interactive Multisensor Snow and Ice Mapping System (IMS) 4km snow maps, we have identified at least 32 lake-effect (LE) storms emanating from Lake Erie and/or Lake Ontario that deposited snow in the Catskill/Delaware Watershed in the Catskill Mountains of southern New York State between 2004 and 2017. This represents a large underestimate of the contribution of LE snow to the Catskills snowpack because many of the LE snowstorms are not visible in the IMS snow maps when they travel over snow-covered terrain. Most of the LE snowstorms that we identified originate from Lake Ontario but quite a few originate from both Erie and Ontario, and a few from Lake Erie alone. Using satellite, meteorological and reanalysis data we identify conditions that contributed to LE snowfall in the Catskills. Clear skies following some of the storms permitted measurement of the extent of snow cover in the watershed using multiple satellite sensors. IMS maps tend to overestimate the extent of snow compared to MODerate resolution Imaging Spectroradiometer (MODIS) and Landsat-derived snow-cover extent maps. Using this combination of satellite and meteorological data, we can begin to quantify the important contribution of LE snow to the Catskills Mountain snowpack. Changes that are predicted in LE snowfall from the Great Lakes could impact the distribution of rain vs snow in the Catskills which may affect future reservoir operations in the NYC Water Supply System.

Keywords: lake-effect snow, Catskills, Lake Erie, Lake Ontario, IMS, MODIS

INTRODUCTION

Snowmelt is an important source of water for approximately nine million people in New York City (NYC) as well as others in New York State who rely on the NYC Water Supply System (NYCWSS) for their water needs. The NYCWSS is the largest unfiltered water supply system in the United States (Matonse et al., 2011). On average, runoff emanating from the six basins of the Catskill/Delaware watershed in the Catskill Mountains has supplied 90 percent of NYC's water demands. The westernmost basin, the Cannonsville, contains the second largest reservoir used for NYC drinking water. The contribution of snowfall to total annual precipitation in the Catskill/Delaware Basin has been 20%–30% between ~1950 through ~2010 (Frei et al., 2002; Pradhanang et al., 2011; Anandhi et al., 2011). Some portion of the snowfall in the Catskills emanates from lake-effect (LE) snow from Lake Erie and Lake Ontario.

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In this paper we examine the contribution of LE snowfall to the Catskills Mountain snowpack in southern New York State using satellite snow-cover maps derived from NOAA's National Ice Center 4km Interactive Multisensor Snow and Ice Mapping System (IMS), NASA's 500-m resolution MODerate resolution Imaging Spectroradiometer (MODIS) images and standard snow-cover map products, Landsat-derived snow maps, meteorological and reanalysis data.

BACKGROUND

Lake Effect Snowfall in the Eastern Great Lakes Region

During the 20th century, annual snowfall increased across the lake-effect zone of the Great Lakes Basin, likely due to warming of lakes and diminished ice cover (Burnett et al., 2003; Kunkel et al., 2009; Notaro et al., 2013). Specifically, significant increases in LE snow were found between 1951 and 1990 (Norton and Bolsenga, 1993; Leathers and Ellis, 1996; Burnett et al., 2003). However LE snowfall has generally been declining in recent decades in some areas in the Great Lakes Basin (Hartnett et al., 2014) and is projected to decline during the 21st century in part because the air temperature is expected to continue to rise, causing less precipitation to fall as snow (Suriano and Leathers, 2016).

LE snowfall is generated when a cold air mass moves over a warmer lake causing relatively low (3000-m cloud tops) stratocumulus clouds to develop from convective cells (Peace and Sykes, 1966; Pease et al., 1988; Kunkel et al., 2000). Heat and moisture is transferred from the lake to the air. This process is especially effective when the lake is not ice-covered, or at least not fully ice-covered (Norton and Bolsenga, 1993) and when there is a large contrast in temperature (at least 13°C) between the lake surface and the 850 mb air temperatures (Holyroyd, 1971). The air and lake temperatures must have a large temperature contrast for convective transfer of heat from the relatively warm lake surface to the much-colder overlying air. The development and intensity of LE snow depend strongly on the temperature difference between air and water, the extent of ice cover, fetch, and wind direction and speed.

Narrow (5 – 20 km) and elongated (50 – 300 km) snow bands form on the leeward side of lakes (Figure 1), the movement of which is controlled by winds aloft, rather than by surface conditions (Eichenlaub, 1979; Peace and Sykes, 1966; Niziol, 1987; Hartnett, 2013 and Hartnett et al., 2014). In addition to LE snow that forms over a lake, lake-induced snowfall, a term that includes both LE and lake-enhanced snowfall, contributes large amounts of snowfall on the leeward sides of the Great Lakes (Bard and Kristovich, 2012; Suriano and Leathers, 2016). The combination of long, overwater fetch and strong winds can cause narrow bands of precipitating clouds to propagate considerable distances inland (for example, see Niziol et al., 1995). New research by Villani et al. (2017) describes atmospheric parameters that have the greatest influence on the ability of a LE storm to extend inland from Lake Ontario. They concluded that the primary and secondary parameters most-strongly correlated with inland extent of LE snowfall are: 1) the presence of a multi-lake/upstream moisture source connection, and 2) the difference between the lake's surface water temperature and the air temperature at 850 mb.

Lake Erie is the shallowest and the southernmost of the Laurentian Great Lakes with an average depth of only 19 m, resulting in Erie having the greatest amount of ice cover of all of the Great Lakes during most winters. In contrast, Lake Ontario, with an average depth of 85 m, remains ice-free or has only a small percentage of its surface covered by ice during many winters (Wang et al., 2012). Furthermore the east-west orientation of Lake Ontario can allow a long fetch (up to ~300 km) when prevailing northwesterly winds that bring cold, dry air across the relatively warm lake surfaces, are oriented over the long axis of the lake; this long fetch can increase the intensity of the LE storms by allowing the storm to pick up more moisture from the lake.

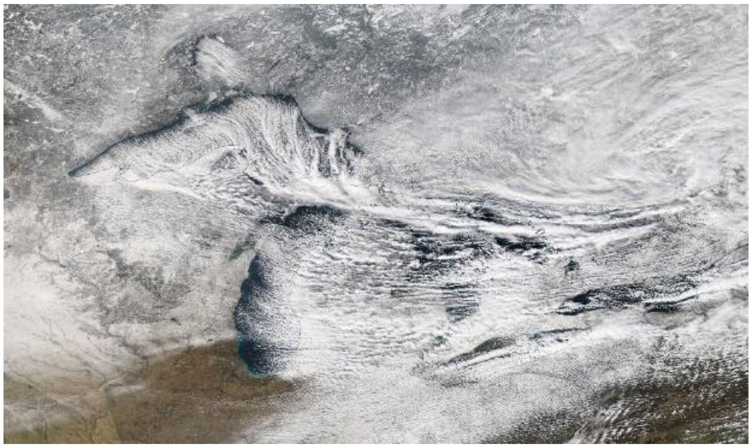

Figure 1. Suomi NPP Visible Infrared Imaging Radiometer Suite (VIIRS) image from 18 November 2014, showing narrow, elongated snow bands over Lake Superior and Lake Michigan / Huron. In this storm the west-southwesterly winds were parallel with the long axis of Lake Erie (which is barely visible below the clouds in the image above) creating a long fetch, allowing the air flowing over the lake to pick up a large amount of moisture. The Cooperative Institute for Meteorological Satellite Studies (CIMSS) Satellite Blog of the University of Wisconsin – Madison [http://cimss.ssec.wisc.edu/goes/blog/archives/17196] reported that cold arctic air with temperatures in the range of about -7 to -4°C flowed across the warm waters (~8-10°C) of Lake Erie and Lake Ontario helping to cause a major LE snowfall event on 18 November 2014. Credit: CIMSS and NASA Earth Observatory.

