Using Stable Water Isotope Measurements to Determine Lake Michigan Evaporation Influence on Atmospheric Moisture

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Introduction

- The Great Lakes region provides energy and moisture to fuel seasonal convective storms and lake-effect snow (Sharma, et al. 2018).
- Estimates of the Great Lakes influence downwind have been constructed using water isotopes and the Craig Gordon Model (Equation 1), but there is some uncertainty about how large the kinetic fractionation (ε_k) is in this environment.
  - Gat, et al. (1994) found ~5.7-9.5% of the atmospheric water vapor downwind of the lakes is from lake evaporation using ε_k = 14.2‰ $\delta^{18}O$ and 12.5 ‰ δD (Lake ε_k).
  - Xiao, et al. (2018) found ~7.4% when using the Lake ε_k and ~16.8% when using the ocean ε_k parameterization (ε_k = 6.2‰ $\delta^{18}O$ and 5.5‰ δD).
- The difference between the two fractionation factors may be partially due to a lake self-influence parameter, based on humidity, turbulence, and where the atmosphere was measured (Xiao, et al. 2018).
- To better constrain downwind Great Lakes influence, aircraft measurements of atmospheric water vapor isotopes around Lake Michigan were made.

Objectives:

- Measure the gradient of H_2O_v and isotopic values across upwind to downwind lake influence gradients to test the isotopic predictions of the Craig-Gordon model of evaporation.

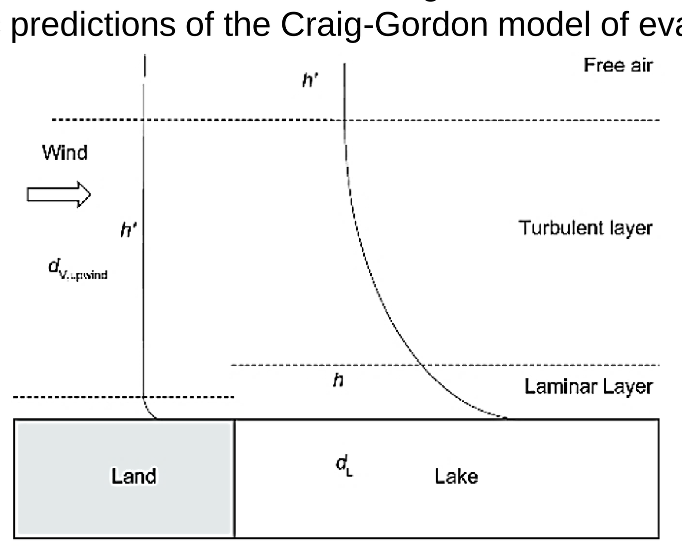

Figure 1. Conceptual diagram of lake influence from Xiao, et al. (2018).

Materials and Methods

$$\delta_E = \frac{a_{eq}^{-1}\delta_L - h\delta_A - \varepsilon^* - \varepsilon_k(1-h)}{(1-h) + 10^{-3}(1-h)\varepsilon_k}$$

Equation 1. Craig and Gordon Model (Xiao et al. 2016). This equation was created to explain the isotopic composition of evaporation (δ_E) in oceans. Parameters include equilibrium fractionation (α_{eq}), the isotopic value of the lake and atmosphere (δ_L and δ_A), relative humidity (h), and a kinetic fractionation factor (ε_k). This equation parameterizes ε_k as a factor of wind speed .

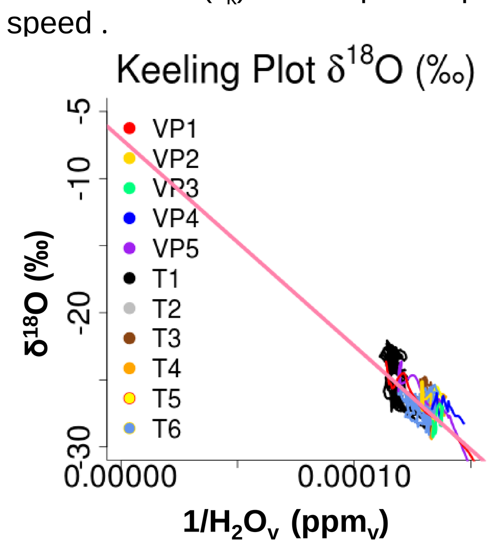

Figure 2. (a) Example Keeling Plot for Flight 4.Keeling Plot intercepts are an estimate of δ_E when it is assumed that there are two sources and the upwind value doesn't change significantly over time. and . Ordinary Least Squares regression and data screening based on a height 500 m, wind direction, and CO_2 were used (Pataki et al, 2003).

