On the Frequency of Lake-Effect Snowfall in the Catskill Mountains

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ABSTRACT

Meltwater from snow that falls in the Catskill/Delaware Watershed in the Catskill Mountains in south-central New York contributes to reservoirs that supply drinking water to approximately nine million people in and near New York City (NYC). Using the Interactive Multisensor Snow and Ice Mapping System (IMS) 4km snow maps from the National Oceanic and Atmospheric Administration's National Ice Center, we identified and tracked 28 lake-effect (LE) storms that deposited snow in the Catskill Mountains from 2004-2017. These storms, that generally originated from Lake Ontario, but sometimes from Lake Erie, represent an underestimate of the number of LE storms that contribute snowfall to the total Catskills snowpack because snowstorms are not visible on the IMS maps when they travel over already-snow-covered terrain. Using satellite, meteorological (including NEXRAD and National Weather Service Cooperative Observer Program), and reanalysis data we identify conditions that contributed to the LE snowstorms and map snow-cover extent (SCE) following the storms when possible. IMS 4km maps tend to overestimate SCE compared to MODerate-resolution Imaging Spectroradiometer (MODIS) and Landsat. Though the total amount of snow from each LE snow event that contributes snow to the Catskills is often small, there are a large number of

events in some years that, together, add up to a great deal of snow. Changes that are predicted in LE snowfall events could impact the distribution of rain vs. snow in the Catskills which may affect future reservoir operations in the NYC Water Supply System and winter recreation in the Catskills.

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) and others in New York State who rely on the NYC Water Supply System (NYCWSS) for a significant portion of their water needs. The NYCWSS, the largest unfiltered water supply system in the United States (Matonse et al., 2011), derives most of its water from runoff emanating from the six basins of the Catskill/Delaware Watershed in the Catskill Mountains in south-central New York. This watershed has traditionally supplied 90 percent of NYC's water demands. The westernmost basin, the Cannonsville, contains the second largest reservoir used for NYC drinking water and historically has contributed ~50% of the total water supply. The estimated contribution of snowfall to total annual precipitation in the Catskill/Delaware Basin is 20% - 30% from ~1950 through 2010 (Frei, Armstrong, Clark & Serreze, 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.

In this paper we examine the frequency of LE snowstorms that impact the Catskill Mountains for a 13-year period (2004 – 2017). We use satellite snow-cover maps derived from the National Oceanic and Atmospheric Administration's (NOAA's) National Ice Center (NIC) 4km Interactive Multisensor Snow and Ice Mapping System (IMS), the National Aeronautics and Space Agency's (NASA's) 500-m resolution MODerate resolution Imaging Spectroradiometer (MODIS) images and standard snow-cover map products, Landsat satellite-derived snow maps, weather radar and other meteorological and reanalysis data.

Background

Lake Effect Snowfall in the Eastern Great Lakes Region

During the 20th Century, annual snowfall increased across the LE zone of the Great Lakes Basin, likely due to warming of lakes and diminished ice cover (Burnett, Kirby, Mullins & Patterson, 2003; Kunkel et al., 2009; Notaro, Zarrin, Vavrus & Bennington, 2013). Significant increases in LE snow were found between 1951 and 1990 (Norton & Bolsenga, 1993; Leathers & Ellis, 1996; Burnett, Kirby, Mullins & Patterson, 2003), however LE snowfall has generally been declining since the early 1970s in some parts of central New York (Hartnett, Collins, Baxter & Chambers, 2014) and is projected to decline further during the 21st Century in part because the air temperature is expected to continue to rise, causing less precipitation to fall as snow (Suriano & Leathers, 2016). Trends in cloudiness over this region are consistent with declining LE trends; Ackerman et al. (2013) found a small but significant decreasing trend in cloud amount over the Great Lakes region of about 2 percent per decade through analysis of 31 years of imager data from polar-orbiting satellites.

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 & Sykes, 1966; Pease, Lyons, Keen & Hielmfelt, 1988; Kunkel, Wescott & Kristovich, 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 & Bolsenga, 1993) and when there is a large contrast (at least 13°C) between the lake surface temperature and the 850 mb air temperature (Holyroyd, 1971).

In addition to ice coverage and air-water temperature contrast, fetch, wind direction, and wind speed also affect the development and intensity of LE snow (e.g., see Villani, Jurewicz & Reinhold, 2017). Long fetch can increase the intensity of the LE storms by providing a greater surface area to allow more evaporation from the non-ice-covered lake surface (Steiger et al., 2013). 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 & Kristovich, 2012; Suriano & Leathers, 2016). Lake-enhanced snow results when a storm system that is already producing precipitation travels over a lake, resulting in more convective transfer of heat and moisture to the overlying air mass.

During typical LE events, narrow (5 – 20 km) and elongated (50 – 300 km) snow bands (e.g., see Holyroyd, 1971) form on the leeward side of lakes (Figure 1) (Eichenlaub, 1979; Peace & Sykes, 1966; Niziol, 1987; Hartnett, 2013; Hartnett, Collins, Baxter & Chambers, 2014). These bands are often easily observable on satellite imagery (Kristovich and Steve, 1995; Ackerman et al., 2013). Kristovich and Steve (1995) found, using Geostationary Operational Environmental Satellites (GOES) visible satellite imagery, that the frequency of LE cloud bands increased from October through February, and then decreased rapidly in March. They also found that LE events peaked in December over Lake Erie as freezing of Lake Erie was very common during their study period (1988-1993) in January and February, thus cutting off the source of heat and moisture needed for LE convection.

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). Thus more LE storms typically emanate from Lake Ontario. In addition the east-west orientation of Lake Ontario presents a long fetch (up to ~300 km) when prevailing winds are aligned with the long axis of the lake.