Up to seven LE synoptic types have been reported to be associated with LE snowfall over Lake Erie and Lake Ontario (Leathers and Ellis, 1996; Suriano and Leathers, 2017). All seven types are associated with low pressure to the north and/or east and high pressure to the west and/or south of Buffalo, NY, and usually with an upper level trough over the United States (Suriano and Leathers, 2017). Irrespective of the origin, the LE snowstorms that garner the most media attention occur when orographic lifting produces a large amount of snowfall that is restricted to a relatively small area on the leeward sides of the lakes. In Figure 2 a time series of IMS 4km snow maps from the 12-13 October 2006 storm that dumped up to 142 cm of snow on parts Buffalo, New York [https://en.wikipedia.org/wiki/Lake_Storm_%22Aphid%22] may be seen. The snow did not extend very far away from the shore of Lake Erie, but had a major meteorological and economic impact, though the snow depth was highly variable in the local area.

Heavy LE snow can form in response to surges of cold air from Alberta Clippers that are associated with an anticyclone in the central part of the U.S., especially if in conjunction with a cyclone that is also located over the northeastern U.S. or in the Atlantic Ocean just off of the East Coast of the United States (Notaro et al., 2013). This meteorological situation can produce heavy snow downwind of Lake Erie and Lake Ontario (Niziol, 1987; Ellis and Leathers, 1996; Ballentine et al., 1998). Those storms can also bring moisture and very cold air inland to the Catskills.

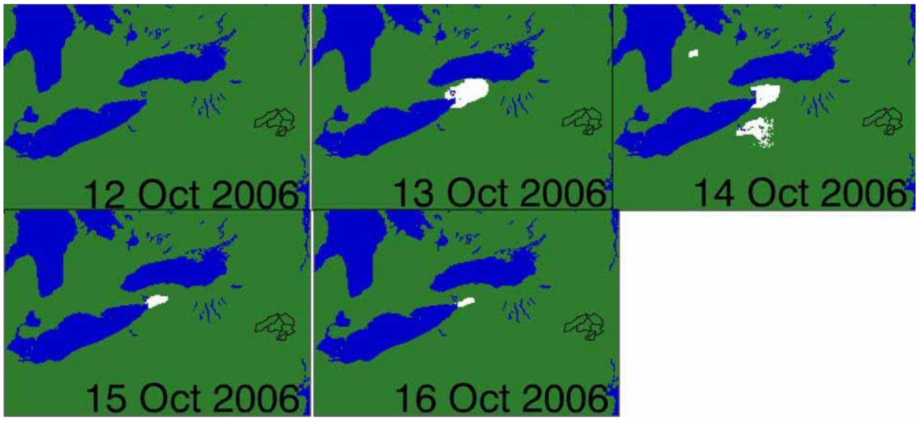

Figure 2. Time series of NOAA IMS 4km resolution snow maps from 12-16 October 2006 showing a LE storm developing and dissipating; a major LE storm dumped up to 142 cm of snow on parts of Buffalo, New York, on 12-13 October 2006. The snow from this storm did not travel very far from the source and did not get close to the Catskill/Delaware Watershed. The six basins of the Catskill/Delaware Watershed are outlined in black.

STUDY AREA

There are six basins of the Catskill/Delaware Watershed: Ashokan, Schoharie, Rondout, Neversink, Cannonsville and Pepacton (Figure 3) that are located up to about 200 km northwest of NYC. Snow conditions can be quite variable within the watershed, both spatially and temporally (Frei et al., 2002; Hall et al., 2016). In particular, the Cannonsville, because of its location, topography and elevation (with elevations ranging from 329 m to 1014 m and a mean elevation 580 m), tends to intercept most of the snow traveling from the west. The Cannonsville Reservoir in the Cannonsville Basin, is about 170 km southeast of Lake Ontario and about 300 km east of Lake Erie.

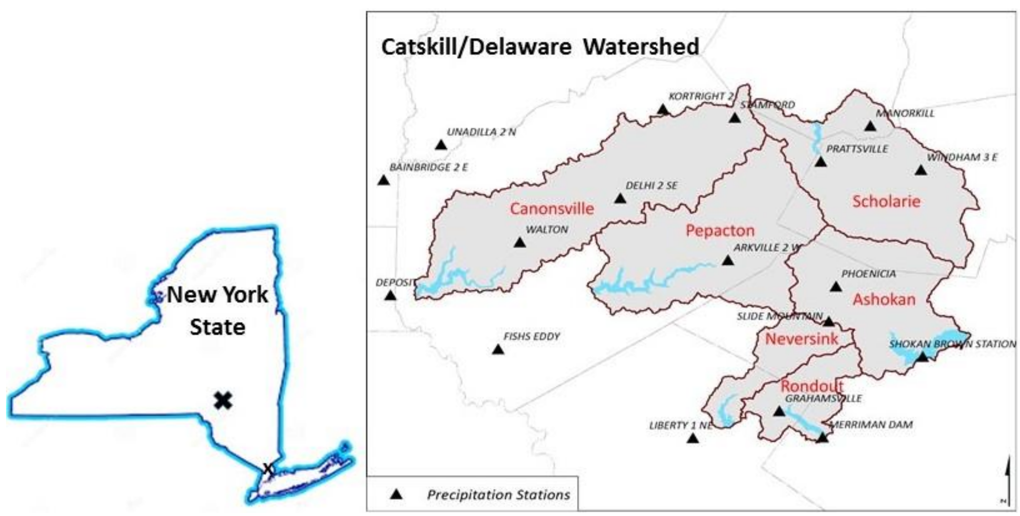

Figure 3. Six basins in the Catskill/Delaware watershed showing locations of meteorological stations (Source: J. Gass, NYC Department of Environmental Protection (NYCDEP) Bureau of Water Supply). The outline of New York State shows the approximate location of the Catskills Mountains (large black X) and of NYC (small black x). Outline of New York State from: Dreamstime.com.

DATA AND METHODOLOGY

Satellite Data

In this paper, we use the following satellite data: 1) NOAA IMS 4km resolution snow maps; 2) MODerate resolution Imaging Spectroradiometer (MODIS) Collection 6 (C6) standard 500-m resolution snow-cover maps; 3) MODIS C6 standard 250-m or 500-m surface-reflectance maps; 4) MODIS C6 standard 1-km land-surface temperature (LST) maps; 5) Landsat-derived snow maps, and 6) Suomi NPP Visible Infrared Imaging Radiometer Suite (VIIRS) imagery.