Flights were completed using the Purdue University Airborne Laboratory for Atmospheric Research (ALAR), a modified Beechcraft Duchess aircraft.

- Best Air Turbulence (BAT) Probe measures winds and temperatures
- Picarro CO_2 /CH_4/H_2O Cavity Ringdown Spectroscopy analyzer
- Los Gatos Research (LGR) 1 Hz Triple Water Vapor Isotope Off-axis Integrated Cavity Output Spectroscopy analyzer
- Flight plans based on many factors, including weather, safety, and aircraft availability

Results

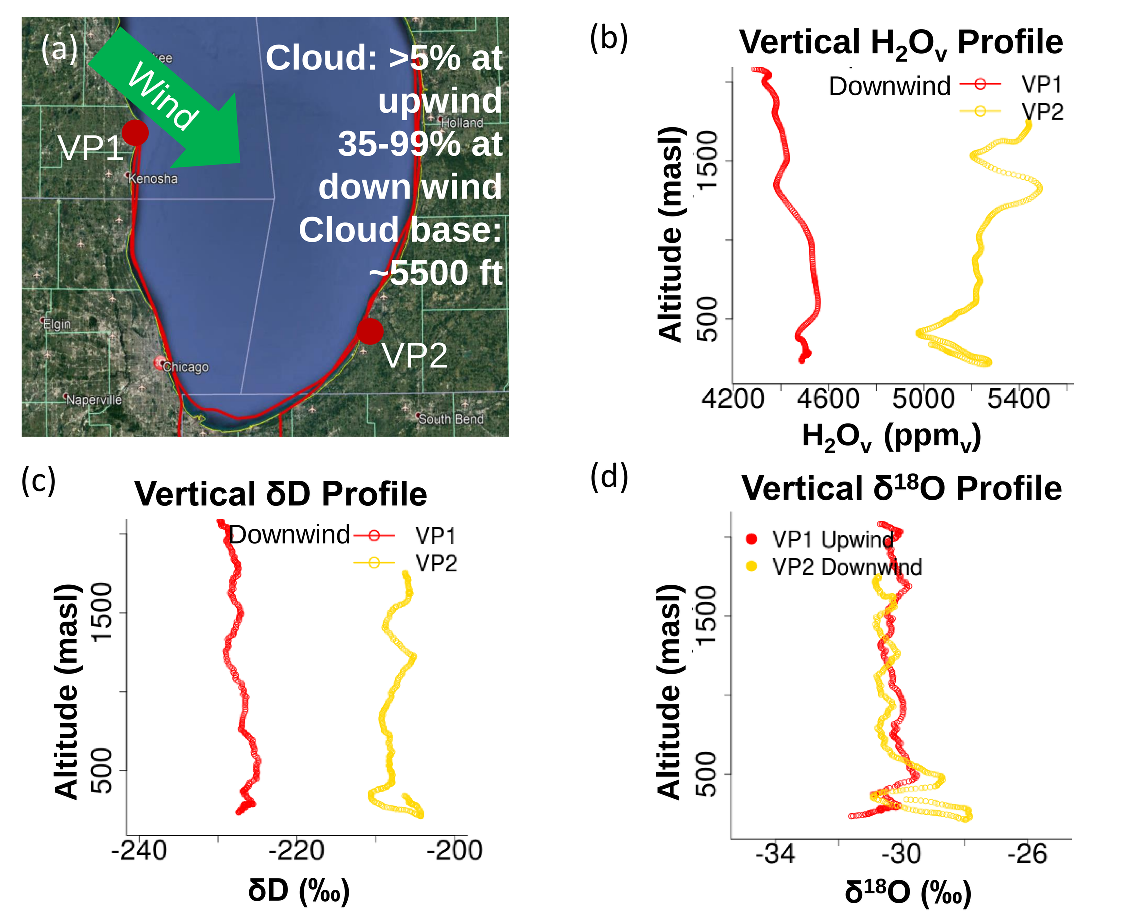

Figure 3. (a) Map of flight 2 path Monday, October 17, 2018. Flight occurred from approximately 11am to 3:30pm local time (EDT). (b) Two Vertical Profiles (VP's) indicate change in (b) water vapor change and (c) deuterium isotopes across the lake. (d). The VPs converge in $\delta^{18}O$ space above ~500 masl, but diverge nearer to the surface.

Table 1. Average parameters for flight days (in parentheses) and ranges for Monte Carlo simulations.

Flight Parameters			
	Flight 2 10/17	Flight 4 10/27	Flight 5 10/29
Time (UTC)	1600 to 1900	1600 to 2000	1800 to 2000
Air Temperature (°C)	6.1-8 (6.68)	9.6-10.9 (10.25)	9-11 (9.84)