Up to seven LE synoptic types are associated with LE snowfall over Lake Erie and Lake Ontario (Leathers & Ellis, 1996; Suriano & 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 & Leathers, 2017). They identify seven types based on prevailing wind direction: WNW-1, W-1, SW-1, WSW-1, W-2, WSW-2, and NW-1 (see Table 1 in Suriano and Leathers, 2017). There is a wide range of surface and 850 mb temperatures, winds, sea-level pressures and snowfall intensities that characterize the synoptic types resulting in large differences in the location and strength of LE snowfall (Suriano and Leathers, 2017).

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. A time series of IMS 4km snow maps from the 12-13 October 2006 storm, Aphid, that originated from Lake Erie and deposited up to 57 cm of snow in a ~16-hour period on parts of Buffalo, New York [https://www.weather.gov/buf/lesEventArchive2006-2007_a] may be seen in Figure 2. Snowfall extended less than about 100 km from the shore of Lake Erie, according to the IMS, yet the storm had a major meteorological and economic impact, though the snow depth was highly variable in the local area.

In contrast to localized LE storms, the combination of long, overwater fetch and strong winds can cause narrow bands of precipitating clouds to propagate considerable distances inland (e.g., see Niziol, Snyder & Waldstreicher, 1995). The atmospheric parameters that have the greatest influence on the ability of a LE storm to extend inland from Lake Ontario are: 1) the presence of a multi-lake/upstream moisture source, and 2) the difference between the lake's surface water temperature (SWT) and the air temperature at 850 mb (Villani, Jurewicz & Reinhold, 2017).

Study Area

The six basins that comprise the Catskill/Delaware Watershed in the Catskill Mountains of south-central New York: Ashokan, Schoharie, Rondout, Neversink, Cannonsville and Pepacton, are shown in Figure 3. The watershed is located up to about 200 km northwest of NYC with an approximate center coordinate of 42.2°N, 74.6°W. Snow conditions can be quite variable within the watershed, both spatially and temporally (Frei, Armstrong, Clark & Serreze, 2002; Hall et al., 2016). In particular, the Cannonsville, because of its location as the westernmost basin, and its topography and elevation (with elevations ranging from 329 m to 1014 m and a mean elevation 580 m), tends to intercept much 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. The six National Weather Service (NWS) Cooperative Observing Program (COOP) stations that are located within the watershed are shown in Figure 3 as red dots.

Data and Methodology

Satellite Data

In this paper, we use the following satellite data: 1) NOAA IMS 4km resolution snow-cover extent (SCE) maps; 2) MODIS Collection 6 (C6) standard 500-m resolution SCE maps; 3) MODIS C6 standard 250-m or 500-m surface-reflectance maps; and 4) Landsat-derived SCE maps.

IMS snow maps

Multiple satellite and ground station data have been utilized to develop the IMS 4km daily SCE maps, to provide daily, cloud-cleared snow maps to users since 2004 (Helfrich et al., 2007). Processing of the IMS maps is partially automated but 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 maps.

MODIS snow maps

The fully-automated MODIS standard 500-m resolution C6 daily snow maps are produced daily, but the ground surface can be fully or partially obscured by cloud cover so a usable snow map is not available every day. In addition, because of the conservative nature of the MODIS cloud mask (Ackerman et al., 1998) and snow/cloud confusion, there can be cloud-free areas that are mapped as "cloudy" on the daily snow maps. Details on the MODIS C6 snow-cover maps may be found in Riggs, Hall & Román (2017).

Other satellite data

MODIS standard surface-reflectance products (Vermote, El Saleous & Justice, 2002) and Landsat-7 Enhanced Thematic Mapper Plus (ETM+) images are used to identify and map SCE in the Catskills. The biggest uncertainty in snow-cover mapping is due to clouds and snow/cloud discrimination. Additionally, using Landsat data, the problem of acquiring a clear scene is exacerbated by the fact that the exact repeat pass for the Landsat satellites is 16 days, thus daily data are not available.

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 employed to analyze atmospheric conditions leading to the LE storms identified on the IMS snow maps. In addition images archived from NWS 0.5° NEXRAD Level III base reflectivity radar data from Albany, Binghamton and Buffalo New York and from Cleveland, Ohio, [https://www.ncdc.noaa.gov/wct/] were analyzed, when available, for two case studies. Hydrometeor precipitation data from NOAA's National Climatic Data Center (NCDC) were also examined for the case studies. Furthermore we studied data from the NEXRAD weather radar composites archive of the University Corporation for Atmospheric Research (UCAR) [http://www2.mmm.ucar.edu/imagearchive/] for all of the LE storms identified on the IMS snow maps (Table 1). The intensity of precipitation is measured by a ground-based radar that bounces radar waves off of precipitation. Radar reflectivity is measured in dBZ which quantifies echo intensity.

Daily lake SWT and percent ice concentration from Great Lakes Surface Environmental Analysis maps were 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). We also used MERRA-2 850 mb air temperatures. In addition to the MODIS and Landsat data mentioned above, to investigate snow on the ground, we used COOP station data in the Catskill/Delaware Watershed from the following six stations in New York: Claryville (41.91°N, 74.57°N, 504 m elevation), Delhi 2 SE (42.25°N, 74.91°W, 445 m), East Jewett (42.24°N, 74.14°W, 607 m), Slide Mountain (42.02°N, 74.42°W, 808 m), Walton (42.18°N, 75.15°W, 451 m) and Windham 3 E (42.30°N, 74.20°W, 512 m).

Methodology

We inspected all of the IMS daily 4km SCE maps from November through April for each year of the study period, to identify and track snow on the ground that emanated from Lake Erie and/or Lake Ontario and was deposited in the Catskill/Delaware Watershed. Using visible-band imagery it is only possible to identify "new" snow, meaning snow that was visible when there had previously been no snow or very little snow already on the ground just prior to the event.

Meteorological conditions were investigated for each suspected LE storm using Unisys and NEXRAD data; in addition, for two case studies we compared MERRA-2 850 mb air temperatures with SWT. The hourly temperatures derived from the MERRA-2 data at 850 mb were averaged for each day to calculate a daily 850 mb air temperature.

