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Key Points:
- High deuterium excess occurs during National Weather Service-defined lake effect snowstorms
- *d*-excess and moisture recycling are higher when air temperature is cold and lake water is much warmer than air
- Sites downwind of the Great Lakes have higher annual mean *d*-excess than have upwind sites, due to greater moisture recycling

Supporting Information:
- Supporting Information S1

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Event-Based Precipitation Isotopes in the Laurentian Great Lakes Region Reveal Spatiotemporal Patterns in Moisture Recycling

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Abstract Lake effect snowstorms influence climate, ecology, and agriculture in the Laurentian Great Lakes region and can be costly to surrounding communities in the United States and Canada. Stable isotopes of lake effect precipitation events throughout the year display a distinct signature that can be used to better understand how these storms may respond to a changing climate. Here we present event-based $\delta^{18}O$ and $\delta^{2}H$ of precipitation from a site in Skaneateles, NY, downwind of Lakes Ontario and Erie, between April 2015 and February 2018. We find a seasonal isotopic cycle with a well-defined signature of high deuterium excess (*d*-excess) during National Weather Service-defined lake effect snowstorms. Application of a previously developed moisture recycling model to this data set shows that up to 25% more moisture recycling takes place when the lake water and air temperature difference is large, air temperature is below freezing, and wind direction permits storms to move over Lake Ontario or Lake Erie. Moisture recycling occurs less frequently during spring, summer, and early fall due to meteorological and lake parameters that are less conducive to moisture recycling. Comparison of annual mean precipitation *d*-excess at sites both upwind and downwind of the Laurentian Great Lakes provides evidence that this high *d*-excess signature is characteristic of mean annual precipitation isotopic composition at downwind sites and therefore may be used to quantify changes in moisture recycling that occur on event to annual time scales in response to past and future climate changes.

1. Introduction

Lake effect precipitation in the Great Lakes region of the United States and Canada affects regional agriculture, ecosystems, and economies (Burnett et al., 2003; Henne et al., 2007; Horton et al., 2014; Norton & Bolsenga, 1993). Increased precipitation with greater flooding may cause reductions in crop yields and force different crops to be planted later in the season (Pryor et al., 2014). Increased precipitation in conjunction with projected temperature increase in the Great Lakes region promotes the growth of blue-green and toxic algae in the lake, harming fish communities, water quality, and habitats while permitting and amplifying impacts of invasive species (Pryor et al., 2014). In addition, lake effect snowstorms are both costly and dangerous to communities (Schmidlin, 1993). For example, the lake effect snowstorm of 17–19 November 2014 left Buffalo, NY, under 65 in. of snow (National Weather Service [NWS] National Oceanic and Atmospheric Administration [NOAA], 2018) with 14 reported storm-associated deaths and over $46 million in damages and emergency response costs (Lam et al., 2014). Costs associated with these snowstorms will increase as infrastructure becomes denser, as flooding increases, and if snowstorms become more frequent or intense (Pryor et al., 2014; Schmidlin, 1993). Detailed modern observations of precipitation in the Great Lakes region during all seasons allow for a strong understanding of how these storm events behave today, aiding predictions of future storm response to today's warming climate, which in turn can inform community adaptation and preparation (Kunkel et al., 2002; Kunkel et al., 2009; Schmidlin, 1993).

Lake effect precipitation events occur as relatively dry air masses move across a warm body of water, pick up moisture, and subsequently pass over topographic highs on land and cool, releasing moisture in the form of rain or snow (Miner & Fritsch, 1997). The evaporation of lake water and reprecipitated moisture, or moisture recycling, sets lake effect events apart from other synoptic snowstorms, which occur when cold and warm air collide, creating a front where clouds form, carrying precipitation from any direction, not necessarily over a lake. Specific meteorological conditions and lake thermal characteristics are necessary for lake effect precipitation events to occur (Hjelmfelt, 1990). Strong lake effect snowstorms occur when air temperatures are below freezing, wind speeds are high, wind direction carries air masses over a lake, and relative humidity is low (Hjelmfelt, 1990; Niziol, 1987). Lake conditions required for these storms include minimal ice cover and a large temperature gradient between warm lake water and cold air (Niziol, 1987; Niziol et al., 1995). Determining the amount of moisture recycling that occurs during NWS-defined lake effect snowstorms provides insights into moisture recycling processes and links to evaporation and atmospheric circulation. Similarly, paleoclimate records of lake effect precipitation spanning intervals longer than the observational record provide an opportunity to address how lake effect precipitation responded to large changes in mean air and lake temperatures (Burnett et al., 2003; Henne & Hu, 2010). Addressing such questions can improve predictions of lake effect precipitation but requires proxies that can be used to reconstruct moisture recycling on appropriate time scales.

Moisture recycling from the Great Lakes also occurs in all seasons, accounting for 4.6% to 15.7% of precipitation downwind of the Great Lakes in the spring through fall (Gat et al., 1994). Even so, meteorological conditions during these seasons may be less conducive to moisture recycling than during winter. For example, lake water in the spring and summer is cooler than the air, limiting lake water evaporation (Miner & Fritsch, 1997). Tracking event-based moisture recycling throughout the year may provide insights into lake-atmosphere interactions under a range of meteorological and lake conditions (Bowen et al., 2012; Burnett et al., 2003; Kristovich et al., 2017; Trenberth, 1999). This, in turn will improve precipitation predictions.

Predictions of moisture recycling in the Great Lakes region are often contradictory. Most existing predictions are based on the correlation between past observed snowfall amounts and temperatures, which are dependent on the time frame and spatial cover examined (Bard & Kristovich, 2012; Burnett et al., 2003; Ellis & Johnson, 2004; Hartnett et al., 2014; Hjelmfelt, 1990; Kunkel et al., 2009; Kunkel et al., 2007; Niziol et al., 1995; Norton & Bolsenga, 1993; Notaro et al., 2015; Suriano & Leathers, 2017; Wright et al., 2013). For example, Burnett et al. (2003) hypothesize that lake effect snowfall has been increasing as ice cover decreases, causing the lake water to remain warm later in the winter, resulting in greater water-air temperature differences. In contrast, Notaro et al. (2015) observed a weaker increase in lake effect snowstorm frequency than reported in previous studies (Burnett et al., 2003; Kunkel et al., 2009). The weaker increase is due to warmer air temperatures, which prevent snow formation, resulting in more lake effect rainstorms than snowstorms in the warmer southern Great Lakes region. Our event-based data set compares precipitation isotopes to meteorological and lake water conditions during precipitation events, with the goal of identifying variables that most strongly influence moisture recycling.

Different isotopologues of water molecules ($^1H_2{}^{16}O$, $^1H^2H^{16}O$, and $^1H_2{}^{18}O$) in precipitation reflect moisture source, transport history, and evaporation and condensation processes (Akers et al., 2017; Dansgaard, 1964; Gat, 1996; Rozanski et al., 1993). Isotopic fractionation occurs throughout the hydrological cycle as water molecules evaporate, condense, and freeze. Equilibrium fractionation occurs between the isotopes of hydrogen (δ^2H) and oxygen ($\delta^{18}O$) during phase changes: Water vapor that condenses into rain preferentially contains the heavier isotopes, ^{18}O and ^2H, while the lighter isotopes remain in the vapor phase. However, kinetic fractionation imparts an additional control on δ^2H and $\delta^{18}O$ during diffusive processes. Molecules with smaller mass ($^1H_2{}^{16}O$ and $^1H^2H^{16}O$) evaporate more readily than do more massive $^1H_2{}^{18}O$ molecules (Dansgaard, 1964), resulting in excess ^2H relative to ^{18}O in the vapor phase and in subsequent precipitation. Deuterium excess (d-excess = $\delta^2H - 8.0 \cdot \delta^{18}O$) provides a measure of mass-dependent kinetic fractionation between water isotopologues. Increased evaporation, stronger winds, and lower relative humidity are conducive to greater kinetic fractionation, which causes vapor, and subsequent precipitation, to have high d-excess (Dansgaard, 1964). Because the Great Lakes have a d-excess of 3.5‰, the d-excess of vapor evaporating from them is higher than that of vapor carried from the Pacific Ocean, Atlantic Ocean, or Gulf of Mexico (Jasechko, Gibson, et al., 2014). Thus, d-excess in vapor and precipitation can be used to track moisture recycling from the Great Lakes.