Multiple satellite and ground station data are utilized to develop the IMS 4km daily SCE maps, so that daily, cloud-cleared snow maps can be provided (Helfrich et al., 2007). Production of the IMS daily snow maps began in 2004. Detection of snow to develop the IMS maps is partially automated and then the maps are finalized manually so that ancillary information, such as might be obtained from meteorological stations, can be in included in the final snow map.

The MODIS standard 500-m resolution daily snow maps, MOD10A1 from the Terra satellite and MYD10A1 from the Aqua satellite, are produced daily, but the ground surface can be fully or partially obscured by cloud cover. In addition, because of the conservative nature of the MODIS cloud mask (Ackerman et al., 1998), there can be clear areas that appear to be cloudy on the daily snow maps. In response to this, a feature of the new C6 MODIS snow maps allows a user to "remove" the cloud mask to visually determine if snow exists beneath the cloud mask. When a clear scene is available, the MODIS snow maps provide an accurate map that may be used to measure the extent of snow cover. Details on the MODIS C6 snow-cover maps may be found in Riggs et al. (2016 and 2017).

MODIS standard surface-reflectance products, MOD09 (Terra) and MYD09 (Aqua) (Vermote et al., 2002) are also used in this work. Additionally the MODIS standard LST product, MOD11_L2 of Wan et al. (2002) was used to estimate lake surface temperatures. Landsat images are used to map SCE in the Catskills using a method similar that used in Hall et al. (2015).

Other Data

Synoptic analyses from NOAA National Centers for Environmental Prediction, Hydrometeorological Prediction Center [http://www.wpc.ncep.noaa.gov/dailywxmap/index_20050105.html], and Unisys surface data plots [http://weather.unisys.com/surface/] were used to study the atmospheric conditions leading to the LE storms identified.

Percent ice concentration and daily lake SWT from Great Lakes Surface Environmental Analysis maps was obtained through the CoastWatch site [https://coastwatch.glerl.noaa.gov/statistic/statistic.html] [https://coastwatch.glerl.noaa.gov/ftp/glsea/avgtemps/2005/glsea-temps2005_1024.dat] operated by NOAA's Great Lakes Environmental Research Laboratory (GLERL). In fact, three methods are evaluated for use in determing the average daily surface water temperature (SWT) of Lake Ontario for the four case studies: MODIS standard LST product, skin temperatures from Modern-Era Retrospective analysis for Research and Applications - 2 (MERRA-2) https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/ and daily lake average SWT from GLERL's CoastWatch site. MERRA-2 is a reanalysis data product produced at Goddard Space Flight Center with a native resolution of 0.5° latitude x 0.625° longitude x 72 vertical levels (Gelaro et al., 2017). Air temperatures at 850 mb from MERRA-2 were also used. The GLERL SWT is considered to be the most accurate of the three methods.

METHODOLOGY

We inspected each of the IMS daily 4km SCE maps acquired between November and April during each year of the 13-year study period, 2004 – 2017, to identify snow that appeared to emanate from Lake Erie and/or Lake Ontario and was deposited in the Catskills. It was only possible to identify "new" snow, meaning under conditions when there was no snow or very little snow already on the ground immediately prior to the event.

Meteorological conditions were investigated for each suspected LE storm, and in addition, for the four case studies we also used MERRA-2 skin and air temperatures at 850 mb (to compare with LST and daily SWT from GLERL). For the MERRA-2 data the hourly temperatures were averaged for each day, and also skin temperatures from five MERRA-2 pixels covering Lake Ontario were averaged to derive SWT.

The MODIS LST standard product was used to measure SWT in the following manner. A 10 X 10 pixel "box" was selected for Lake Ontario for each day from the clear-sky portions of the lake. Temperatures from both the Terra and Aqua daily products were averaged for the 10 X 10 pixel box to calculate a daily SWT. To provide some quantification of the location and impact of the storm, measurements of SCE from Landsat, MODIS and IMS snow maps were made in the Catskills when possible.

RESULTS

During the 13-year study period 32 suspected LE storms were identified to be emanating from Lake Erie or Lake Ontario (or both lakes) from which snow reached the Catskill Mountains (Table 1). Most of the storms (17) originated from Lake Ontario, six from Lake Erie and the rest came from both lakes. The number of LE snowstorms affecting the Catskills that we identified represents a large underestimate of the number of LE storms that deposited snow in the Catskills during the study period because it is not possible to see the aftermath of snowstorms in the IMS maps developing and moving across the landscape when snow is already on the ground.

We focused on four storms or case studies during the study period: **Case Study 1**: 22 – 24 November 2005, **Case Study 2**: 5 – 10 December 2006, **Case Study 3**: 31 March – 4 April 2013, and **Case Study 4**: 14 – 15 November 2014. Clear skies after the storms enabled MODIS and/or Landsat snow maps to be acquired for three of the four case studies. SCE measured using MODIS and Landsat was in good agreement, while IMS 4km maps tended to overestimate SCE, in part due to the coarser resolution of the IMS as compared to MODIS and Landsat.

We found the expected large (at least 13°C) difference between SWT and air temperature over Lake Ontario for all of the case studies.

Table 1. Dates and day of year (DOY) of suspected lake-effect (LE) storms on which snow reached the Catskill Mountains. The lake from which the storm emanated is also shown. Dates of the four case studies are shown with an asterisk (*).

Date	DOY	Lake
03 Dec 2004	338	Erie
13 Dec 2004	348	Erie then Ontario
05 Jan 2005	005	Both
23 Nov 2005*	327	Ontario
04 Dec 2005	338	Both
19 Jan 2006	019	Ontario
02 Feb 2006	033	Ontario
16 Mar 2006	075	Ontario
05 Dec 2006*	339	Ontario
10 Jan 2007	010	Ontario
17 Jan 2007	017	Ontario
18 Apr 2007	108	Erie
17 Nov 2007	321	Ontario
01 Dec 2007	335	Both?
19-22 Nov 2008	324-327	Both

27 Nov 2010	331	Erie
04 Dec 2010	338	Ontario?
02 Apr 2013*	092	Ontario?
14-15 Nov 2014*	318-319	Ontario?
01 Jan 2015	001	Both?
21 Dec 2015	355	Erie
05 Jan 2016	005	Both
12 Jan 2016	012	Ontario, then Erie
25 Feb 2016	056	Erie
04 Apr 2016	095	Ontario
21 Nov 2016	326	Ontario
29 Nov 2016	334	Ontario
08 Dec 2016	343	Erie
27 Dec 2016	362	Ontario
25 Jan 2017	025	Ontario
28 Feb 2017	059	Ontario
03-05 Mar 2017	062-064	Ontario, then Erie

CASE STUDIES

Case Study 1: 22 – 24 November 2005

Using a time series of IMS 4km snow maps we identified and tracked a massive LE storm emanating from Lake Ontario that deposited snow in the Catskills on 23 – 24 November 2005 (Figures 4 and 5). The banding of snow over Lake Ontario extends inland to the Catskills (Figure 5). According to the IMS snow map, the entire Catskill/Delaware Watershed was snow covered by 23 or 24 November.