Using the NEXRAD images, we created animations that began one day prior to each suspected LE snow event. Intensity of precipitation (in dBZ) as well as location, direction and cloud banding were used to identify storms. LE storms were confirmed when we observed precipitation in the weather radar data that appeared to form over Lake Erie or Lake Ontario, and when we tracked the precipitation using NEXRAD images into the Catskill/Delaware Watershed, thus confirming that such precipitation, emanating from the storm, fell in the Catskills. The IMS snow maps, and sometimes the MODIS- and Landsat-derived snow maps, also provided proof that precipitation fell as snow. Occasionally we were also able to use the COOP data to confirm that snow was on the ground, though data from key COOP stations were often not available.

To provide some quantification of the location and impact of the storm, measurements of SCE from Landsat- and MODIS-derived, and IMS SCE maps were made in the Catskills when possible. MODIS and IMS maps were used, as described earlier, and Landsat SCE maps (see Hall et al., 2015) were derived using an algorithm similar to that used for to map snow using MODIS (see Riggs, Hall and Román, 2017).

Results

During the 13-year study period 28 LE storms were identified to emanate from Lake Erie and/or Lake Ontario from which snow reached the Catskill/Delaware Watershed (Table 1) as determined through inspection of IMS snow maps. Each of the 28 cases was confirmed to be LE following analysis of archived NEXRAD weather radar data of each event. Most of the storms originated from Lake Ontario but some originated from Lake Erie or from both lakes.

The number of LE snowstorms reaching the Catskills that we identified is a large underestimate of the actual number of LE storms that deposited snow in the Catskills during the study period because it is not possible to see or track the snowstorms on the IMS maps developing and moving across the landscape when snow is already on the ground. For example, the winter of 2013-14 was a big snow year for western New York State, including the Catskill Mountains to the east. It was also a year with a high number of LE snowstorms (Laird et al., 2017). Our inspection of NEXRAD radar data for that winter corroborated this. Using the NEXRAD data we tracked numerous LE storms that deposited snow into the Catskills, yet we were able to confirm only one LE storm that reached the Catskills using IMS snow maps, alone, during the 2013-14 snow season (Table 1) because there was so much snow already on the ground.

We focus on two storms during the study period to illustrate the use of satellite and NEXRAD data for identifying and measuring LE snow in the Catskills: Case Study 1: 22 – 24 November 2005 and Case Study 2: 14 – 15 November 2014. We also compare snow maps acquired after the storms when the sky was clear.

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). Unisys Surface Data Plots show a cold front from Canada moving in a southeasterly direction on 21-22

November 2005 [http://weather.unisys.com/surface/]. LE snow was deposited overnight and in the morning of 23 November in the Catskills. The difference between the SWT of Lake Ontario and the 850 mb air temperature increased from 14°C on 22 November to 22.3°C by 23 November (Table 2). The temperature differences on all three dates shown in Table 2 are greater than the 13°C required to spawn LE storms (Holyroyd, 1971). Percent ice coverage on Lake Ontario was zero on 22 – 24 November. Out of the six COOP stations in the watershed, five were operational, reporting from 3 – 23 cm of snow on the ground on 24 November as shown in Table 2.

The banding of precipitating clouds over Lake Ontario extends inland to the Catskills as seen on the NEXRAD image (Figure 6). The entire Catskill/Delaware Watershed was snow covered on 23 and 24 November, according to the IMS snow maps, after having been snow-free prior to that.

Case Study 2: 14 – 15 November 2014

A LE storm was responsible for snowfall in areas to the east of Lake Erie and Lake Ontario on 14-15 November 2014 (Figure 7). Cool, dry air flowing over the Great Lakes evaporated moisture from the warmer lake surfaces, forming cloud streets similar to those seen in the VIIRS satellite image in Figure 1. The snow that subsequently fell on the Catskills originated from a LE storm that was first observed over Lake Ontario. This is evident in the NEXRAD data as well as in the hydrometeor snow data (Figure 8a & b). Later in the day of 14 November and on the next day, snowfall originating from, or enhanced by air flowing over Lake Erie contributed more snowfall to the Catskills as seen in both the radar and hydrometeor data.

The difference between the SWT of Lake Ontario and the 850 mb air temperature increased from 13.8°C on 13 November to 19.7°C during the storm (Table 3) having been enhanced by “cold” air flowing over the “warm” lake surface. The percent ice coverage was zero on 12 – 15 November. Out of the six COOP stations in the watershed, three were operational, reporting from 3 – 8 cm of snow on the ground.

Comparing areal extent of SCE using different snow maps

When the sky is clear, such as on 10 December 2006, MODIS provides imagery (Figure 9a), and a snow map (Figure 9b) that is generated automatically. The extent of snow was measured from the standard Aqua MODIS C6 snow map and showed that 1004 km^2, or ~24 percent, of the watershed was snow covered (Figure 9b). SCE was also measured using the IMS 4km map (not shown), and showed that 3573 km^2, or ~71 percent, of the watershed was snow covered, or more than 3.5 times greater as compared to SCE from the MODIS snow map (Table 4). Out of the six COOP stations in the watershed, five were operational, reporting from 0 – to a trace of snow on the ground following the event, clearly showing that the COOP stations were not capturing the snow that was actually on the ground over the extent of the Catskill/Delaware Watershed.

During another LE snow event in early April 2013, IMS provided greater SCE than either MODIS- or Landsat-derived snow maps (Table 5). The IMS snow map showed about 3 times more SCE than did the Landsat-derived SCE map, and almost 2.5 times more SCE than did the MODIS SCE map. Yet on this date the COOP station data show only 0 – 5 cm of snow on the ground, with only three stations reporting.

Snow was mapped on 19 November 2014 using the C6 Terra MODIS snow map (Figure 10a), a Landsat-7-Enhanced Thematic Mapper Plus (ETM+)-derived snow map (Figure 10b) 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 6). COOP station data show only 0 to a trace of snow on the ground, with only three of the six stations reporting.