The effect of moisture recycling from the Great Lakes on regional precipitation isotopes can be quantified by combining observed precipitation d-excess with regional isotopic and atmospheric variables, including temperature and relative humidity (Aemisegger et al., 2014; Pfahl & Sodemann, 2014). Previous studies have found that summertime moisture recycling accounts for up to 16% of annual precipitation downwind of the Great Lakes (Bowen et al., 2012; Gat et al., 1994; Machavaram & Krishnamurthy, 1995). For this

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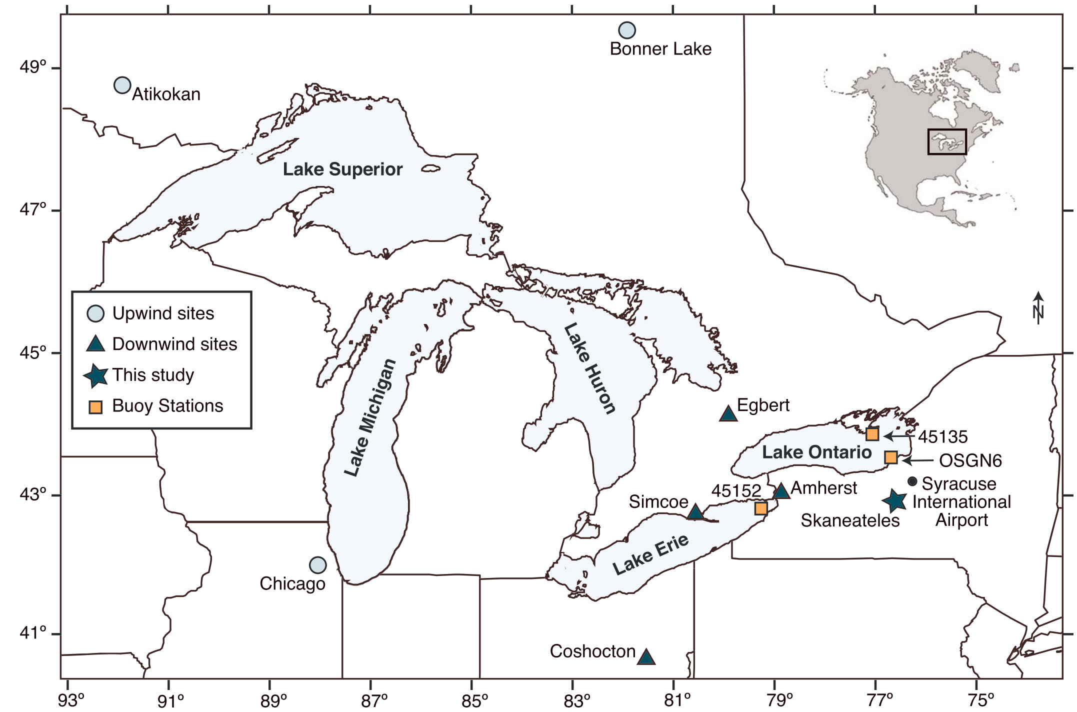

Figure 1. Map of the Great Lakes region including Skaneateles precipitation sampling location (star), Global Network of Isotopes in Precipitation stations upwind (light blue dots), downwind, and Amherst sampling location (dark blue triangles), and other sites where meteorological data were used in the fraction recycled moisture model (orange squares).

study, we apply the calculation used in previous studies to quantify the proportion of recycled moisture contributing to precipitation events in Skaneateles, NY, from April 2015 to February 2018. In order to understand how individual events are integrated over time, we calculate monthly and annual average precipitation isotopes at our study site. We compare these results to previous seasonal and annual studies to analyze how moisture recycling during all seasons has changed over time. We also calculate annual amount-weighted mean *d*-excess at sites throughout the Great Lakes region to examine regional trends in moisture recycling on annual time scales. In addition, we use this event-based, multiyear data set to assess the relationship between water isotopes, lake effect precipitation, and meteorological parameters to understand how and why moisture recycling changes throughout the year in the Great Lakes region. Understanding moisture fluxes from the Great Lakes to the atmosphere in the present at event-based and annual resolutions will provide a useful baseline to compare with past and future changes and will provide guidance for choosing paleoclimate proxies that may be used to reconstruct moisture recycling (Bowen et al., 2012; Henne & Hu, 2010; Xiao et al., 2017).

2. Methods and Approach

2.1. Sample Collection

Precipitation samples were collected in two locations in upstate New York—Skaneateles (42.96°N, 76.43°W) and Amherst (43.00°N, 78.79°W)—in all seasons from April 2015 to February 2018 (Figures 1 and S2 and Tables S3 and S4). Samples were collected in Skaneateles, NY, each morning around 0700 local time using a 4-in.-diameter Stratus All-Weather Rain Gauge with a sun shade and a ping pong ball placed in the funnel to prevent evaporation (Figure S1; Michelsen et al., 2018; Scholl, 2006). Samples were collected using the same setup in Amherst, NY, on a daily to weekly basis. At both sites, liquid precipitation was collected using the funnel and 1-in. cylinder, whereas solid precipitation was collected from the 4-in. cylinder. These locations downwind of Lake Ontario and Lake Erie were chosen for site accessibility. Temperature and rainfall amount or snow water equivalent was recorded at each sample collection. Snow water equivalent data are not available for the winter of 2015–2016. Frozen samples were brought inside to melt in a sealed container before being transferred to a sample vial. We also collected groundwater samples beginning in August 2017 at a well located 6.3 km from the precipitation sampling location in Skaneateles. These samples were collected every 2 weeks, excluding winters. All samples were collected in 4-ml vials, capped, sealed with parafilm, and kept cold until analysis.

Samples are indicative of precipitation from the previous 24-hr period. Because samples were collected at 0700 local time, we compare meteorological parameters from the day before the sample was collected to the isotopic results of each precipitation sample for all further analyses.

2.2. Sample Analysis

Samples were filtered using a 0.2-μm polytetrafluoroethylene filter and were analyzed on Picarro L2130-*i* cavity ring down spectrometer water isotope analyzers at the University of Massachusetts-Amherst and at the University at Buffalo with instrumental precision of 0.5‰ for δ^2H-H_2O and 0.1‰ for $\delta^{18}O$-H_2O for both analyzers. The last three sample measurements were used to calculate the sample mean value and standard deviation. Samples were normalized to the Vienna Standard Mean Ocean Water (VSMOW) scale (‰) and corrected for memory and drift using secondary water isotope standards that were originally normalized to (Vienna Standard Mean Ocean Water 2) VSMOW2, Standard Light Antarctic Precipitation 2 (SLAP2), and Greenland Ice Sheet Precipitation (GISP) primary standards (Geldern & Barth, 2012).

2.3. Recycled Moisture Model

We applied a moisture recycling model developed in previous studies (Bowen et al., 2012; Gat et al., 1994; Machavaram & Krishnamurthy, 1995) to determine the fraction of recycled moisture that contributed to each of the precipitation events in Skaneateles, NY. The input parameters and data sources that we used for this moisture recycling model are listed in Table S1. This model combines the *d*-excess of moisture traversing across Lake Ontario, d_a, with the *d*-excess of surface lake water of Lake Ontario, d_w, and relative humidity, h, to calculate evaporative flux, d_E:

$$d_E - d_a = \frac{d_w - d_a}{1 - h} + 107 \times \theta$$

Daily relative humidity over the lake, h, was acquired from the NOAA National Data Buoy Center (NDBC) OSGN6 on the shore of Lake Ontario (US DOC/NOAA/NWS, 2018). There is no buoy located in the center of the lake that records humidity year-round, so this nearshore buoy was used. The constant, 107, describes the kinetic isotope fractionation during evaporation from the lake (Gat et al., 1994). We use the *d*-excess of Lake Ontario (d_w) surface lake water from Jasechko, Gibson, et al. (2014). We use monthly precipitation isotopes at Egbert, ON, the only site northwest of Lake Ontario with publicly available precipitation isotope data (International Atomic Energy Agency [IAEA]/World Meteorological Organization [WMO], 2018; Figure 1) to determine the *d*-excess of the moisture traversing Lake Ontario (d_a). We calculated d_a using monthly precipitation isotopes from the Global Network of Isotopes in Precipitation (IAEA/WMO, 2018) and monthly temperature data from the Canadian Historical Climate Database (Government of Canada, 2018; http://climate.weather.gc.ca/) and accounted for temperature-dependent fractionation when converting precipitation isotopes to vapor isotopes using the following equations for δ^2H (Majoube, 1971):

