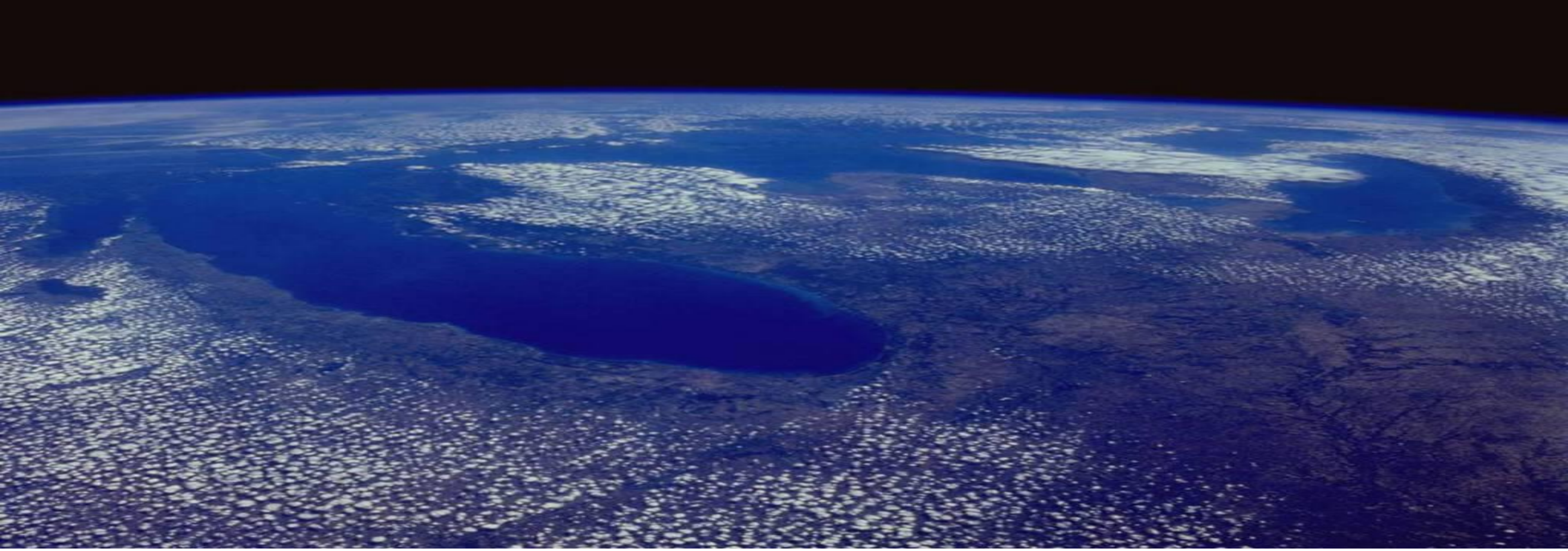

Quantifying the role of lakes in the water and climate system based on mass balance of oxygen-18 and deuterium