SCE measured using MODIS and Landsat is in good agreement for the events that we studied, while IMS 4km maps tend to overestimate SCE. The same basic algorithm (see Hall et al., 2015) is used to map snow using Landsat and MODIS data which could partly explain their excellent agreement. Overestimation of SCE using the IMS data is at least partly due to the coarser resolution of the IMS 4km snow map, as compared to the MODIS (500 m) and Landsat (30 m) snow maps.

Discussion and Conclusion

Analysis of IMS snow cover in the Catskill/Delaware Watershed for other work that was unrelated to LE snowfall caused us to notice that many of the storms taking snow into the Catskills were LE storms emanating from Lake Ontario. At the time, we recognized that IMS snow maps are not suitable for mapping the frequency and/or contribution of LE snow in the Catskill Mountains because storms cannot be tracked when snow is already on the ground. Nevertheless, the IMS maps provided a useful way to track the storms traveling over *non-snow-covered terrain*, and this caused us study the frequency of LE storms reaching the Catskills in conjunction with other data such as NEXRAD radar.

Use of satellite data to study LE snow in the Great Lakes has typically focused on studies of cloud cover (e.g., Ackerman et al., 2013; Laird et al., 2017). We employed a combination of data sources, including a time series of NOAA IMS 4km snow maps along with weather radar and precipitation maps. As a result of our analysis, 28 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 as air flowed over Lake Ontario, though a few of the storms also appeared to originate from Lake Erie, or from both lakes. We used archived NEXRAD images and other meteorological data to begin to assess the frequency of LE snowstorms that travel inland into the Catskills, and to confirm the importance of LE snow for the Catskill/Delaware Watershed that is important for the NYCWSS.

Lake-effect storms can extend quite far inland and can contribute a significant percentage of the total snowfall to inland sites (e.g., Schmidlin, 1992; Villani, Jurewicz & Reinhold, 2017). Yet there has been very little discussion in the literature about the significance of the contribution of LE snow to the Catskills because the Catskill/Delaware Watershed in the Catskills is so far inland from the

Great Lakes (~170 km from the closest point on the shoreline of Lake Ontario to the Cannonsville Reservoir in the Cannonsville Basin, and ~300 km from the closest point on the shoreline of Lake Erie to the Cannonsville Basin) (Figure 3). While Blechman (1996) reported that LE snow “occasionally” reaches the Catskills, depositing only ~0.3 – 1.3 cm of snow per event, our results indicate that LE snow can make an important contribution to the Catskills snowpack because of the frequency of events, even though the total amount of each event may, on average, be small.

Using the techniques presented here, it is not possible to quantify the contribution or the volume of snow deposited in the Catskills by LE storms because visible and near-infrared satellite data provide only SCE, not depth or snow-water equivalent. In addition, there is an insufficient meteorological station density in our study area to enable a quantification of snow depth or SWE using station data. Furthermore, the NWS COOP stations in the Catskill/Delaware Watershed are located at lower elevations in the watershed, with the exception of the Slide Mountain station, and are therefore not representative of the amount of snow higher in the mountains where much of the snow falls. Finally, COOP stations were sparse in the study area and much of the data from the six COOP stations was missing during the 13-year study period.

After the snow falls and the sky clears, both MODIS and Landsat data allow accurate mapping of SCE. MODIS measurements using the standard MODIS C6 Terra and Aqua snow-cover maps at 500-m resolution are consistent with measurements made using 30-m resolution Landsat ETM+ derived snow maps, both providing an excellent way to measure SCE in the Catskills. 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 for the snowfall events described in this paper. The coarser resolution of the IMS is likely responsible for some of the observed overestimation of snow cover.

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. 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, Armstrong, Clark & Serreze, 2002; Matonse et al., 2011). Regional climate warming can affect the processes that lead to LE snowfall in a number of ways. As SWT continues to increase in the Great Lakes (Austin & Colman, 2007; Schneider & Hook, 2010), the contrast between the SWT and 850 mb air temperature may be affected, possibly influencing LES intensity, and thus the ability of LE storms to travel as far inland. Warmer temperatures, on the other hand, will continue to lead to less ice formation on the lakes (Wang et al., 2012), thus promoting more LE snow during cold periods.

One result from this study with regards to water supply management is in the area of evaluating future scenarios. The Climate Change Integrated Modeling Project (CCIMP), under which NYC is engaging this question, must evaluate potential scenarios of future changes, including (but not limited to) specific scenarios from specific models. It may help NYC identify models that are particularly useful for this analysis if we can understand which models correctly capture the different processes that contribute to precipitation in the watershed.

Meltwater from Catskills Mountain snowpack can flow into reservoirs or seep into groundwater aquifers providing important extra storage for the reservoirs that supply water to NYC. In addition to its importance for the NYCWSS, changes in snow cover have economic implications because of the importance of winter recreation to the region's economy. If the winter circulation changes, and less LE snowfall occurs in the future as predicted (e.g., Notaro, Lorenz, Hoving & Schummer, 2014; Suriano and Leathers, 2016), it is likely to impact the reservoir management for NYC as well as winter tourism in the Catskills.

Future Work

Using a combination of visible and near-infrared satellite images, weather radar, meteorological station and reanalysis data, we can begin to understand the frequency of LE snowstorms traveling to the Catskills. The extensive fall and winter season cloud cover in New York State precludes acquisition of adequate satellite imagery of the ground surface to reliably assess SCE from satellite data alone. In future work, we will evaluate methods to quantify LE snowfall reaching the Catskill Mountains using modeling, augmented by ground-based snow observations, weather radar and satellite data, to estimate the contribution of LE snow to the Catskill Mountain snowpack.

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Tables

Table 1. Dates of lake-effect (LE) storms emanating from Lake Erie and Lake Ontario on which snow reached the Catskill Mountains. The lake from which the storm emanated is also shown. Column three refers to the number of stations within the watershed that reported snow depth on the date shown, or the last date if there is a range of dates shown. It is common for data to be missing or for a station to not report for an entire month. There is an asterisk (*) next to the dates of the two case studies, and a plus sign (+) next to the dates for which areal extent of snow cover was mapped from different satellite sensors after a storm passed.