$$10^3 \ln\alpha = e^{\left(24.844\left(\frac{10^6}{T^2}\right) - 76.248\left(\frac{10^3}{T}\right) + 52.612\right)}$$

$$\delta^2H_{vapor} = \frac{\delta^2H_{precip} + 1,000}{\alpha} - 1,000$$

We use the following equations for $\delta^{18}O$ (Majoube, 1971):

$$10^3 \ln\alpha = e^{\left(1.137\left(\frac{10^6}{T^2}\right) - 0.4156\left(\frac{10^3}{T}\right) - 2.0667\right)}$$

$$\delta^{18}O_{vapor} = \frac{\delta^{18}O_{precip} + 1,000}{\alpha} - 1,000$$

We are limited to monthly precipitation isotopes values at upwind locations, as these are the only available data. Thus, we use an average monthly d_a value for our model and acknowledge that this is a limitation, as we would ideally use daily upwind d_a values to calculate a more accurate fraction of recycled moisture.

Contributions of atmospheric humidity to lake evaporation are noted by theta, θ, which is described as the parameter with the greatest uncertainty in this model (Bowen et al., 2012; Gat, 1995). This factor was estimated from relative humidity using the following equation (Gat, 1995):

$$\theta = \frac{1-h}{1-h'}$$

where h is relative humidity downwind of Lake Ontario and h' is relative humidity upwind of Lake Ontario. Upwind and downwind relative humidity measurements were accessed for Egbert, ON, from Canadian Historical Climate Database (Government of Canada, 2018) and for buoy OSGN6 from the NOAA National Data Buoy Center (US DOC/NOAA/NWS, 2018), respectively. Daily θ values were calculated for each precipitation sample collected, differing from previous studies that have used a representative constant value or an average monthly constant value. For example, Gat et al. (1994) used a value of 0.88 for the Great Lakes when determining the amount of recycled moisture at a multimonth scale, over summer and fall. Bowen et al. (2012) used monthly values ranging from 0.16 to 1.14 for Lake Michigan for monthly values of moisture contributing to groundwater. Our daily calculation of θ ranges from 0.1008 to 6.3036, with a median value of 0.8958 (one standard deviation of 0.7149 to 1.1001), similar to values in previous publications (Figure S4). The values at the high end of the calculated θ range may result from the use relative humidity measured from a buoy near the downwind lake shore, rather than relative humidity directly over the center of the lake, which is not available, but may have provided a more accurate estimate of the role of humidity in lake evaporation (Bowen et al., 2012). Nevertheless, most of our θ values fall within the range of previous publications.

The fraction of recycled moisture, f_r (Figure 2a), is calculated using the following equation:

$$f_r = \frac{d_s - d_a}{d_E - d_a}$$

where d_s is the *d*-excess for individual samples. A Monte Carlo simulation was performed in MATLAB using this recycling model, incorporating uncertainty of measured parameters where available. This method uses randomness to determine a range of outcomes of fraction of recycled moisture that combines any possible scenario of parameters. We used the one sigma standard deviations for Egbert monthly precipitation δ^2H and $\delta^{18}O$ values, one sigma standard deviation of mean annual Lake Ontario water, and analytical uncertainty of δ^2H and $\delta^{18}O$ for precipitation in Skaneateles to generate 10,000 (chosen because this provides a full estimate of the range of each parameter) randomly distributed possible values for each parameter. These 10,000 values for each parameter were then combined using the equations above to calculate a range of possible values of the fraction of recycled moisture for each precipitation event. We then identified the median fraction of recycled moisture value for each event. We apply this model to all precipitation events occurring in Skaneateles but discuss the fraction recycled moisture results only for events in our data set that cross over Lake Ontario or Lake Erie, which occurs 76% of the time (see section 2.5).

We also ran the model using Chicago, IL, monthly precipitation isotopes (IAEA/WMO, 2018) and Lake Erie lake water *d*-excess (Jasechko, Gibson, et al., 2014), using daily temperature data as the upwind endmember. This model setup provided similar results, in that the same events in Skaneateles, NY, contained a higher fraction of recycled moisture (Figure S3). This suggests that even with different upwind values, the *d*-excess of each event is the main parameter controlling the result of this model, and regardless of other inputs, results in similar patterns of estimated fraction recycled moisture.

We note that crystallization from vapor to solid may impact the *d*-excess of snow samples. The kinetic effect in mixed-phase clouds can cause elevated *d*-excess values at temperatures below −5 °C, unrelated to lake water evaporation (Casado et al., 2016; Jouzel & Merlivat, 1984; Nusbaumer et al., 2017). This effect increases with decreasing temperatures. Using twice-daily radiosonde data at the Buffalo airport (42.94°N, −78.72°W, 184 m above sea level), we determine that 40% of measurements taken over the 3-year study period were associated with temperatures below −5 °C, while 10% of measurements were below −15 °C (National Climatic Data Center (NCDC) NOAA, 2018). We do not have data for the conditions under which precipitation condensed for our samples, and therefore do not account for the kinetic effect in mixed-phase clouds in our data set, but acknowledge that this effect may impact the *d*-excess in our data set. Evidence

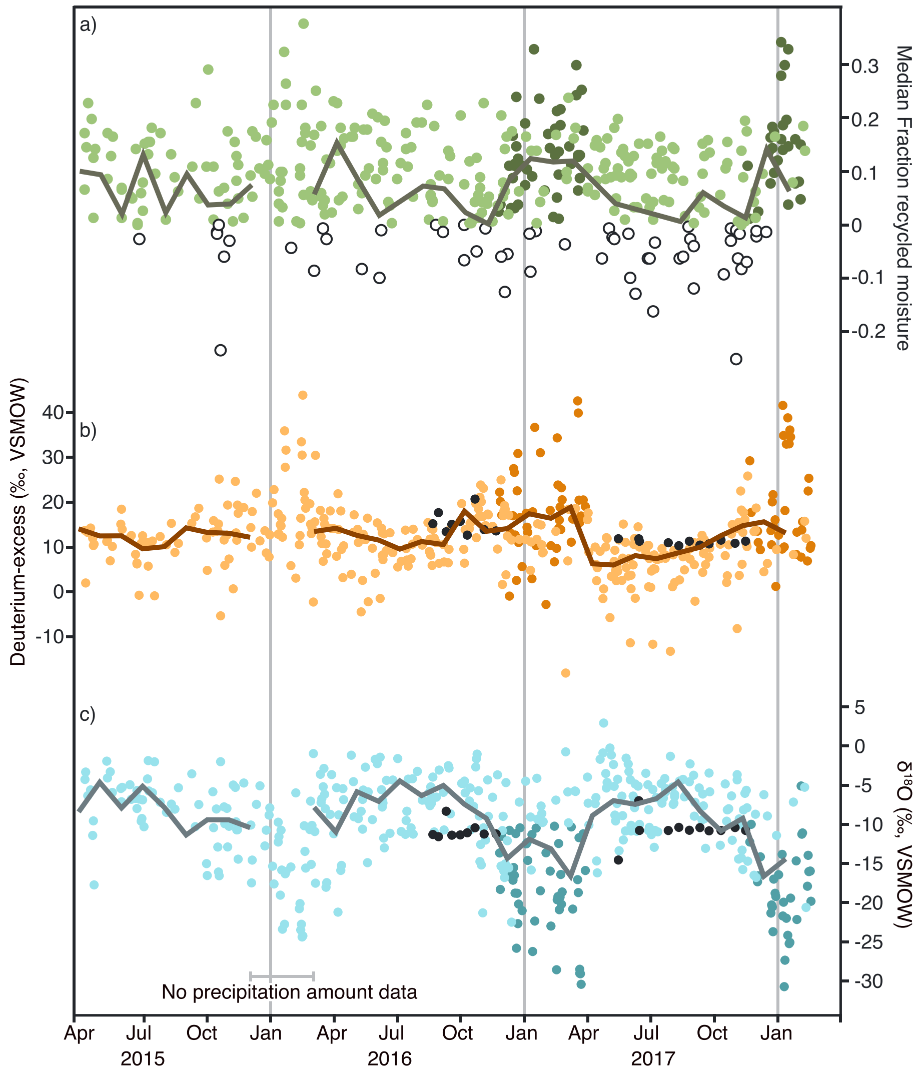

Figure 2. Event-based precipitation isotopes and fraction recycled moisture (f_r) between April 2015 and February 2018 for each precipitation event sampled in Skaneateles, NY. (a) Calculated median f_r. Open circles are samples with negative f_r. (b) *d*-excess and (c) $\delta^{18}O$. Groundwater samples from a well near the precipitation sampling site (black dots). Dark circles are samples that were frozen upon collection (not noted during winter 2015–2016). Solid lines in all panels indicate monthly amount-weighted values; precipitation amount data (in mm water equivalent) were not collected in winter 2015–2016.