H_2O Temperature (°C)	(12.20)	(12.41)	(9.53)
RH with respect to air (%)	52-68 (60.29)	63-70 (66.83)	40- 71 (66.4)
RH with respect to lake surface (%)	25-52 (42)	50-65 (58)	40-70 (67.88)
Wind Speed (m/s)	5.9-8.9 (7.63)	3-4 (3.13)	0.70 to 6.2 (3.90)
H_2O range (ppm)	4,400 to 5,500	5,500 to 9,000	4,000 to 9,500
δD Atmosphere	-230 to -190 (-225)	-220 to -180 (-200)	-205 to -170 (-190)
$\delta^{18}O$ Atmosphere	-34 to -25 (-30)	-30 to -24 (-29)	-28 to -22 (-26)
Kinetic Fractionation ε_k δD	2-3.5	5-6 (5.54)	5-6 (5.405)
ε_k $\delta^{18}O$	2.5-4	6-7 (6.28)	6-7 (6.129)
Equilibrium Fractionation α_{eq} δD	(1.10230) ± 0.001	(1.09734) ± 0.001	(1.09790) ± 0.001
α_{eq} $\delta^{18}O$	(1.01103) ± 0.0001	(1.01068) ± 0.0001	(1.01072)±0.0001
δ_E δD CG	-100.48 ± 16.48	-52.94 ± 20.95	-100.20 ± 13.52
δ_E δD KP intercepts (Adjusted R^2)	-169.1 (0.69)	-36.0 (0.73)	-143.0 (0.86)
δ_E $\delta^{18}O$ CG	-11.682 ± 3.263	-8.219 ± 3.497	-12.405 ± 3.925
δ_E $\delta^{18}O$ KP intercepts (Adjusted R^2)	-23.98 (0.80)	-7.0 (0.70)	-28.21 (0.14)
d-excess CG	-7.0 ± 18.1	9.72 ± 25.46	-0.960 ± 21.73
d-excess KP	22.9	22.1	82.7