Date	**Lake**	**Snow measured at 1-6 stations in the watershed**
03 Dec 2004	Erie	T to 3 cm at 3 stations
14 Dec 2004	Both?	Snow 0 – 4"
22-24 Nov 2005*	Ontario	3-23 cm at 5 stations
04 Dec 2005	Both	3-8 cm at 4 stations
19 Jan 2006	Ontario	T to 5 cm at 3 stations that reported
02 Feb 2006	Ontario	5-8 cm at 2 stations
16 Mar 2006	Ontario	0-3 cm at 4 stations
05 Dec 2006+	Ontario	0-3 cm at 4 stations
10 Jan 2007	Ontario	T to 3 cm at 6 stations
17 Jan 2007	Ontario	T to 3 cm at 5 stations
17 Nov 2007	Ontario	0 to 5 cm at 6 stations
01 Dec 2007	Both?	T to 5 cm at 5 stations
21-22 Nov 2008	Both?	0 to 8 cm at 5 stations
04 Dec 2010	Ontario?	T to 3 at 5 stations
02 Apr 2013+	Ontario?	0 to 5 cm at 3stations
14-15 Nov 2014*+	Ontario?	3-8 cm at 3 stations
01 Jan 2015	Both?	5 cm at 1 station
21 Dec 2015	Erie	0-T at 3stations
05 Jan 2016	Both?	0-8 cm at 4 stations
12 Jan 2016	Both?	0-3 cm at 2 stations
25 Feb 2016	Erie	0 cm at 2 stations
04 Apr 2016	Ontario	10-18 cm at 3 stations
21 Nov 2016	Ontario	0-18 at 2 stations
08 Dec 2016	Erie	T to 3 cm at 3 stations
27 Dec 2016	Ontario	0 cm at 3 stations
25 Jan 2017	Ontario	3-8 cm at 3 stations
28 Feb 2017	Ontario	0 cm at 5 stations
03-05 Mar 2017	Both?	0 cm - T at 3 stations

Table 2. Surface water temperature (SWT) of Lake Ontario from GLERL's CoastWatch site, and 850 mb Tair from MERRA-2.

Date	SWT in °C	Tair in °C	Difference between SWT and Tair in °C
22 Nov 2005	7.9	-6.4	14.3
23 Nov 2005	7.7	-14.6	22.3
24 Nov 2005	7.6	-11.5	19.1

Table 3. Surface water temperature (SWT) of Lake Ontario from GLERL's CoastWatch site, and 850 mb Tair from MERRA-2.

Date	SWT in °C	Tair in °C	Difference between SWT and Tair in °C
12 Nov 2014	8.6	-4.4	13.8
13 Nov 2014	7.2	-9.7	18.7
14 Nov 2014	6.8	-10.9	19.6
15 Nov 2014	6.4	-11.3	19.7

Table 4. Snow-cover extent (SCE) in the Catskill/Delaware Watershed using Aqua MODIS (MYD10A1 Collection 6 [C6]) and IMS 4km SCE maps, 10 December 2006.

Snow Map	Percent Snow Cover in Watershed	Area of Snow Cover in km^2
Aqua MODIS SCE	23.7	1004
IMS 4km SCE	71.1	3573

Table 5. Measurement of snow-cover extent (SCE) 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 SCE* - 6 Apr	20.2	829
MODIS C6 MOD10A1 SCE - 4 Apr	24.3	1029
IMS 4km SCE - 4 Apr	49.4	2482

*LE70140312013096EDC00

Table 6. Measurement of snow-cover extent (SCE) in the Catskill/Delaware Watershed using Landsat-7 Enhanced Thematic Mapper Plus (ETM+), Terra MODIS and IMS 4km SCE maps, 19 November 2014.

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

*LE70140312014323EDC00

Figures

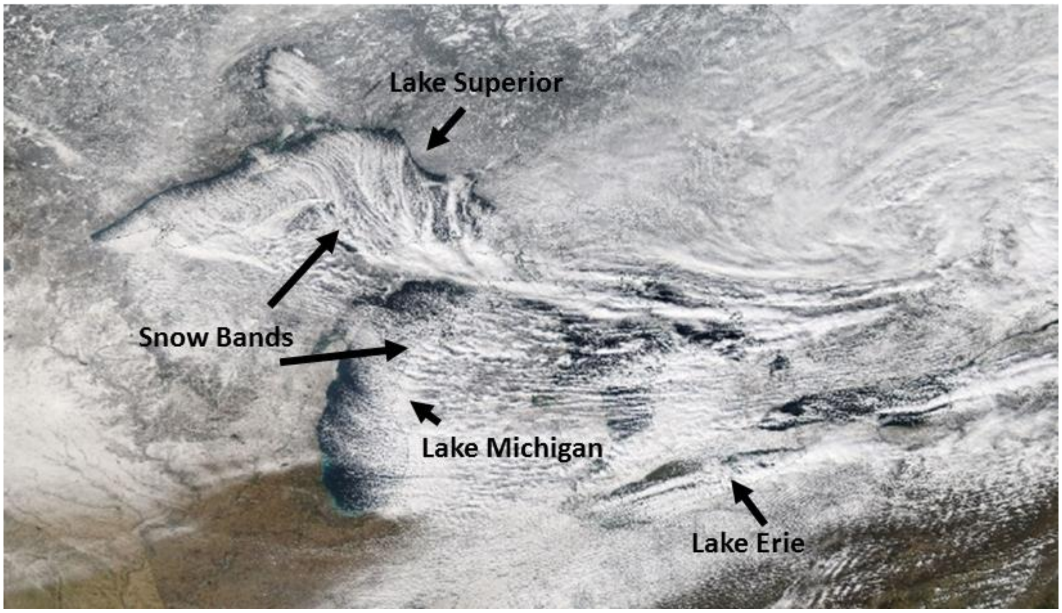

Figure 1. Suomi NPP Visible Infrared Imaging Radiometer Suite (VIIRS) image from 18 November 2014, showing narrow, elongated snow bands over Lake Superior and Lake Michigan. In this storm the west-southwesterly winds were parallel with the long axis of Lake Erie (barely visible below the clouds) creating a long fetch, which allowed 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 to 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.