Figure 4. Time series (22-24 November 2005) of IMS 4km snow maps showing the progression of a LE storm that deposited snow in the Catskills. The six basins of the Catskill/Delaware Watershed are outlined in black.

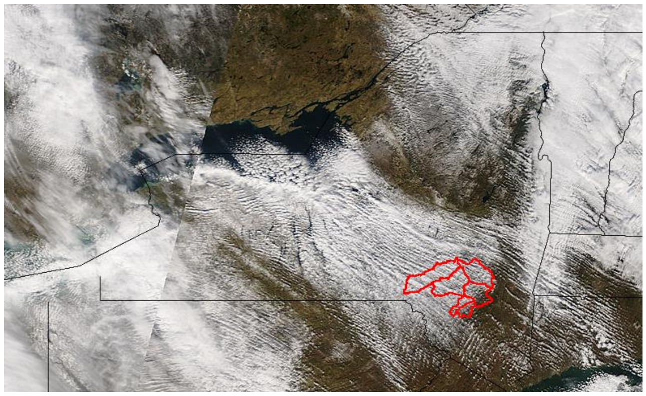

Figure 5. Terra MODIS true-color image of LE snow emanating from Lake Ontario on 23 November 2005. Snow from that storm was deposited in the Catskills. The six basins of the Catskill/Delaware Watershed are outlined in red. Image obtained from NASA's Land, Atmosphere Near real-time Capability for EOS (LANCE) https://lance.modaps.eosdis.nasa.gov/imagery/subsets/USA4/2005327/USA4.2005327.terra.1km.jpg.

Unisys Surface Data Plots show a cold front from Canada moving in a southeasterly direction on 21-22 November 2005, with winds from the west [http://weather.unisys.com/surface/]. LE snow was generated, and deposited overnight and in the morning of November 23rd in the Catskills.

The temperature difference between the SWT of Lake Ontario and the Oswego air temperature increased to 22.3°C by 23 November during the storm (Tables 2a & b). The temperature differences shown in Table 2b are considerably greater than the 13°C, required to spawn LE storms.

Table 2a. Surface water temperature (SWT) of Lake Ontario was determined in three different ways: using land-surface temperature (LST) from MODIS, Tskin from MERRA-2 (M2) and daily SWT from GLERL's CoastWatch site, all shown. Percent ice coverage was zero for all dates.

Date	Avg LST	Daily SWT from CoastWatch	Tskin M2	850 mb Tair
22 Nov 2005	5.0	7.9	6.8	-6.4
23 Nov 2005	5.2	7.7	6.0	-14.6
24 Nov 2005	--	7.6	5.7	-11.5

Table 2b. Differences between GLERL's daily SWT, and MERRA-2 850 mb Tair, in °C.

Date	Temp difference
22 Nov 2005	14.3
23 Nov 2005	22.3
24 Nov 2005	19.1

For comparison, we show the results of three different methods that we used to determine SWT in Table 2a. The most reliable is the measured SWT from GLERL. In Table 2a the temperatures vary by 2.9°C, from a low of 5.0°C using the MODIS LST method, to a high of 7.9°C from GLERL's CoastWatch site.

Case Study 2: 5 – 10 December 2006

Between 5 – 10 December 2006 there was a progression of LE and other storms that contributed to snow deposition in the Catskills. Starting by the morning of 2 December precipitation occurred over Lake Ontario and to the east as determined from Unisys Surface Data Plots. This continued through the evening, but by the next morning (3 December) precipitation had diminished though no snow was evident in the Catskills (Figure 5). On that afternoon, a cold front affected both Lake Erie and Lake Ontario and a low-pressure system traveled over the northern part of the lakes, pulling a front through. Snowfall resumed that evening and continued in the morning of 4 December by which time snow fell from a LE storm emanating from Lake Erie. By the evening of 4 December, winds were from the southwest (over Lake Erie) so LE snow was probably falling by then. Thus for the early part of the event, snow in the Catskills came from Lake Ontario, then a contribution from Lake Erie may have been added.

By 5 December another front deposited still-more snow. During that afternoon, a front was over the Catskills. On the morning of 6 December it was snowing again in the Catskills with some winds from the south so the resulting snowfall was probably not predominately LE snow by that time. Between 5 – 7 December snow is evident in the northwestern part of the Catskill/Delaware Watershed. By 8 December, snow covered most of the watershed's six basins according to the IMS 4km maps, but it is not clear that the more-extensive snow from 8 – 10 December was caused by LE snow alone, though was probably enhanced by moisture from Lake Ontario. Some snow had melted by 10 December as seen on the IMS, Terra MODIS image (Figure 6) and the standard Aqua MODIS C6 snow map (Figure 7). Using a normalized-difference snow index (NDSI) value of 10% or greater, the extent of snow was measured from the MODIS snow map; extent was also measured using the IMS 4km maps. Measurement of SCE was three times greater using IMS as compared to the MODIS snow map (Table 3).

Table 3. Measurement of snow-cover extent in the Catskill/Delaware Watershed using Aqua MODIS and IMS 4km SCE maps, 10 December 2006.

Snow Map	Percent Snow Cover in Watershed	Area of Snow Cover in km^2
Aqua MODIS C6 MOD10A1 snow map	23.7	1004
IMS 4km snow map	71.1	3573

The difference between the SWT of Lake Ontario from GLERL's CoastWatch site and the air temperature at 850 mb from MERRA-2, increased by 4 December during the LE storm (Table 4b) to 20.3°C. The percent ice coverage was zero for each date.

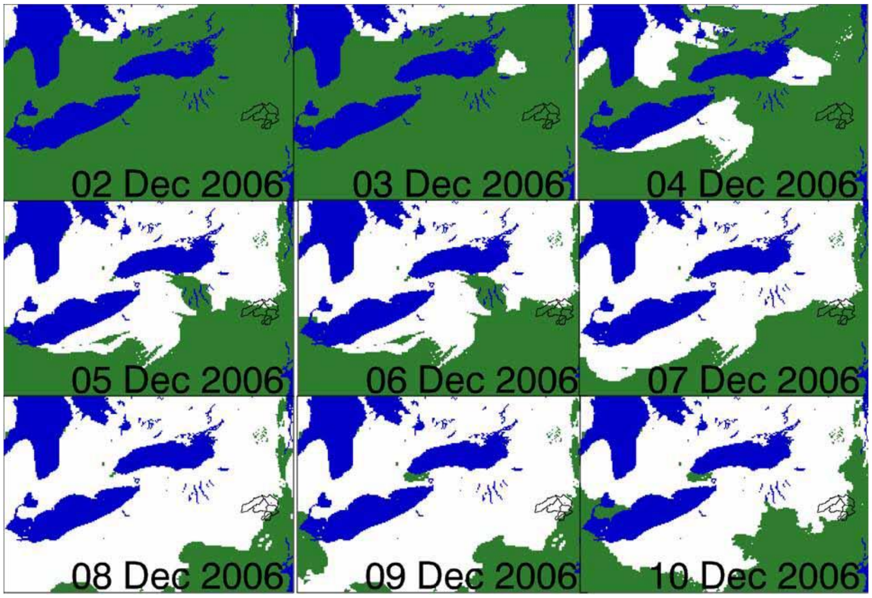

Figure 5. Time series (2 – 10 December 2006) of IMS 4km snow maps showing the progression of the LE storm that deposited snow in the Catskills. The snow that fell in the Catskills originated from a LE storm that appeared to start over Lake Ontario. The six basins of the Catskill/Delaware Watershed are outlined in black.