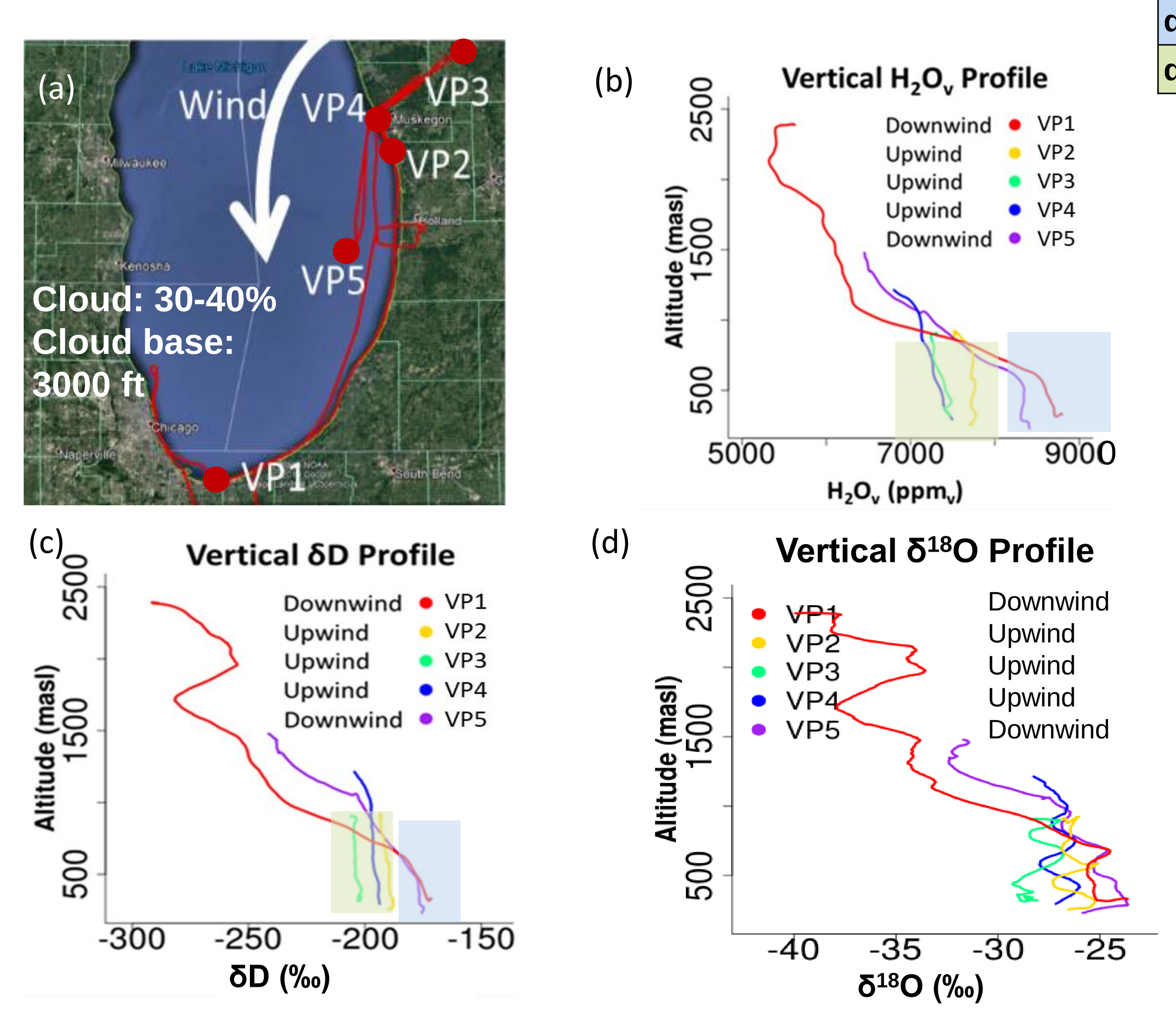

Figure 4. (a) Map of flight 4 path Monday, October 27, 2018. The flight occurred from approximately 12 pm to 5pm local time (EDT). (b) Indicates both horizontal and vertical water vapor gradients. This gradient is also evident in δD space (c) but is more variable in $\delta_{18}O$ space (d).