within this data set suggests that this kinetic effect may be minimal: Several precipitation events that were not classified as lake effect snowstorms occurred under conditions below −5 °C. Some of these events have a *d*-excess around 10‰, lower than the *d*-excess for events classified as lake effect snowstorms that occurred under similar thermal conditions (Figure 4b). We discuss these results and the kinetic effect in more detail with relevance to our data set in section 4.1.

2.4. Lake Effect Precipitation Events

Lake effect snowstorms in our data set were identified using the U.S. NWS Lake Effect page (NWS NOAA, 2018). The NWS classifies "lake effect snowstorms" as events that snowed 7 in. or more in 12 hr or less. Precipitation samples were collected for 20 of the 25 lake effect snowstorms that occurred during the sampling period. We do not have samples following the NWS-defined lake effect snowstorm events of 18 October 2015, 27 January 2016, 2 February 2017, 6 December 2017, and 8 February 2018. We compare the timing of all precipitation events, including these NWS-identified lake effect snowstorms, with the

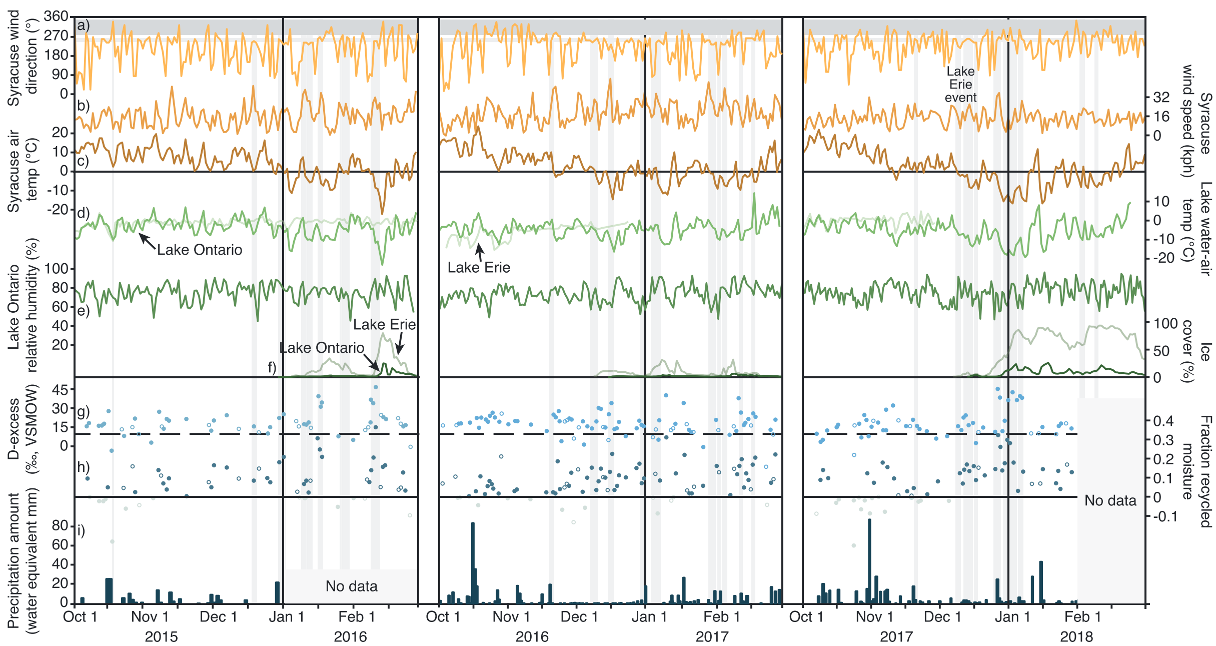

Figure 3. Daily climate and lake parameters compared to calculated fraction of recycled moisture and *d*-excess for events in Skaneateles during winters 2015–2016, 2016–2017, and 2017–2018 (a) Syracuse International Airport wind direction. Horizontal dark gray bar shows a wind direction range of 275–350° (likely direction for snowstorm to Skaneateles from Lake Ontario). Horizontal light gray bar shows a wind direction range of 255–265° (likely direction for snowstorm to Skaneateles from Lake Erie). (b) Syracuse International Airport wind speed. (c) Syracuse International Airport air temperature, solid line at 0°C. (d) Lake water surface temperature and air temperature difference (negative values mean that lake is warmer than air). Data for Lake Ontario (dark lines) from buoy station 45135, data for Lake Erie (light lines) from buoy 45152 (NOAA-GLERL, 2018; U.S. DOC/NOAA/NWS, 2018). (e) Relative humidity at buoy station OSGN6 over Lake Ontario (U.S. DOC/NOAA/NWS, 2018). (f) Percentage ice cover on Lake Ontario (dark lines) and Lake Erie (light lines; NOAA-GLERL, 2018). (g) Skaneateles precipitation *d*-excess; dashed line shows global average *d*-excess, 10‰. Open dots are events that did not cross over Lake Erie or Ontario. (h) Calculated fraction of recycled moisture for each event. Solid black line at 0. Open dots are samples that did not cross over Lake Erie or Ontario. (i) Precipitation amount (mm water equivalent) measured each time a sample was taken. There are no amount data in January and February 2016. Vertical gray bars highlight National Weather Service-defined lake effect snowstorms at Syracuse, NY (NWS NOAA, 2018). VSMOW = Vienna Standard Mean Ocean Water.

fraction of recycled moisture, *d*-excess, and precipitation amount in Skaneateles, NY, and regional meteorological parameters (Figures 3–5). Lake Ontario and Lake Erie ice cover and lake water temperature records are from the NOAA Great Lakes Environmental Research Laboratory (NOAA-GLERL, 2018). Other climate data are from NOAA (U.S. Department of Commerce (DOC)/NOAA/NWS, 2018) and from the Canadian Historical Climate Database (Government of Canada, 2018). Syracuse climate data are from the Syracuse Hancock International Airport weather station (43.11°N, −76.11°W, 128 m above sea level; National Climatic Data Center (NCDC) NOAA, 2018).

2.5. Individual Precipitation Events Throughout All Seasons

Precipitation events from all seasons were sorted based on Syracuse wind direction, which indicates whether the events crossed Lake Ontario, Lake Erie, or neither. Wind direction is northwesterly for the majority of the lake effect storms, as the traversing air mass moves over Lake Ontario and carries snow to the study site. However, wind direction may also be westerly for events in which moisture is brought from Lake Erie to the study site. Precipitation events that fell in Skaneateles whose wind direction ranges from 275° to 350° are classified as lake effect storms from Lake Ontario, whose wind direction ranges from 255° to 265° as lake effect storms from Lake Erie, and all other wind directions as nonlake, meaning that the precipitation event did not cross either lake. Events were sorted into the Lake Erie or Lake Ontario categories if at any time during the day the wind direction fell within one of these ranges. Relationships between precipitation isotopes and meteorological variables were determined for events in each of the three categories using linear regressions (Figure 4). These relationships were determined for all precipitation events occurring throughout the year. There are some events in which Lake Erie water temperatures were not available, and thus, we plot all events for which data are available. We sort all events into warm (March to October) and cold (November to February) months (Figures 4a–4d). There are some events classified within warm months that have an air