Figure 6. Terra MODIS 250-m "true-color" image acquired on 10 December 2006. The six basins of the Catskill/Delaware Watershed are outlined in red.

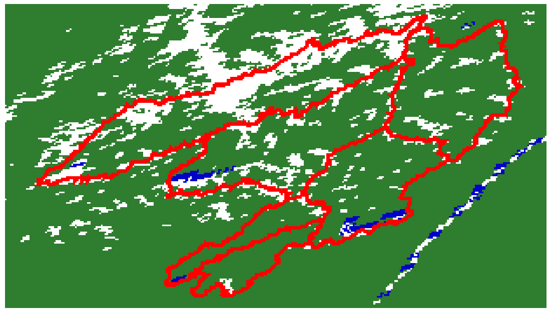

Figure 7. Aqua MODIS C6 snow map from 10 Dec 2006. In this snow map, white represents snow, green represents "no snow," and blue represents water. The six basins of the Catskill/Delaware Watershed are outlined in red. [MYD10A1.A2006344.h12v04.006.2016080151145.hdf]

Table 4a. Surface water temperature (SWT) of Lake Ontario was determined in three different ways: using land-surface temperature (LST) from MODIS, Tskin from MERRA-2 and daily SWT from GLERL's CoastWatch site, all shown. Percent ice coverage was zero for all dates.

Date	Avg LST	Daily SWT from CoastWatch	Tskin M2	Tair 850 mb M2
2 Dec 2006	5.2	7.6	5.9	-10.1
3 Dec 2006	--	7.3	5.3	-8.4
4 Dec 2006	5.7	7.1	4.5	-13.2
5 Dec 2006	5.1	6.9	4.3	-13.2

Table 4b. Differences between daily SWT from GLERL and MERRA-2 850 mb Tair, in °C.

Date	**Temp Difference**
2 Dec 2006	17.7
3 Dec 2006	15.7
4 Dec 2006	20.3
5 Dec 2006	20.1

On 4 December the SWT estimates from MODIS and MERRA-2 and the measurement from GLERL varied by 2.6°C, from a low of 4.5°C using the MERRA-2 skin temperature, to a high of 7.1°C from GLERL's CoastWatch site (Table 4a).

Case Study 3: 2 April 2013

By the end of March/early April 2013, a series of cold fronts brought cold air to Lake Erie and Lake Ontario from Canada. Winds were west-southwest on 2 April 2013. The IMS 4km SCE maps show the progression of a LE storm that deposited snow in the Catskills in early April 2013 (Figure 8). The Terra MODIS captured a clear view of snow in the Catskill Mountains on 4 April (Figure 9). SCE was measured using different satellite sensors following this storm (Table 5). The Landsat-7 derived snow map and the MOD10A1 snow map provided similar measurements of SCE in the Catskills/Delaware Watershed, while the IMS 4km snow map showed about three times the amount of SCE derived using Landsat-7 data.

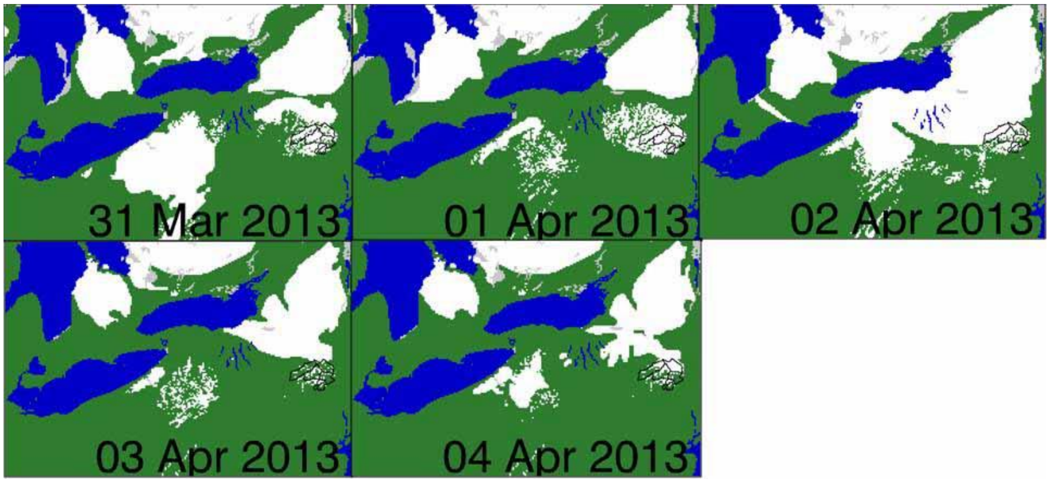

Figure 8. Time series (31 March – 4 April 2013) of IMS 4km snow maps showing the progression of a LE storm that deposited snow in the Catskills. The snow that fell on the Catskills originated from a LE storm that probably started over Lake Ontario. The six basins of the Catskill/Delaware Watershed are outlined in black.

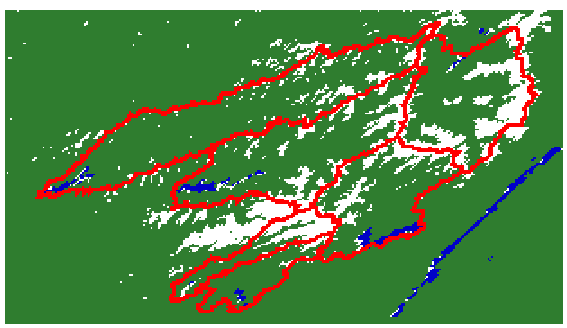

Figure 9. Terra MODIS standard snow map from 4 April 2013. In this snow map, white represents snow, green represents "no snow," and blue represents water. The six basins of the Catskill/Delaware Watershed are outlined in red. [MOD10A1.A2013094.h12v04.006.2016139202830.hdf]

Table 5. Measurement of snow-covered area in the Catskill/Delaware Watershed using Landsat-7 Enhanced Thematic Mapper Plus (ETM+), Terra MODIS and IMS 4km SCE maps, April 2013.