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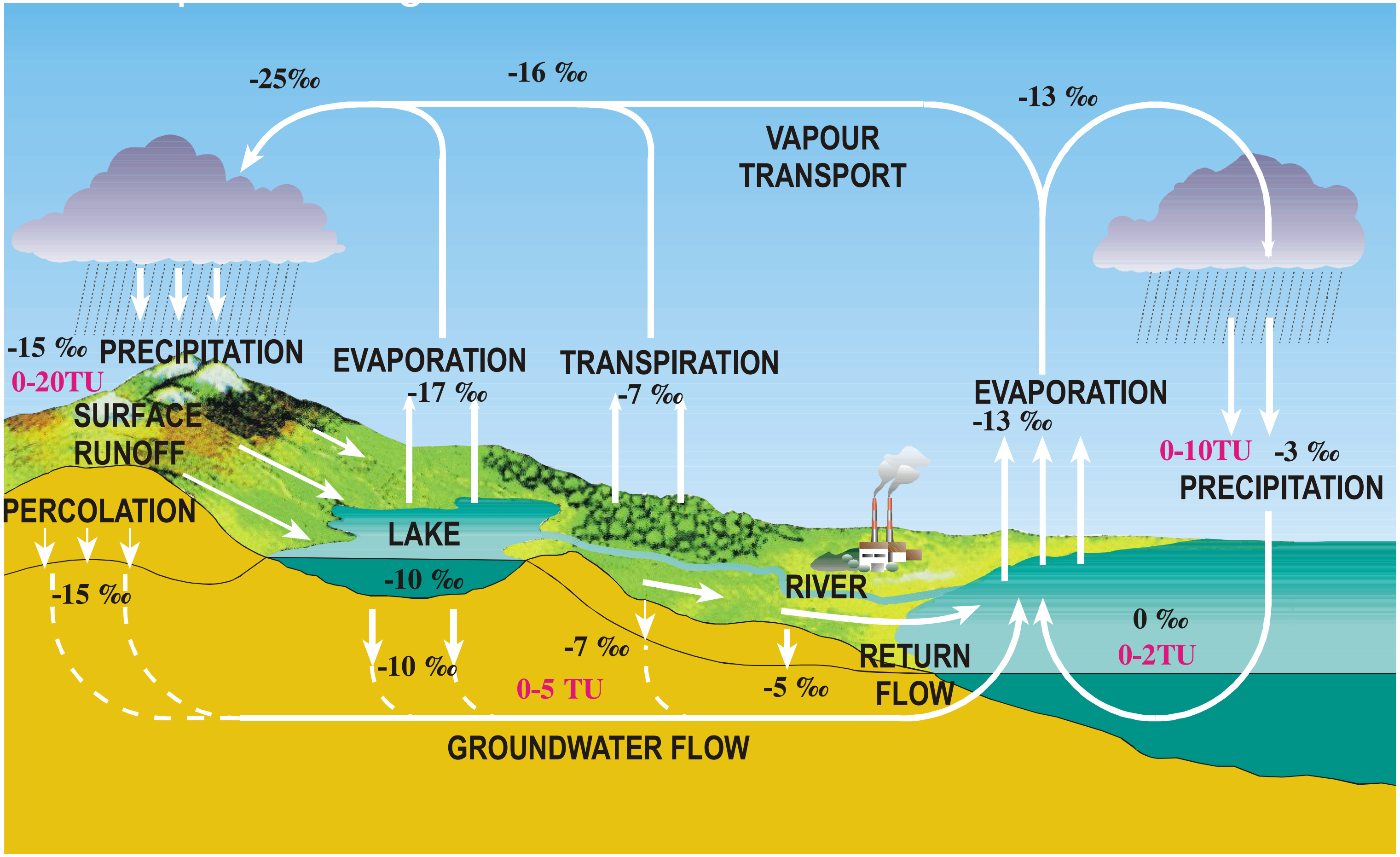
Outline

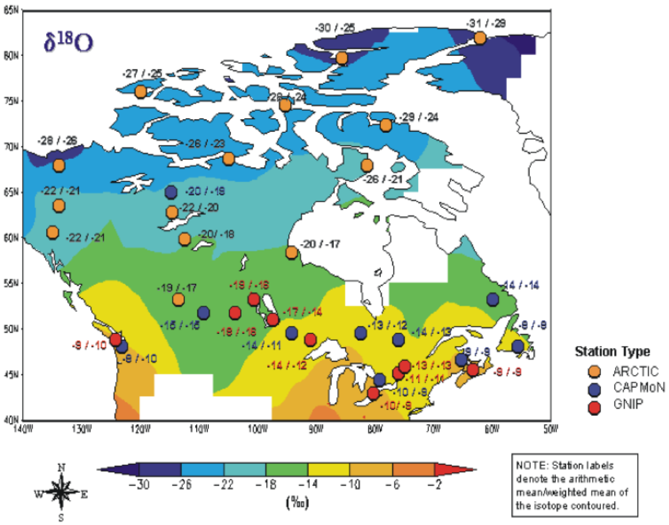
- Background on Isotopes in Water Cycle
- Evaporation – the Craig and Gordon model
- Global, regional, local predictability
  - Isotope Mass Balance
  - Seasonality and slopes of Local Evaporation Lines
- Weighting and atmospheric feedbacks
- Case studies
  - Laurentian Great Lakes
  - Salmita 20-year time-series
  - U.S. EPA National Lake Assessment surveys
  - Water yield mapping in Southern Athabasca region (+ radon-222)
- Implications
  - role of lakes in water and climate system processes
  - limitations