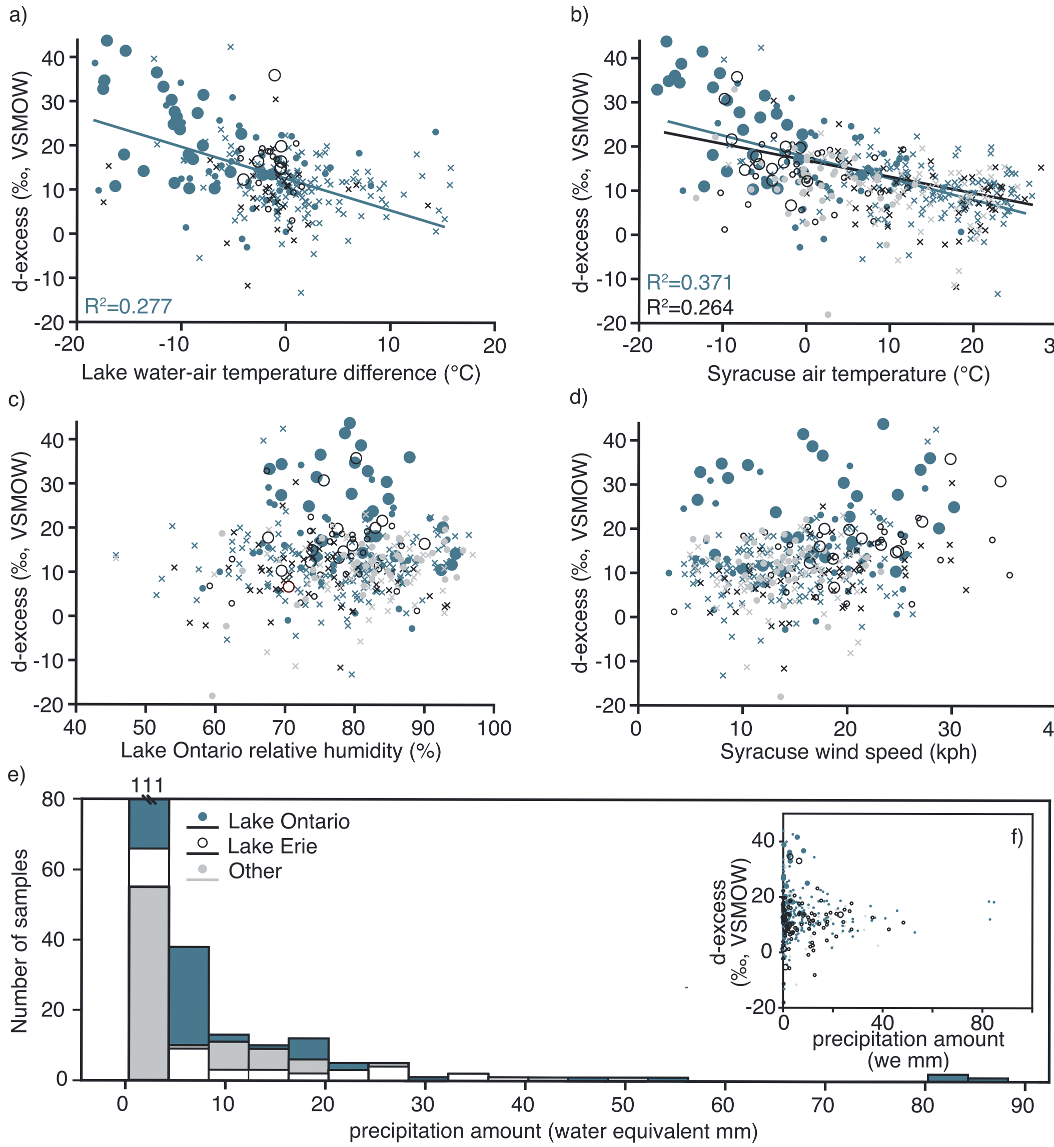

Figure 4. Scatter plots of *d*-excess in Skaneateles, NY, compared to the following regional meteorological parameters for each event: (a) Lake Ontario (or Lake Erie) water and air temperature difference (negative values mean that lake is warmer than air), (b) Syracuse International Airport air temperature, (c) relative humidity at buoy station OSGN6, (d) Syracuse International Airport wind speed, and (f) precipitation amount in Skaneateles, NY. Events grouped by wind direction: Events that crossed over Lake Ontario (dark blue), Lake Erie (white with dark outline), and Other (gray). Large dots are events that coincide with National Weather Service-defined lake effect snowstorms at Syracuse, NY. Warm season (March to October) and cold season (November to February) events are designated by crosses and circles, respectively. (e) Histogram of precipitation amount for each of the three groups listed above. Colors are the same for each group as in panels (a)–(d). Blue and gray lines are linear correlations for events that passed over Lake Ontario and Lake Erie, respectively. VSMOW = Vienna Standard Mean Ocean Water.

temperature below −5 °C, occurring in March. Monthly *d*-excess was calculated for each of the three categories to determine seasonal patterns of *d*-excess. A two-sample *t* test was performed to determine statistical significance between the three groupings listed above for months that had more than three events per grouping (Figure 5a).

2.6. Comparison of *d*-excess Between Sites Upwind and Downwind of the Great Lakes

Whereas event-based precipitation isotope data sets are rare, monthly precipitation isotope data sets are more common (Bowen et al., 2019; IAEA/WMO, 2018). In addition, precipitation isotope proxies (e.g., groundwater, leaf wax δ^2H, and carbonate δ^{18}O) often reflect seasonal or annual averages (Boutt et al., 2019; Bowen et al., 2012; Burnett et al., 2003; Jasechko, Birks, et al., 2014; Shuman et al., 2006). Thus, understanding how the isotopic signature of lake effect events is preserved in records of monthly or annual average

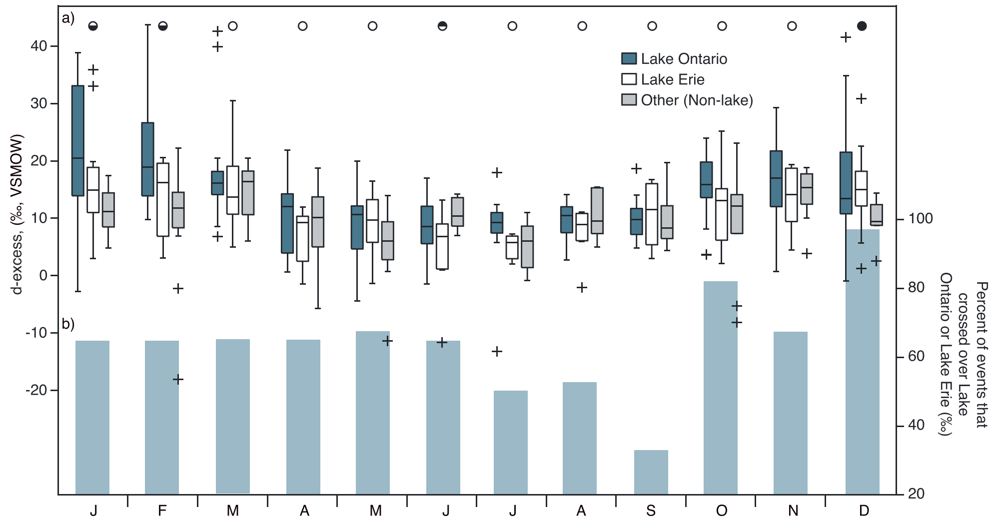

Figure 5. Monthly average *d*-excess for events, sorted by wind direction. (a) *d*-excess values for all precipitation events in Skaneateles, NY, sorted by wind direction at the Syracuse International Airport, NY. For each box plot, middle line designates median *d*-excess, box represents the 25% to 75% quartile range, whiskers represent maximum and minimum values, and outliers are noted by +. Events that crossed over Lake Ontario (dark blue), Lake Erie (white with dark outline), and Other (gray) are also shown. Results of the *t* test along top: Filled-in dots indicate Other (nonlake) storms are statistically different than are Lake Ontario and Lake Erie for that month. Upper half circle indicates Other is statistically different than are Lake Erie storms but not Lake Ontario storms. Lower half circle indicates Other is statistically different than are Lake Ontario storms but not Lake Erie storms. An open dot indicates Other (nonlake) is not statistically different than is either Lake Ontario or Lake Erie. (b) Bar plot indicating the percentage of events in each month that cross either Lake Ontario or Lake Erie. VSMOW = Vienna Standard Mean Ocean Water.

precipitation isotopes is useful to interpret the longer-term average records. We compare precipitation *d*-excess in Skaneateles to precipitation *d*-excess from sites located upwind of the Great Lakes (Bonner Lake, ON; Atikokan, ON; and Chicago, IL) and downwind of the Great Lakes (Coshocton, OH; Egbert, ON; and Amherst, NY; IAEA/WMO, 2018). These upwind and downwind locations were dictated by data availability. Egbert, ON, may be considered both an upwind location and a downwind location because of its location upwind of Lake Ontario and downwind of Lake Huron. Annual amount-weighted precipitation *d*-excess was calculated for each of these locations for which precipitation amount and isotope values were available, using Global Network of Isotopes in Precipitation isotope data (IAEA/WMO, 2018) and the Canadian Historical Climate Database for precipitation amount (Government of Canada, 2018; Figure 6). Only years that had 9 months or more of available data were used in the annual averages. Missing months were random, so there is minimal seasonal weighting in these calculations.