Snow Map/Day Month	**Percent Snow Cover in Watershed**	**Area of Snow Cover in km^2**
Landsat-7-derived snow map* / 6 Apr	20.2	829
MODIS C6 MOD10A1 snow map / 4 Apr	24.3	1029
IMS 4km snow map / 4 Apr	49.4	2482

*Derived from: LE70140312013096EDC00

The difference between the SWT of Lake Ontario from GLERL's CoastWatch site and the air temperature at 850 mb from MERRA-2 increased by 2 April during the storm (Table 6b) to 16.8°C. The percent ice coverage was zero for each date.

Table 6a. Surface water temperature (SWT) of Lake Ontario was determined in three different ways: using land-surface temperature (LST) from MODIS, Tskin from MERRA-2 and daily SWT from GLERL's CoastWatch site, all shown. Percent ice coverage was zero for all dates.

Date	**Avg LST**	**SWT from CoastWatch**	**Tskin M2**	**Tair M2 850 mb**
31 Mar 2013	--	3.1	3.3	0.9
01 Apr 2013	1.6	3.0	2.8	-8.6
02 Apr 2013	1.5	3.0	1.9	-13.8

Table 6b. Differences between daily SWT from GLERL and MERRA-2 850 mb Tair, in °C.

Date	**Temp Difference**
31 Mar 2013	4.0
01 Apr 2013	11.6
02 Apr 2013	16.8

On 2 April SWT estimates from MODIS and MERRA-2, and the measurement from GLERL varied by 1.5°C, from a low of 1.5°C using the MODIS LST method, to a high of 3.0°C from GLERL's CoastWatch site.

Case Study 4: 14 – 15 November 2014

A lake-effect storm was responsible for copious amounts of snowfall in areas to the east of Lake Erie and Lake Ontario on 14-15 November 2014 (Figure 10). Cool, dry air flowed over the Great Lakes, picking up moisture from the warmer lake surface water, forming cloud streets similar to those seen in the VIIRS satellite image in Figure 1. The snow that fell on the Catskills originated from a LE storm that probably started over Lake Ontario.

A Terra MODIS image was obtained for 19 November 2014 and the study area was enlarged to show detail (Figure 11). Snow was mapped on the same date using the standard MODIS C6 snow map (Figure 12), a Landsat-7-Enhanced Thematic Mapper Plus (ETM+)-derived snow map (Figure 13) and the IMS snow map (not shown). While the Landsat- and MODIS-derived SCE measurements are similar, the IMS 4km maps show almost five times more SCE than was measured using Landsat-7 (Table 7).

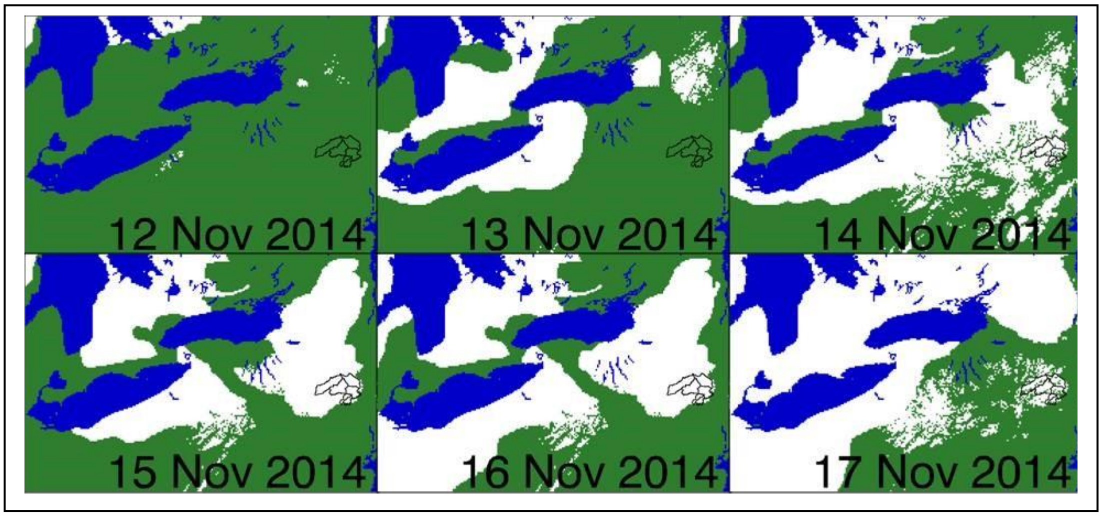

Figure 10. Time series (12 – 17 November 2014) of IMS 4km snow maps showing the progression of the LE storm that deposited snow in the Catskills. The six basins of the Catskill/Delaware Watershed are outlined in black.

Figure 11. MODIS Terra true-color image of the Catskill/Delaware Watershed, 19 November 2014. Source: NASA Worldview.

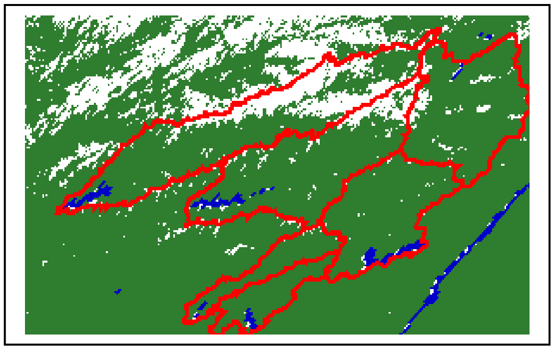

Figure 12. MOD10A1 C6 NDSI snow map of the Catskill/Delaware Watershed, 19 November 2014. In this snow map, white represents snow, green represents "no snow," and blue represents water. The six basins of the Catskill/Delaware Watershed are outlined in red.
[MOD10A1.A2014323.h12v04.006.2016179181758.hdf]

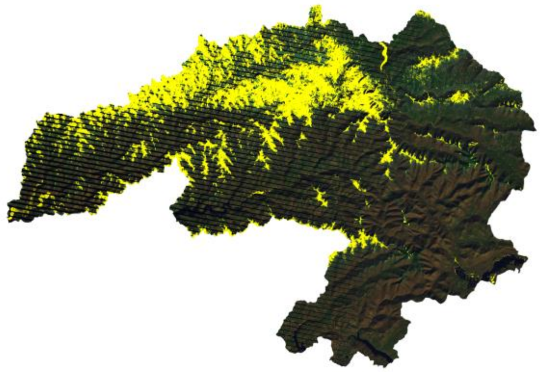

Figure 13. Landsat-7 Enhanced Thematic Mapper Plus (ETM+) – derived snow map Catskill/Delaware Watershed, 19 November 2014. [LE70140312014323EDC00]

Table 7. Measurement of snow-cover extent in the Catskill/Delaware Watershed using different satellite sensors, 19 November 2014.

Snow Map	Percent Snow Cover in Watershed	Area of Snow Cover in km^2
Landsat-7-derived snow map	15.7	647
MODIS MOD10A1 snow map	15.7	664
IMS 4km snow map	65.5	3292

The difference in temperature between the surface of Lake Ontario from GLERL's CoastWatch site and the air temperature at 850 mb from MERRA-2, increased by 15 November during the storm (Table 8b) to 19.7°C. The percent ice coverage was zero for each date.