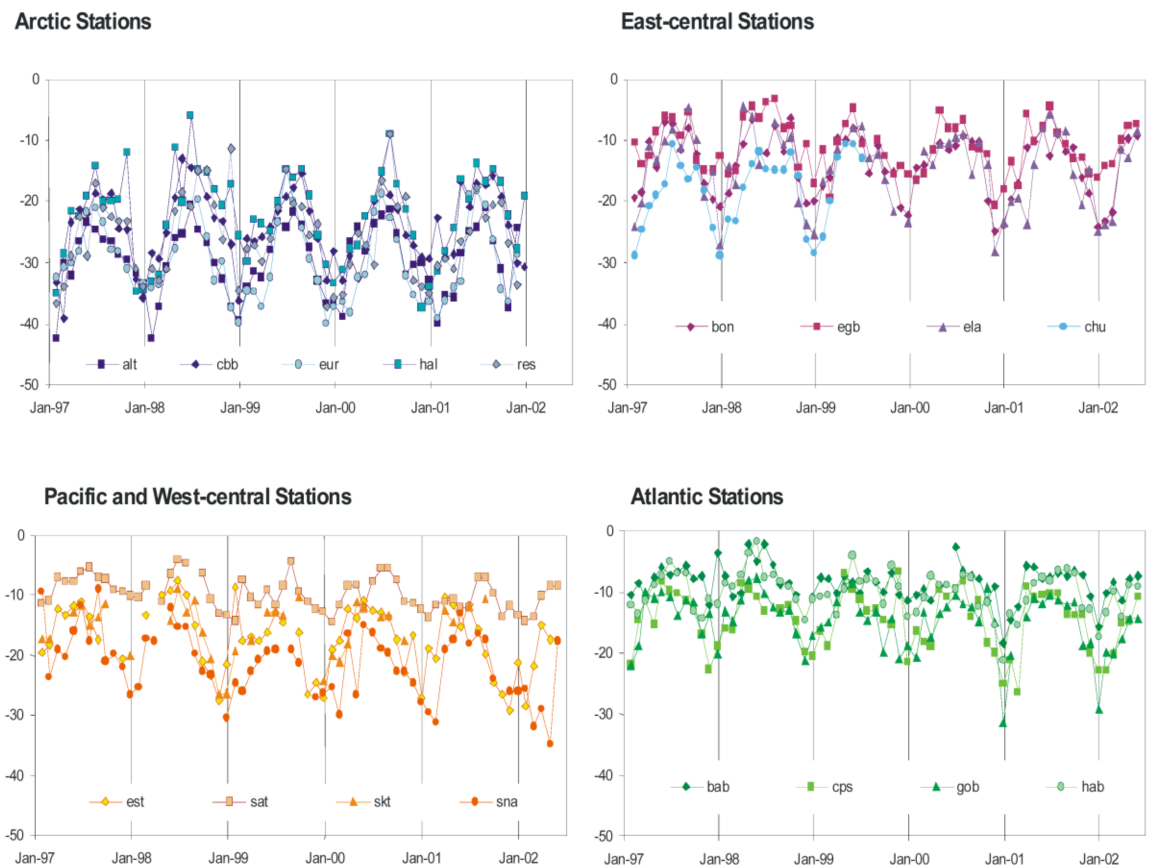
Isotopes in the water cycle



- incorporated within the water molecule (^{18}O, ^{2}H, ^{3}H)
- label individual hydrologic components
- mass conservative during mixing
- systematic fractionation during phase changes and diffusion