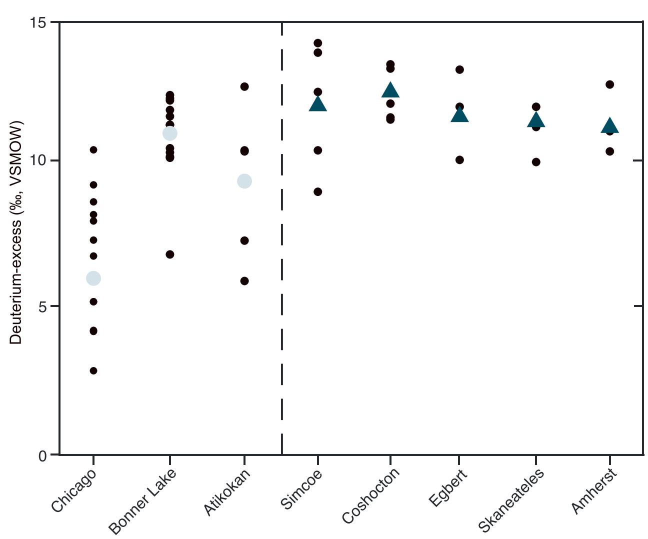

Figure 6. Annual average amount-weighted precipitation *d*-excess of sites upwind (light blue dots) and downwind (dark blue triangles) of the Great Lakes (IAEA/WMO, 2018). Black dots represent individual years, and colored dots and triangles represent mean of all years at a given site. VSMOW = Vienna Standard Mean Ocean Water.

3. Results

Skaneateles precipitation from April 2015 to February 2018 had δ^2H and $\delta^{18}O$ values ranging from −235.9‰ to 24.2‰ and −31.6‰ to 3.0‰, respectively (Figure 2c). A total of 408 precipitation samples was collected during this time with no large gaps in sampling, and thus, amount-weighted averages are representative of monthly and seasonal average isotope values. Relatively ^2H- and ^{18}O-depleted values are observed in winter months, defined here as November through February, with lake effect snowstorms occurring during these months throughout the Great Lakes region (NWS NOAA, 2018) of all collection years. Winter precipitation events have an average and one sigma standard deviation of −83.1‰ ± 21.6‰ for δ^2H and −12.2‰ ± 2.8‰ for $\delta^{18}O$ (Figure 2c). Summer (June through August) precipitation events have an average and one sigma standard deviation of −47.7‰ ± 22.1‰ for δ^2H and −6.9‰ ± 2.9‰ for δ^{18}O (Fig. 2c). *d*-excess values are higher in the winter months (14.6‰ ± 1.9‰) than in the summer months (7.6‰ ± 5.4‰; Figure 2b).

Two hundred precipitation samples were collected in Amherst, NY, during our study period. These precipitation samples had δ^2H and δ^{18}O values ranging from −194.7‰ to 7.6‰ and −25.9‰ to 2.7‰, respectively. The *d*-excess of these samples ranges from −13.8‰ to 37.9‰ with higher *d*-excess during winter months (Figure S2). We do not examine event-based isotopes and fraction of recycled moisture in the Amherst, NY, data set due to the coarse sampling resolution.

Calculated event-based fraction recycled moisture (f_r) for Skaneateles ranges from 0.37 to −0.26 (Figure 3). Nineteen percent of events have negative fraction recycled moisture, which is not physically possible. These negative values may be due to several factors, including the different resolutions of data inputs into the model. For example, average monthly vapor isotope values at Egbert, the site upwind of Lake Ontario, may not be indicative of the actual weather parameters occurring during each precipitation event during that month. Finally, we calculate the fraction of recycled moisture for all precipitation events. The events with a negative fraction of recycled moisture generally occur when air mass trajectories do not cross over Lake Ontario or Lake Erie (Figures 4b and 4j), when the model is not representative of the weather conditions at that time. Events that did pass over Lake Erie or Lake Ontario but have a negative fraction of recycled moisture may be associated with periods when there was ice cover, causing no moisture recycling. We therefore exclude negative fraction of recycled moisture values from further analyses.

Monthly amount-weighted fraction of recycled moisture was calculated using daily precipitation amount measurements (mm water equivalent) and the nonnegative median fraction of recycled moisture values from the Monte Carlo simulation (Figure 2a). Monthly median amounted-weighted values range from 0.04 to 0.17 f_r. Higher fraction of recycled moisture occurs in winter months than in summer months (Figure 2a) and during lake effect snowstorm events (Figure 3b).

We compared meteorological parameters hypothesized to influence lake effect snowstorms and precipitation *d*-excess from each event in order to address which factors correlate to precipitation isotopes in our data set. There is a strong correlation between the lake-air temperature difference ($R^2 = 0.277$) and Syracuse air temperature ($R^2 = 0.371$) for events that crossed over Lake Ontario (Figures 4a and 4b). Events that crossed Lake Erie show the same strong correlation with Syracuse air temperature ($R^2 = 0.264$). Higher *d*-excess occurs during winter months when air temperature is low (typically below 0 °C) and when the lake water-air temperature is low (Figures 4a and 4b). There is no relationship between relative humidity or wind speed and *d*-excess in warm or cold months (Figures 4c and 4d).

4. Discussion

4.1. Winter Lake Effect Snowstorms

Our results demonstrate that winter precipitation events that pass over Lake Ontario or Lake Erie often have a unique isotopic fingerprint, implying greater moisture recycling. Precipitation from NWS-defined lake effect snowstorms exhibits higher *d*-excess and fraction of recycled moisture than does precipitation from events not identified as lake effect snowstorms (Figures 3b and 3c). The *d*-excess of NWS-defined events ranged from −5.3‰ to 43.9‰ with a mean of 21.2‰, whereas events that were not defined as lake effect snowstorms by the NWS had a *d*-excess range of −18.1‰ to 34.4‰ and a mean of 13.5‰. There are 12 events with high *d*-excess and fraction of recycled moisture that do not coincide with NWS-defined lake effect snowstorms in Syracuse, NY, including events on 16 January 2017 and 8 November 2017 (see section 4.1.1 for further details).

We also observe lake effect snowstorms from Lake Erie that caused snowfall in Skaneateles. Lake effect snowstorms that occurred during the first half of December 2017, during a prolonged period of westerly winds in Syracuse, NY (Figure 3a), would have carried moisture that passed over Lake Erie. The Lake Erie-derived precipitation exhibits slightly lower *d*-excess and lower fraction of recycled moisture than do most Lake Ontario lake effect storms during our study period.