Table 8a. Surface water temperature (SWT) of Lake Ontario was determined in three different ways: using land-surface temperature (LST) from MODIS, Tskin from MERRA-2 and daily SWT from GLERL's CoastWatch site, all shown. Percent ice coverage was zero for all dates.

Date	Avg LST	SWT from CoastWatch	Tskin M2	Tair 850 mb M2
12 Nov 2014	--	9.4	8.6	-4.4
13 Nov 2014	--	9.0	7.2	-9.7
14 Nov 2014	3.1	8.7	6.8	-10.9
15 Nov 2014	6.8	8.4	6.4	-11.3

Table 8b. Differences between daily SWT from GLERL and MERRA-2 850 mb Tair, in °C.

Date	Temp Difference
12 Nov 2014	13.8
13 Nov 2014	18.7
14 Nov 2014	19.6
15 Nov 2014	19.7

On 15 November the surface water temperature measurements varied by 2.0°C, from a low of 6.4°C using MERRA-2, to a high of 8.4°C from GLERL's CoastWatch site.

Another LE storm occurred on 18 November as reported by the NASA Earth Observatory, and the Cooperative Institute for Meteorological Satellite Studies (CIMSS) Satellite Blog [http://cimss.ssec.wisc.edu/goes/blog/archives/17196] but it is unclear from analysis of the IMS snow maps if the snow from that storm that snow reached the Catskills because the ground was already snow covered. See Figure 1 caption for more information.

DISCUSSION AND CONCLUSION

Using a time series of NOAA IMS 4km snow maps, 32 suspected LE storms were identified that deposited snow in the Catskill/Delaware Watershed in the Catskill Mountains during the 13-year study period (2004 – 2017). Most of the storms either originated over Lake Ontario or precipitation was enhanced when air flowed over Lake Ontario, though some of the storms also originated from Lake Erie, or from both lakes. However, we are unable to quantify the contribution of LE storms to the Catskills using satellite methods alone, because it is not possible to track storms that are traveling over already-snow-covered terrain. Also, the visible and near-infrared satellite data provide only snow-cover extent and not snow-water equivalent which would be needed to estimate the amount of snow.

After the snow falls, MODIS and Landsat data allow accurate mapping of SCE when skies are clear. The standard MODIS C6 NDSI snow-cover maps at 500-m resolution provide an excellent way to measure SCE in the Catskills; MODIS measurements of SCE are consistent with measurements made using 30-m resolution Landsat ETM+ derived snow maps. However, the IMS 4km SCE maps tend to greatly overestimate the amount of snow in the Catskill/Delaware Watershed as compared to the Landsat and MODIS maps. The coarser resolution of the IMS is likely responsible for some of the observed overestimation of snow cover.

Lake-effect storms can extend quite far inland and can contribute a large percentage of the total snowfall to inland sites (e.g., Schmidlin, 1992; Villani et al., 2017). Yet there has been some controversy on the extent of the contribution of LE snow to the Catskills because the Catskills are so far inland from the Great Lakes (~170 km from the closest point on the shoreline of Lake Ontario to the Cannonsville Basin, and ~300 km from the closest point on the shoreline of Lake Erie to the Cannonsville Basin). Blechman (1996) reported that LE snow "occasionally" reaches the Catskills depositing only ~0.3 – 1.3 cm of snow per event, yet we show that LE snow makes an important contribution to the Catskills snowpack, especially in some years.

For possible future work on other lakes that might lack daily SWT in-situ measurements as are available from GLERL's CoastWatch site, we investigated the use of two other methods to determine SWT of Lake Ontario for each of the four case studies: determination of SWT from the MODIS LST standard product and from MERRA-2 skin temperature. The measurements varied by up to 2.9°C. The GLERL CoastWatch measurement provided the highest temperature in all cases. We made the assumption that the measured SWT from GLERL's CoastWatch site is the most accurate and thus used the GLERL temperature to compare with the MERRA-2 850 mb air temperature.

All of the measurements of SWT and MERRA-2 air temperature in the case studies showed the expected large (13°C or greater) difference needed to spawn LE snow, with the greatest difference, 22.3°C, found on 23 November 2005 in Case Study 1.

Significance of this work to the New York City Water Supply System and the Catskills

The Cannonsville, which is the westernmost basin of the Catskill/Delaware Watershed, is the second largest reservoir feeding the NYC water supply. It is also the most likely to intercept LE snowfall, and the most vulnerable of the basins to future changes in LE snow patterns because of its location.

Meltwater from Catskills Mountain snowpacks can run off into reservoirs or seep into groundwater aquifers providing important extra storage for the reservoirs that supply water to NYC. Also, a significant portion of the economy in this region is related to winter tourism, so changes in snow cover have economic implications. If the winter circulation changes, and less LE snowfall occurs in the future as predicted (e.g., Notaro et al., 2014; Suriano and Leathers, 2016), this could impact the water availability for NYC and winter tourism in the Catskills.

The projected 21st century temperature increase is likely to affect the Catskills snowpack and the seasonal runoff cycle, resulting in changes in winter vs spring runoff causing reservoir storage levels to increase during the winter (Frei et al., 2002; Matonse et al., 2011). Using a combination of satellite and meteorological data, we can begin to understand the contribution of LE snow to the Catskills Mountain snowpack. In future work, we will focus on methods to quantify the amount of lake-effect snowfall reaching the Catskill Mountains.

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REFERENCES

Ackerman SA, Strabala KI, Menzel WP, Frey RA, Moeller CC, Gumley LL. 1998. Discriminating clear sky from clouds with MODIS. *JGR.* **103**(32): 141–32,157, doi:10.1029/1998JD200032.

Anandhi A, Frei A, Pradhanang SM, Zion MS, Pierson DC, Schneiderman EM. 2011. AR4 climate model performance in simulating snow water equivalent over Catskill Mountain watersheds, New York, USA. *Hydrological Processes.* **25**(21): 3302-3311.

Ballentine RJ, Stamm AJ, Chermack EE, Byrd GP, Schleede D. Mesoscale model simulation of the 4–5 January 1995 lake-effect snowstorm. 1998. *Weather and forecasting.* **13**(4): 893-920.

Bard L, Kristovich DAR. 2012. Trend reversal in Lake Michigan contribution to snowfall. *Journal of Applied Meteorology and Climatology.* **51**(11): 2038-2046.

Blechman JB. 1996. A comparison between mean monthly temperature and mean monthly snowfall in New York State. *National Weather Digest.* **20**(4): 41-53.

Burnett AW, Kirby ME, Mullins HT, Patterson WP. 2003. Increasing Great Lake-Effect snowfall during the Twentieth Century: A regional response to global warming? *Journal of Climate*. **16**: 3535-3542.

Eichenlaub VL. 1979. Weather and Climate of the Great Lakes Region, University of Notre Dame Press, 335 pp.