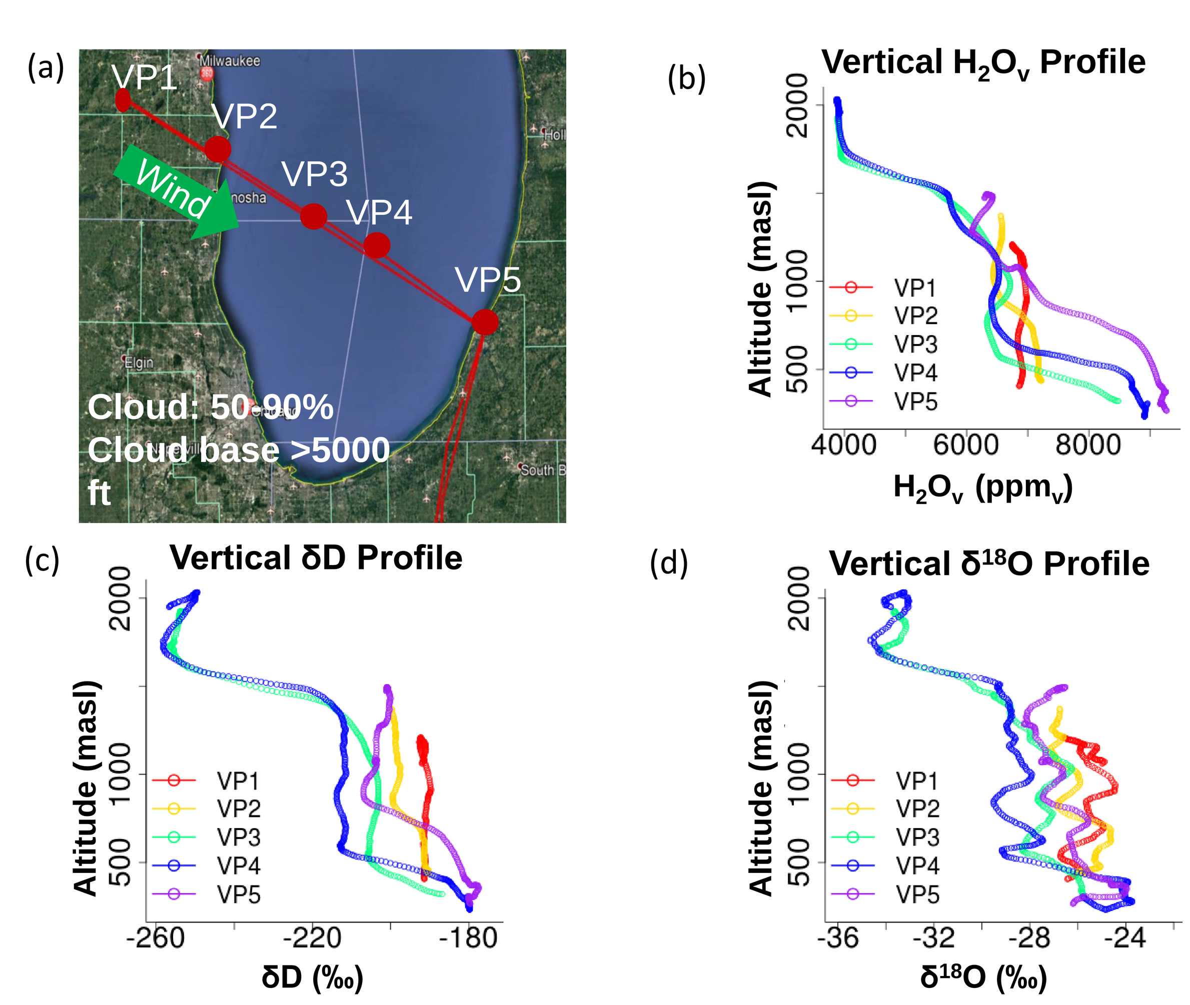

Figure 5. (a) Map of flight path 5 on Monday, October 29, 2018, which occurred from approximately 12pm to 5pm local time (EDT). (b) Water vapor concentration downwind is increased with increasing fetch, indicating both horizontal and vertical water vapor gradients. (c) A similar pattern is seen in δD space, however again, (d) $\delta_{18}O$ profiles are variable.