All of the NWS-defined lake effect storms in our data set have meteorological parameters and lake conditions conducive to a large amount of moisture recycling. These conditions include decreased air temperature, a large air-to-lake temperature difference, minimal ice cover, increased wind speed, and wind direction crossing the lake. For example, the NWS-defined lake effect storm on 29 December 2017 has wind speeds around 32 km/hr, lake and air temperature difference of about 10 °C, and air temperatures around −10 °C. High *d*-excess and fraction of recycled moisture of precipitation in Skaneateles, NY, coincide with independent definitions of lake effect storms, validating the use of *d*-excess as a signature for moisture recycling and supporting the use of the fraction recycled model at an event-based scale.

d-excess for all precipitation events sorted by wind direction shows that during winter months, *d*-excess is higher for those events that cross over Lake Erie or Ontario than for those that cross over neither lake (Figure 5a). However, the *d*-excess of all events, regardless of source, is greater in winter than during the other seasons (National Climatic Data Center (NCDC) NOAA, 2018). Higher winter precipitation *d*-excess is likely due to the kinetic fractionation occurring during crystal formation below −5 °C (Casado et al., 2016; Nusbaumer et al., 2017). Even so, the *d*-excess of events that cross Lake Ontario is statistically different than that of storms that did not cross the lake during winter months. We attribute the higher *d*-excess of winter events that cross Lakes Ontario and Erie to moisture recycling that occurs as air passes over these water bodies.

4.1.1. Precipitation Events Not Classified as Lake Effect Storms

Our results indicate that precipitation *d*-excess in the Great Lakes region may be an independent tool to identify moisture that is evaporated off of the Great Lakes that is not identified by the NWS as a lake effect snowstorm. A dozen events that did not fit the NWS criteria for lake effect snowstorms did exhibit many of the meteorological and isotopic characteristics of lake effect snowstorms (e.g., the storm on 28 October 2016 when air temperatures dropped to near 0 °C, wind passed over Lake Ontario, and precipitation in Skaneateles had high *d*-excess; Figure 3). These events (e.g., 16 January and 8 November 2017) contained high *d*-excess and up to 32% recycled moisture from Lake Ontario or Erie but are not classified as an NWS-defined lake effect snowstorm in Syracuse, NY (light gray bars in Figure 3). Events that contain large amounts of recycled moisture from the Great Lakes may not meet the threshold to be classified as a “lake effect snowstorm” due to one of several reasons:

1. Air temperatures were too warm to allow freezing, resulting in “lake effect rainstorms.” Our record suggests that with the exception of early season storms of 18October 2015 and 19 November 2016, when mean daily air temperatures were 6.6 and 6.7 °C and falling, NWS-defined lake effect snowstorms occur when air temperature is below freezing. We estimate that there were six winter lake effect rain events during our record (Figure 3). These rainstorms were identified based on events whose air temperature was greater than 0 and all the other meteorological parameters such as wind speed, relative humidity, and the air-lake temperature difference were similar to those of NWS-defined lake effect snowstorms. An example of a lake effect rainstorm is the precipitation event of 10 November 2015, when *d*-excess was 24.7‰, the fraction of recycled moisture was 0.15, and air temperature was 9.0°C. Our data demonstrate that precipitation isotopes can be used to track all precipitation with high fraction of recycled moisture, regardless the phase. The presence of lake effect rainstorms in our record implies that as air temperatures rise in the Great Lakes region, lake effect snowstorm frequency may decline, but lake-derived moisture may continue to fall as rain in this region. Assessing whether lake effect snow has been, and will continue to, transition to lake effect rain will be important for planning and adaptation to future climate changes.
2. Precipitation is sourced from the Arctic, causing higher precipitation *d*-excess than precipitation from the North Atlantic (Sjostrom & Welker, 2009). Incursion of Arctic precipitation into the Great Lakes region occurs regularly but may become more frequent as the polar vortex weakens, causing an increase in northerly storm tracks, carrying Arctic moisture with high *d*-excess to this region (Puntsag et al., 2016).
3. Less than 7 in. of snow fell, making the event smaller than the NWS definition.

Our data demonstrate that *d*-excess may be useful to track moisture recycling in the Great Lakes region, even during events that do not meet NWS criteria for lake effect snowstorms. Furthermore, moisture evaporated from the Great Lakes forms a large fraction of total precipitation falling in the region, even during minor precipitation events.

4.1.2. Meteorological and Lake Water Parameters Correlated With Moisture Recycling

The relationship between meteorological and lake water parameters and event-based precipitation *d*-excess may provide insights into which parameters influence moisture recycling, thus aiding predictions of how lake-atmosphere interactions may change in a warming climate. We find that for events that pass over Lake Erie or Ontario, *d*-excess and the fraction of recycled moisture tend to be highest when two parameters are more negative: the lake water-air temperature difference and air temperature (Figures 3 and 4). A larger gradient between lake surface and air temperature would allow for increased evaporation of lake water, increasing *d*-excess (Campbell & Steenburgh, 2017; Cappa et al., 2003; Pfahl & Sodemann, 2014). The majority of NWS-defined lake effect snowstorms in our record correspond to sharp increases in the lake-air temperature difference and have high *d*-excess, an average of 21.3‰ ± 10.9‰ (Figures 3d and 3g). In general, *d*-excess is higher for NWS-defined lake effect snowstorms and when lake water air-temperature difference is greater, supporting the concept that evaporation increases when the lake water-air temperature difference is large.

d-excess is strongly correlated with air temperature for events that pass over Lake Erie or Ontario, increasing relatively linearly as air temperature decreases (Figures 3c, 3g, and 4b). This correlation indicates that *d*-excess is strongly influenced by moisture recycling. There is no relationship between the *d*-excess of the non-lake events and air temperature, further suggesting that air temperature influences moisture recycling and *d*-excess but does not impact the *d*-excess of events that do not interact with the lakes. The majority of NWS-defined lake effect snowstorms occur at temperatures below 0°, further indicating that moisture recycling plays a large role at low temperatures.

We would expect low relative humidity over Lake Ontario to lead to increased moisture recycling, as previously observed during lake effect storms (Benetti et al., 2014), in turn resulting in a higher *d*-excess of precipitation. There appears to be little correlation between *d*-excess and relative humidity for any of our events (Figures 3e, 3g, and 4c). NWS-defined lake effect snowstorms occur over a range of relative humidity, 62% to 95%, further indicating that relative humidity does not have a strong influence on moisture recycling. The lack of correlation between *d*-excess and relative humidity, contrary to what we would expect, for events that pass over Lake Erie or Ontario may be because daily average relative humidity is not necessarily representative of the interval when moisture recycling was occurring. In addition, relative humidity was measured at a buoy on the southern side of Lake Ontario, possibly downwind of the main region of moisture recycling.

We may expect to see a relationship between wind speed and *d*-excess, as increased wind speed may allow for greater flux of heat and moisture from the lake surface to the atmosphere (Kunkel et al., 2002). For events that pass over Lake Erie or Ontario, there is no correlation between *d*-excess and wind speeds in Syracuse, NY (Figures 3b, 3g, and 4b). NWS-defined lake effect snowstorms have a range of wind speeds from 3 to 34 km/hr, also indicating that wind speed is not a major factor in moisture recycling.

We also investigate whether increased moisture recycling results in more precipitation per event. *d*-excess values show no strong relationship with water equivalent precipitation amount (Figures 3g, 3i, 4e, and 4f), indicating that the isotopic composition and fraction of recycled moisture are independent of the total amount of precipitation for a given lake effect event. This finding suggests that moisture recycling and therefore the *d*-excess of these events cannot serve as an indicator for total precipitation amount.

Ice cover can influence moisture recycling by inhibiting lake-atmosphere interactions when the lake freezes over. Lake Ontario rarely exceeds 25% ice cover (Figure 3f; NOAA-GLERL, 2018), meaning that we cannot assess whether ice cover exerts a strong role on lake effect snowfall at this site. As expected, increasing ice cover on Lake Ontario does not correlate with NWS-defined lake effect snowstorm occurrence or with events with high *d*-excess in our record. Ice cover over Lakes Erie, Huron, and Superior may show a stronger correlation with the occurrence and strength of lake effect storms, because these lakes frequently freeze over completely between January and March (NOAA-GLERL, 2018). For example, the series of lake effect snowstorm events that occurred in December 2017 occurred prior to Lake Erie ice concentration increasing to almost 100% (Figures 3f–3h). Thus, while ice cover may play an important role in moisture recycling, we cannot fully assess the impact of ice cover using this data set.