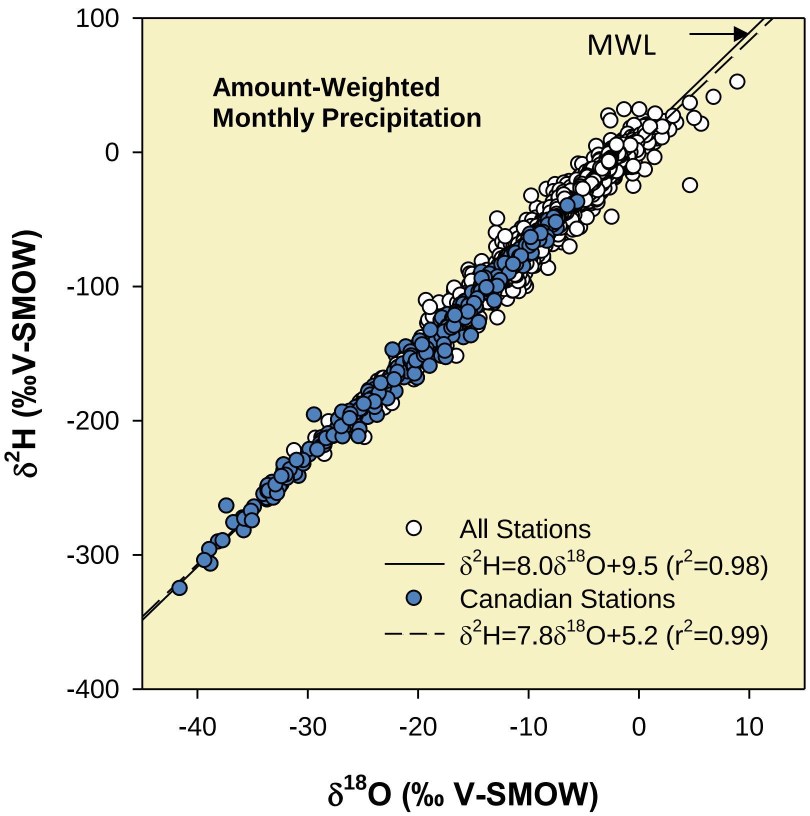
Isotopes in precipitation: temporal variations