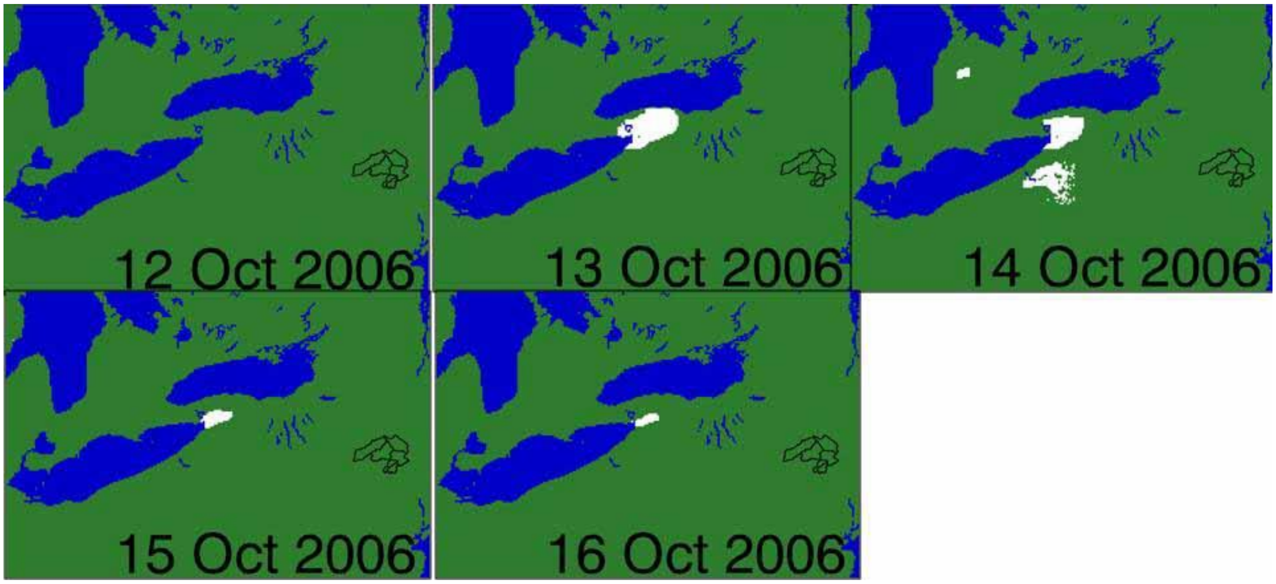

Figure 2. Time series of NOAA IMS 4km resolution snow maps from 12-16 October 2006 showing a lake-effect (LE) storm that originated over Lake Erie, developing and dissipating. A major LE storm dumped up to 57 cm of snow on parts of Buffalo, New York, on 12-13 October 2006 [https://www.weather.gov/buf/lesEventArchive2006-2007_a]. Extensive damage occurred due primarily to the fact that the heavy, wet snow accumulated on fully-leafed-out deciduous trees, causing limbs to fall and many trees to uproot. The six basins of the Catskill/Delaware Watershed are outlined in black.

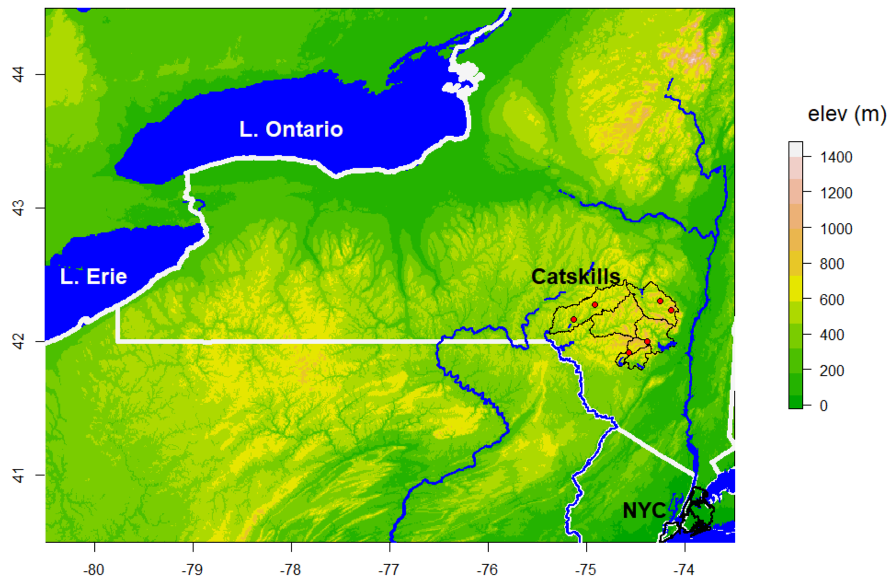

Figure 3. The six basins in the Catskill/Delaware Watershed in the Catskill Mountains are outlined in black, and state boundaries are shown in white. Some of the major rivers, shown in blue, include the Susquehanna, Delaware, Hudson, and Mohawk. The approximate locations of the six National Weather Service (NWS) Cooperative Observing Program (COOP) stations that are within the Catskill/Delaware Watershed are shown as red dots. Note the location of the Catskills with respect to Lake Erie and Lake Ontario, and New York City (NYC) in the lower right of the image. The westernmost part of the Cannonsville Reservoir is located at approximately 42.1°N, 75.4°W.

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.