Event-based precipitation *d*-excess provides a means to determine the main meteorological parameters that influence large moisture recycling events at a site downwind of the Great Lakes. Temporally consistent correlations between the *d*-excess of precipitation in Skaneateles and the lake water-air temperature differences and air temperature suggest that these parameters may influence the amount of moisture recycled during lake effect precipitation events. Inconsistent with previous hypotheses regarding the parameters that influence moisture recycling, our results show that *d*-excess is not correlated with relative humidity, wind speed, or total precipitation amount, suggesting that these parameters are less important than lake and air temperature during these events. Ice cover concentration appears to exert little control on Lake Ontario storms, as this lake rarely freezes over. Determining lake conditions and meteorological parameters influence on event-based isotopes allows for a better understanding of seasonality patterns of *d*-excess in the Great Lakes region.

4.2. Seasonality of *d*-excess and Moisture Sources

This event-based data set demonstrates that large lake water-air temperature contrasts and low air temperatures coincide with most NWS-defined lake effect snowstorms and with events that have higher precipitation *d*-excess, indicating greater moisture recycling. This agrees with previous research that suggests that seasonality in the Great Lakes region influences the production of lake effect snowstorms, as conditions conducive to moisture recycling occur more frequently during late fall and winter (Norton & Bolsenga, 1993). This finding would suggest that moisture recycling is less likely to occur in warmer conditions and when the lake water temperature is similar to or cooler than air temperature. Long-term increases in mean air and lake temperatures may influence the seasonal timing of lake effect events and whether they fall as rain or snow (Bolsenga & Norton, 1993). If temperatures remain high longer into the fall and winter seasons, the Great Lakes may have longer ice-free seasons (Brown & Duguay, 2010; Wright et al., 2013), causing lake effect storms to occur later in the winter (Miner & Fritsch, 1997). Using our multiyear event-based data set, we are able to address whether and how much moisture recycling occurs during warmer seasons (Figure 2).

We establish that NWS-defined lake effect snowstorms that pass over the Great Lakes during winter tend to have higher *d*-excess and greater moisture recycling than do winter events that do not pass over the Great Lakes (Figure 3g and section 3). In contrast, from April to September, precipitation *d*-excess is close to 10‰, the global average, for all three wind direction groups (Figures 2b and 5). This relatively low *d*-excess suggests that even for air masses that pass over the Great Lakes, there is little moisture recycling occurring from April to September. In addition, there are fewer events during the summer months that cross either Lake Ontario or Lake Erie (Figure 5b and Table S2). This change in wind direction has previously been linked to an observed seasonal shift in the dominant moisture sources in the Great Lakes region: There is slightly more moisture from the Gulf of Mexico during summer months and greater moisture from the Arctic during winter months (Sjostrom & Welker, 2009). The moisture source shift is likely linked to seasonal changes in atmospheric circulation in the Northern Hemisphere (Barnston & Livezey, 1987). Less moisture recycling from the Great Lakes occurs during spring, summer, and early fall events, likely because meteorological and lake conditions are not conducive to evaporation. Often during spring and summer months, the lake water is colder than the air, limiting evaporation as air masses pass over the Great Lakes. Our event-based *d*-excess results indicate that moisture recycling does not contribute much moisture to precipitation downwind of the Great Lakes during nonwinter events.

Previous studies examining precipitation isotopes from June 1992 to February 1993 CE and from February 2008 to August 2009 CE have estimated mean summer (June–October) and mean annual moisture recycling from Lake Michigan (Bowen, 2010; Machavaram & Krishnamurthy, 1995). These studies found that 9% to 16% of summer precipitation and that 10% to 18% of annual precipitation were recycled from Lake Michigan (Bowen et al., 2012; Machavaram & Krishnamurthy, 1995). Using IAEA/WMO precipitation isotopic data, Gat et al. (1994) found that evaporation of the Great Lakes contributes between 4.6% and 15.7% of atmospheric moisture downwind during summer and autumn. We integrate our event-based fraction of recycled moisture into amount-weighted mean seasonal values, facilitating comparison to previous studies. We integrated all events that cross Lake Erie or Lake Ontario, excluding those with a negative fraction of recycled moisture. Summer (June–October), annual, and winter (November–February) amount-weighted average fraction recycled moistures in Skaneateles are 8.9%, 9.9%, and 12.1%, respectively. We conclude that summer (June–October) moisture recycling has remained about the same over the past two decades. Long-term studies of precipitation isotopes in a single location are needed to assess this conclusion of whether moisture recycling changes over time. Even so, these seasonally integrated fraction of recycling moisture data further supports the fact that a warming climate will most strongly influence winter moisture recycling.

4.3. Annual Average *d*-excess

Precipitation isotope data are publicly available for Chicago, IL; Bonner Lake, ON; Atikokan, ON; Simcoe, ON; Coshocton, OH; and Egbert, ON in the Great Lakes region, spanning various years from 1960 to 2010 CE (IAEA/WMO, 2018). Average amount-weighted *d*-excess at each of these sites (Figures 1 and 6) indicates that when the *d*-excess of events are integrated together through a year, the high *d*-excess signature of lake effect precipitation is preserved for sites located downwind of the Great Lakes. Mean annual amount-weighted precipitation *d*-excess at upwind sites ranges from 5.9‰ to 11.0‰ (Figure 6). The highest values for a site upwind of the Great Lakes are at Bonner Lake, Ontario, which is farther north and likely receives more high-*d*-excess Arctic precipitation (Kopec et al., 2016; Sjostrom & Welker, 2009) than the other sites. Sites downwind of the Great Lakes have annual amount-weighted precipitation *d*-excess ranging from 11.2‰ to 12.5‰ (Figure 6). The annual amount-weighted *d*-excess using each year for all upwind sites is statistically lower than that for the downwind sites ($p < 0.05$ according to a two-sample t test). Groundwater samples, which reflect winter biased precipitation signals (Jasechko, Birks, et al., 2014), from the lower peninsula of Michigan also have high *d*-excess, indicating greater fraction of recycled moisture on the western side of the peninsula, closer to Lake Michigan (Bowen et al., 2012). The similarity between *d*-excess in our event-based data set, averaged over seasonal and annual scales, and that of previous seasonal and annual studies illustrates that the high *d*-excess of lake effect precipitation events are preserved, even when precipitation *d*-excess is measured at a lower temporal resolution. This therefore suggests that annual mean precipitation *d*-excess can be used to infer the fraction of recycled moisture at sites downwind of the Great Lakes. Dual-isotope (δ^2H and δ^{18}O) proxy records at sites downwind of the Great Lakes may therefore provide insights into prehistoric spatiotemporal patterns of moisture recycling, including during time periods that were relatively warm (Marsicek et al., 2018). Moreover, spatiotemporal patterns of moisture recycling in the Great Lakes region during the modern period of rapid change will be elucidated by continued sampling at our study sites and would be supported by more continuous, publicly available precipitation monitoring sites in the region.

5. Summary

Lake effect snowstorms play an important role in the ecological, economic, and climate systems in the Great Lakes region. Some studies suggest that lake effect storms will fall as rain in the future, thus decreasing the immediate impact on municipalities downwind of the Great Lakes but potentially impacting snow-adapted ecosystems (Henne et al., 2007). Large lake effect events in Skaneateles, NY, downwind of the Great Lakes have a distinct high *d*-excess signature, with an average *d*-excess 21.3‰ ± 10.9‰. Comparing these events to the meteorological parameters that caused them provides an opportunity to better understand spatial and temporal patterns in modern-day lake effect storms during all seasons. Our new 3-year event-based precipitation isotope record downwind of Lakes Ontario and Erie indicates that NWS-classified lake effect snowstorms are more strongly impacted by air temperature and the lake water and air temperature difference than by lake ice cover, wind speed, and relative humidity. This data set indicates that *d*-excess can be used to identify lake effect precipitation events that do not meet the NWS criteria for lake effect snowstorms. We also find that the high *d*-excess signature is preserved in the seasonal and annual integration of precipitation isotopes both at our study site and at other sites throughout the Great Lakes region. Annual amount-weighted *d*-excess of precipitation at sites downwind of the Great Lakes is statistically higher than the *d*-excess of upwind locations, suggesting that the unique *d*-excess signature of lake effect snowstorms should be preserved in precipitation isotope proxy records. Records of precipitation δ^2H and δ^{18}O may therefore be used to understand trends in moisture recycling in the Great Lakes region both today and in the ancient past, providing a tool to better understand how lake effect precipitation will change in the future.

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