Frei A, Armstrong RL, Clark MP, Serreze MC. 2002. Catskill Mountain water resources: vulnerability, hydroclimatology, and climate-change sensitivity. *Annals of the Association of American Geographers*. **92**(2): 203-224.

Gelaro R, McCarty W, Suarez M and many others. 2017. The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). *Jour. Climate.* doi:10.1175/JCLI-D-16-0758.1.

Hall DK, Crawford CJ, DiGirolamo NE, Riggs GA, Foster JL. 2015. Detection of earlier snowmelt in the Wind River Range, Wyoming, using Landsat imagery. *Remote Sensing of Environment.* **162**: 45-54, http://dx.doi.org/10.1016/j.rse.2015.01.032.

Hall DK, Frei A, DiGirolamo NE, Porter JH, Riggs GA. 2016. Snow cover and extreme streamflow events in the Catskill/Delaware watershed, New York. *Proceedings of the IAHR*, 31 May – 3 June, 2016, Ann Arbor, MI.

Hartnett JJ, 2013: Spatial and Temporal Trends of Snowfall in Central New York – A Lake Effect Dominated Region, A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science Department of Geography, Environment, and Planning College of Arts and Sciences, 166 pp.

Hartnett JJ, Collins JM, Baxter MA, Chambers DP. 2014. Spatiotemporal snowfall trends in Central New York. Journal of Applied Meteorology and Climatology. **53**(12): 2685–2697, https://doi.org/10.1175/JAMC-D-14-0084.1.

Helfrich S, McNamara D, Ramsay BH, Baldwin T, Kasheta T. 2007. Enhancements to, and forthcoming developments in the Interactive Multisensor Snow and Ice Mapping System (IMS). *Hydrological Processes.* **21**: 1576-1586, doi:10.1002/hyp.6720.

Holyroyd EW III. 1971. Lake-effect cloud bands as seen from weather satellites, *Journal of Atmospheric Science*. **28**: 1165-1170.

Kunkel KE, Wescott NE, Kristovich DAR. 2000. Climate change and lake-effect snow. *Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change* (2000): 25-28.

Kunkel KE, Palecki M, Ensor L, Hubbard KG, Robinson DR, Redmond K, Easterling D. 2009. Trends in twentieth-century US snowfall using a quality-controlled dataset. *Journal of Atmospheric and Oceanic Technology.* **26**(1): 33-44.

Leathers DJ, Ellis AW. 1996. Synoptic mechanisms associated with snowfall increases on the lee of lakes Erie and Ontario. *International Journal of Climatology*. **16**: 1117-1135.

Matonse AH, Pierson DC, Frei A, Zion MS, Schneiderman EM, Anandhi A, Mukundan R, Pradhanang SM. 2011. Effects of changes in snow pattern and the timing of runoff on NYC water supply system. *Hydrological Processes.* **25**(21): 3278-3288, doi:10.1002/hyp.8121.

Niziol TA. 1987. Operational forecasting of lake effect snowfall in western and central New York. *Weather and Forecasting.* **2**(4): 310-321.

Niziol TA, Snyder WR, Waldstreicher JS. 1995. Winter weather forecasting throughout the eastern United States. Part IV: Lake effect snow. *Weather and Forecasting.* **10**(1): 61-77.

Norton DC, Bolsenga SJ. 1993. Spatiotemporal trends in lake effect and continental snowfall in the Laurentian Great Lakes, 1951–1980. *Journal of Climate.* **6**(10): 1943-1956.

Notaro M, Zarrin A, Vavrus S, Bennington V. 2013. Simulation of heavy lake-effect snowstorms across the Great Lakes Basin by RegCM4: Synoptic climatology and variability. *Monthly Weather Review.* **141**: 1990-2014, doi:10.1175/MWR-D-11-00369.1.

Notaro M, Lorenz D, Hoving C, Schummer M. 2014. Twenty-First-Century Projections of Snowfall and Winter Severity across Central-Eastern North America. *Journal of Climate.* **27**(17): 6526-6550.

Peace RL Jr., Sykes RB Jr. 1966. Mesoscale study of a lake effect snow storm. *Monthly Weather Review.* **94**(8): 495-507.

Pease SR, Lyons WA, Keen CS, Hjelmfelt M. 1988. Mesoscale spiral vortex embedded within a Lake Michigan snow squall band: High resolution satellite observations and numerical model simulations. *Monthly Weather Review.* **116(**6): 1374-1380.

Pradhanang SM, Anandhi A, Mukundan R, Zion MS, Pierson DC, Schneiderman EM, Matonse A, and Frei AP, 2011. Application of SWAT model to assess snowpack development and streamflow in the Cannonsville watershed, New York, USA. *Hydrological Processes*. **25**:3268-3277, doi:10.1002/hyp.8171.

Riggs GA, Hall DK, Román MO. 2016. MODIS Snow Products User Guide for Collection 6, http://modis-snow-ice.gsfc.nasa.gov/?c=userguides.

Riggs GA, Hall DK, Román MO. 2017. Overview of NASA's MODIS and VIIRS Snow Cover Earth System Data Records. *Earth Systems Science Data*, submitted for publication.

Schmidlin TW. 1992. Does lake-effect snow extend to the mountains of West Virginia? *Proc. 49th Annual Eastern Snow Conference*, Oswego, NY, CRREL: 145-148.

Suriano ZJ, Leathers DJ. 2016. Twenty-first century snowfall projections within the eastern Great Lakes region: detecting the presence of a lake-induced snowfall signal in GCMs. *International Journal of Climatology*. **36**: 2200-2209, doi:10.1002/joc.4488.

Suriano ZJ, Leathers DJ. 2017. Synoptic climatology of lake-effect snowfall conditions in the eastern Great Lakes Region. *International Journal of Climatology*. doi:10.1002/joc.5093.

Vermote EF, El Saleous NZ, Justice CO. 2002. Atmospheric correction of MODIS data in the visible to middle infrared: first results. *Remote Sensing of Environment*. **83**(1-2): 97-111.

Villani J, Jurewicz ML, Krekeler J. 2010. The inland extent of lake-effect snow (LES) bands, *Proc. of the 18th GLOMW.* Toronto, Ontario, 22-24 March 2010, http://www.slideserve.com/pearl/the-inland-extent-of-lake-effect-snow-les-bands, last accessed 7 September 2016.

Villani JP, Jurewicz ML Sr., Reinhold K. 2017: Forecasting the inland extent of lake effect snow bands downwind of Lake Ontario. *Journal of Operational Meteorology* **5**(5): 53-70, doi: http://doi.org/10.15191/nwajom.2017.0505.

Wan Z, Zhang Y, Zhang Q, Li Z-L. 2002. Validation of the land-surface temperature products retrieved from Terra Moderate Resolution Imaging Spectroradiometer data. *Remote Sensing of Environ*ment. **83**: 163–180.

Wang J, Bai K, Hu H, Clites A, Colton M, Lofgren B. 2012. Temporal and spatial variability of Great Lakes ice cover, 1973-2010. *Journal of Climate*. **25**: 1318-1329.