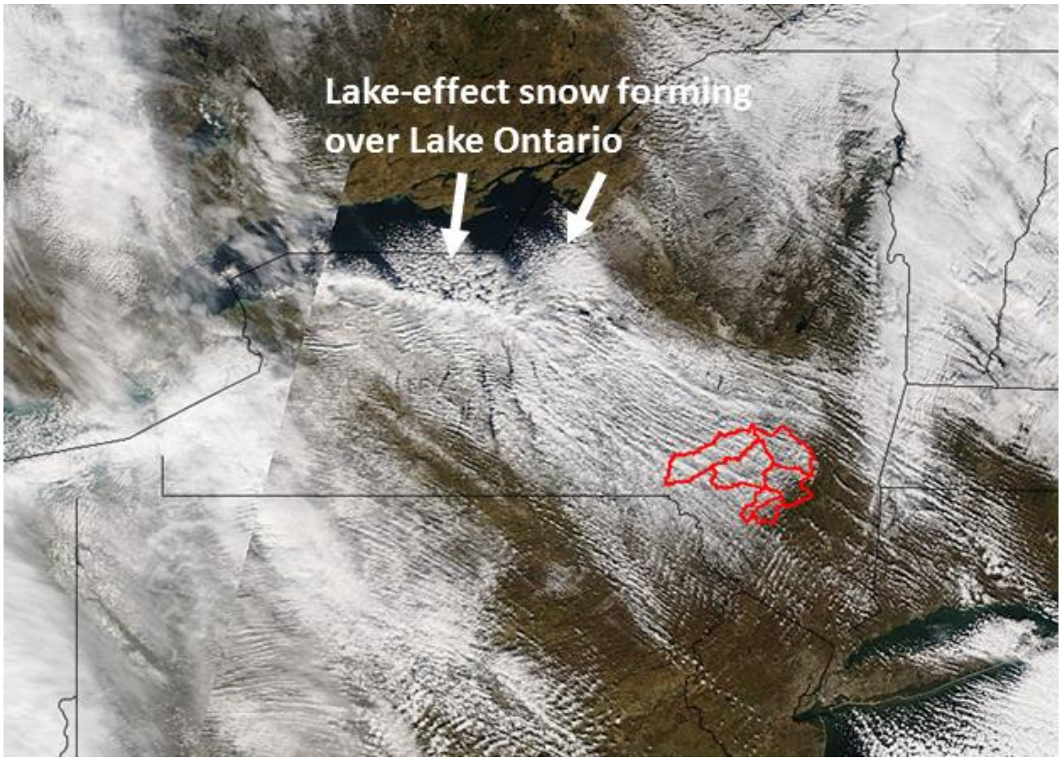

Figure 5. Terra MODIS true-color image of lake-effect (LE) snow emanating from Lake Ontario on 23 November 2005. Snow from that storm was deposited in the Catskills. The six basins of the Catskill/Delaware Watershed are outlined in red. Image obtained from NASA's Land, Atmosphere Near real-time Capability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

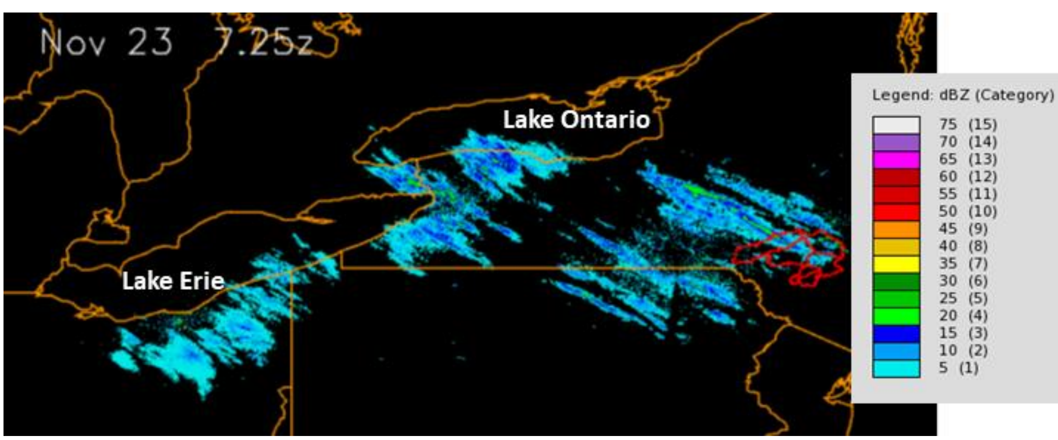

Figure 6. NWS 0.5° NEXRAD Level III base reflectivity radar data [https://www.ncdc.noaa.gov/wct/] from the following four stations were composited to create this map for 23 November 2005 at 07:15 UTC: Albany, Binghamton and Buffalo, NY, and Cleveland, OH. Note the cloud and precipitation "banding" emanating from Lake Erie and Lake Ontario. Echo intensity, in dBZ, from radar is shown in the blue and green colors on the map.