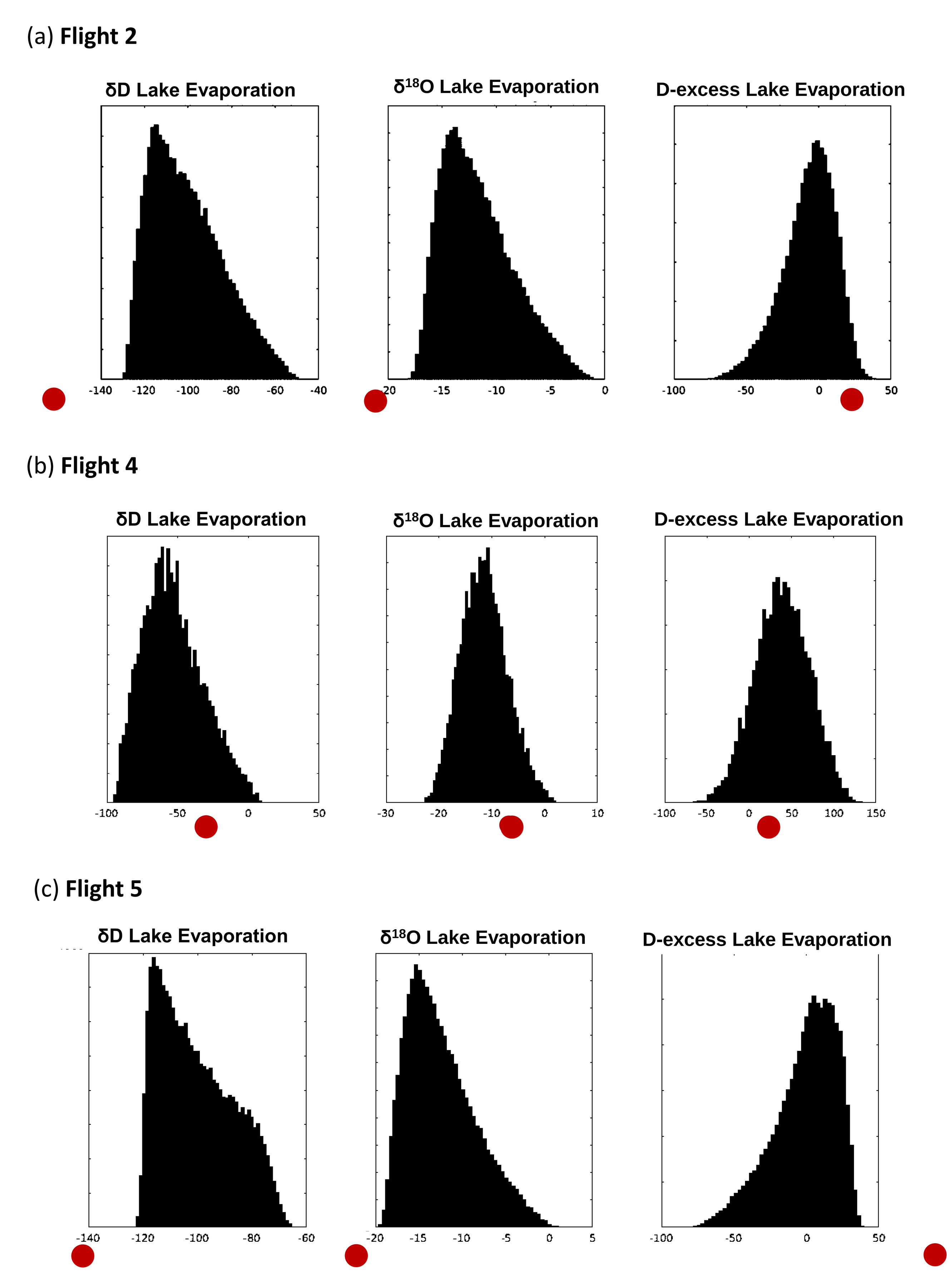

Figure 6. Craig and Gordon Monte Carlo simulations (histograms) are more enriched than a δ_E Keeling Plot from observations around Lake Michigan (red dots) would suggest. This is the case in both δD and $\delta^{18}O$ during both Flight 2 (a) and Flight 5(c). Flight 4 (b) Keeling Plot results fall within the range of the Monte Carlo experiment, and are included in the range of the Monte Carlo mean ± sd.

Summary and Next Steps

- We see an H_2O vapor and deuterium isotope gradient across the lake with increasing fetch. This pattern is more variable but is also seen at the lowest altitudes of $\delta_{18}O$ profiles.
- For Flight 4, our CG predictions match our KP results within the Monte Carlo mean ± sd. These KP results have a relatively high R^2 of about 0.7.
- Flight 2 and Flight 5 KP values are more depleted than would be expected based on the CG model. Possible explanations include atmospheric mixing, measurement height CG δ_A uncertainty, and city/"other" wind influence.
- Future work: Applying a smaller-scale wind direction model to screen data for Keeling Plot applications and exploring observations of δ_A, RH, and ε_k.

References

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8. Flight Path images: NOAA © Google, Landsat/Copernicus

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