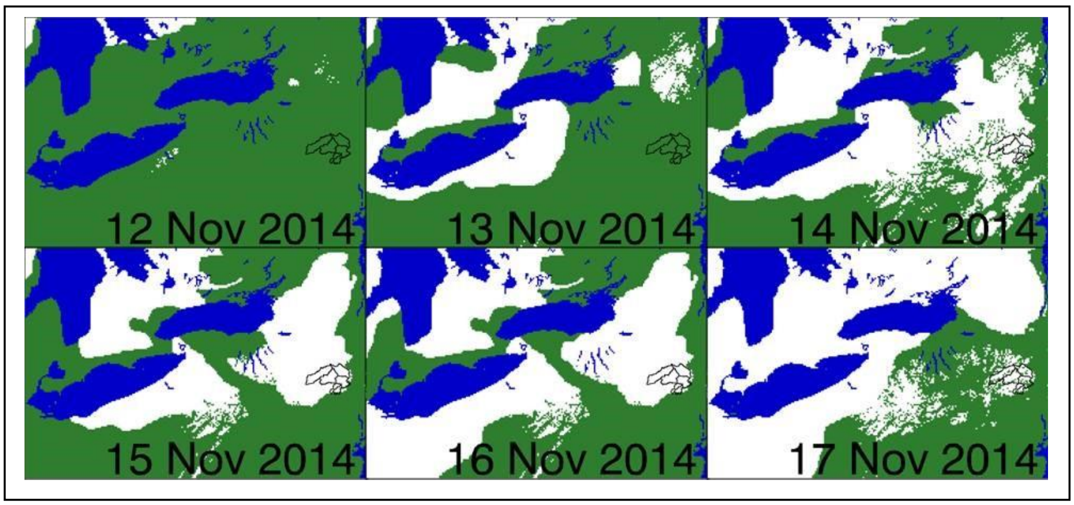

Figure 7. Time series (12 – 17 November 2014) of IMS 4km snow maps showing the progression of the LE storm that deposited snow in the Catskills. The six basins of the Catskill/Delaware Watershed are outlined in black.

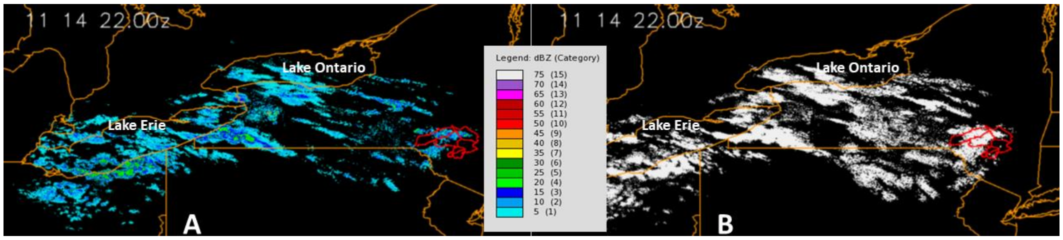

Figure 8a. NWS 0.5° NEXRAD Level III base reflectivity radar data [https://www.ncdc.noaa.gov/wct/] from the following four stations were composited to create this map for 14 November 2014 at 22:00 UTC: Albany, Binghamton and Buffalo, NY, and Cleveland, OH. Note the cloud and precipitation "banding" emanating from Lake Erie and Lake Ontario. Echo intensity, in dBZ, from radar is shown in the blue and green colors on the map.

Figure 8b. Hydrometeor precipitation data from NOAA National Climate Data Center (NCDC) from the following four stations were composited to create this map for 14 November 2014 at 22:00 UTC: Albany, Binghamton and Buffalo, NY, and Cleveland, OH. Note the cloud and precipitation "banding," shown in white, originating from Lake Erie and Lake Ontario. Hydrometeor precipitation is a product derived from NEXRAD.

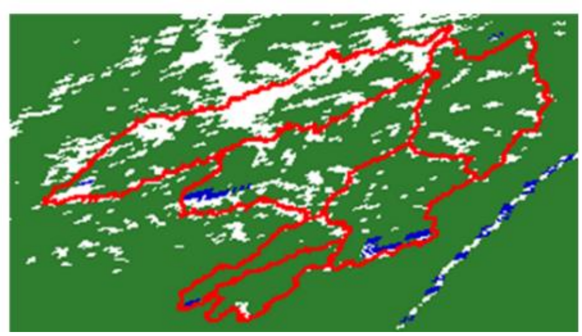

Figure 9a (left panel). Terra MODIS 250-m "true-color" image acquired on 10 December 2006. The six basins of the Catskill/Delaware Watershed are outlined in red.

Figure 9b (right panel). MYD10A1 Collection 6 (C6) normalized-difference snow index (NDSI) snow map, acquired on 10 December 2006

[MYD10A1.A2006344.h12v04.006.2016080151145.hdf]. 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.

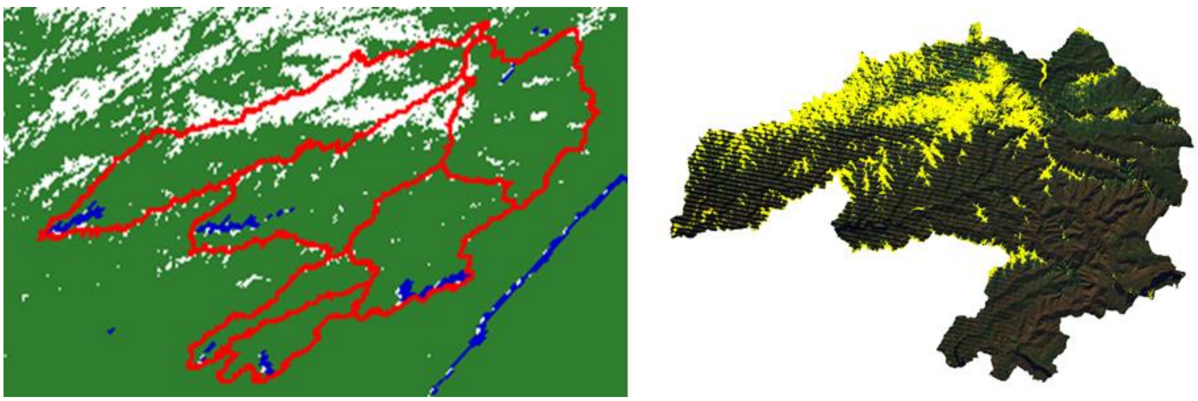

Figure 10a (left panel). MOD10A1 Collection 6 (C6) normalized-difference snow index (NDSI) snow map of the Catskill/Delaware Watershed, 19 November 2014 [MOD10A1.A2014323.h12v04.006.2016179181758.hdf]. In this snow map, white represents snow, green represents “no snow,” and blue represents water. The six basins of the Catskill/Delaware Watershed are outlined in red.

Figure 10b (right panel). Landsat-7 Enhanced Thematic Mapper Plus (ETM+) – derived snow map of the Catskill/Delaware Watershed, 19 November 2014 [LE70140312014323EDC00]. Yellow represents snow.