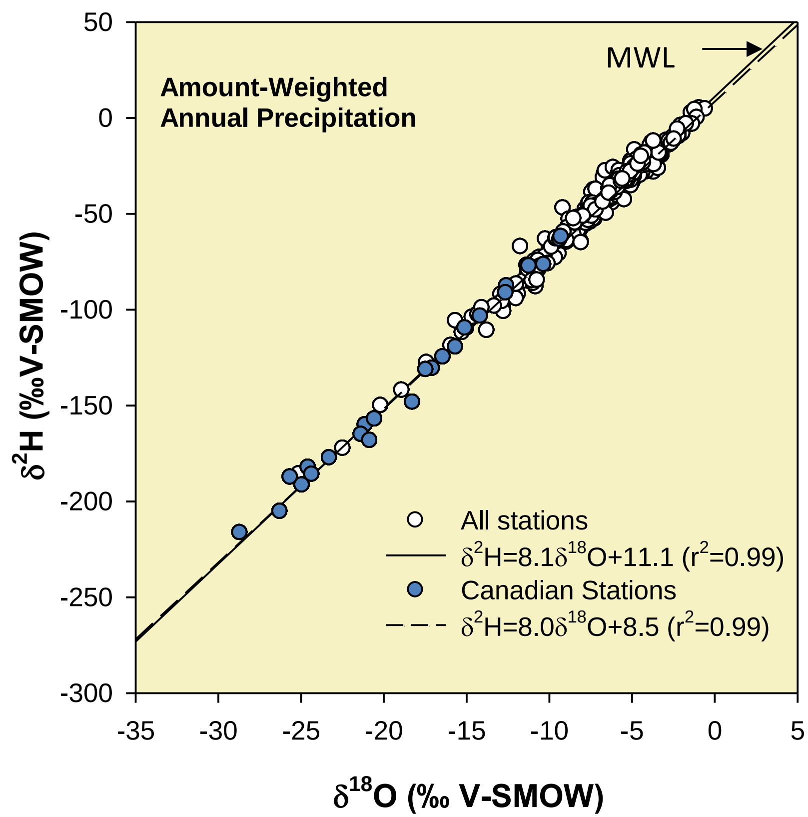




Gibson et al. Hydrol. Process. 2005

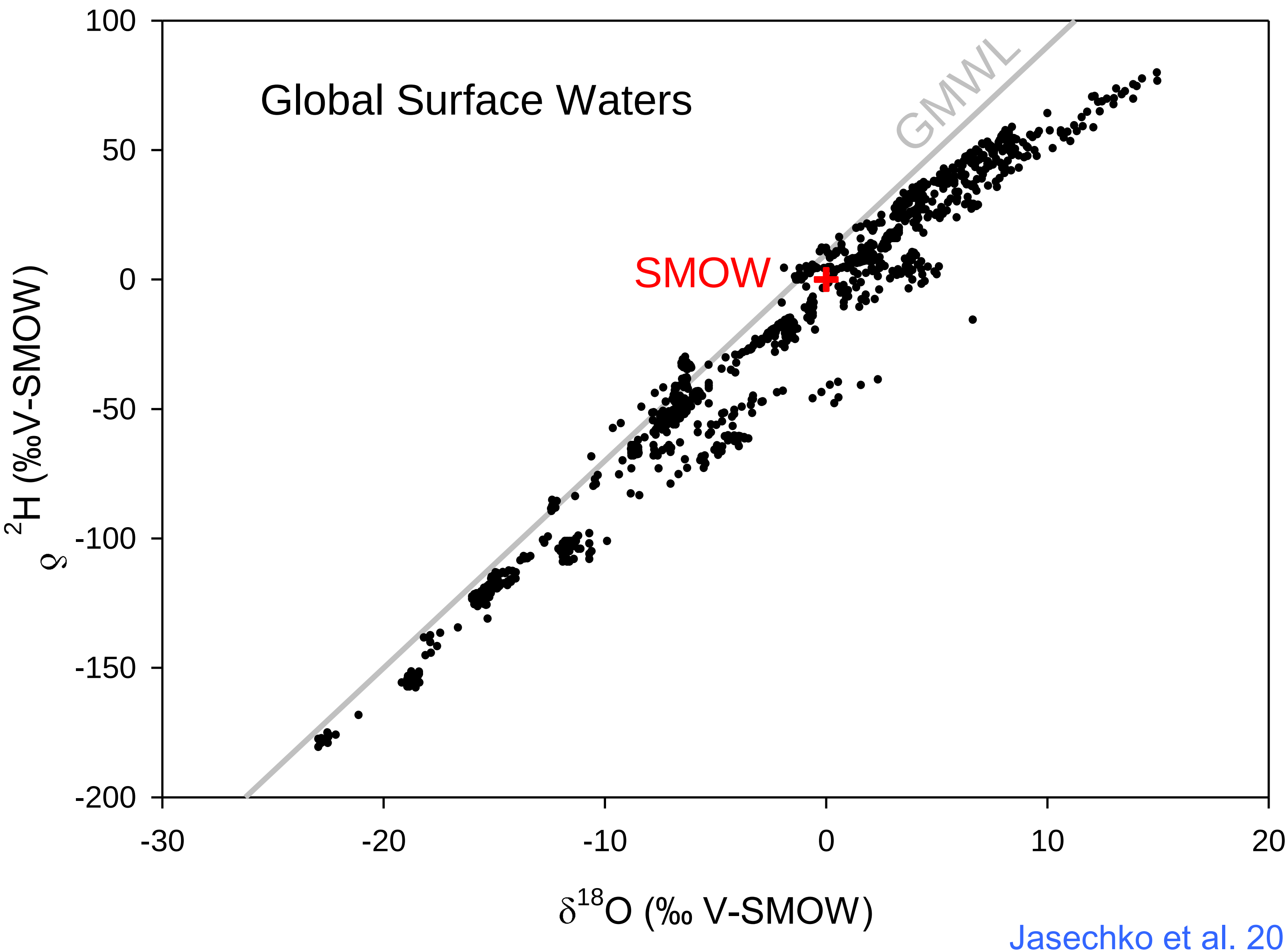
^2H-^{18}O in precipitation: the hydrologic input function





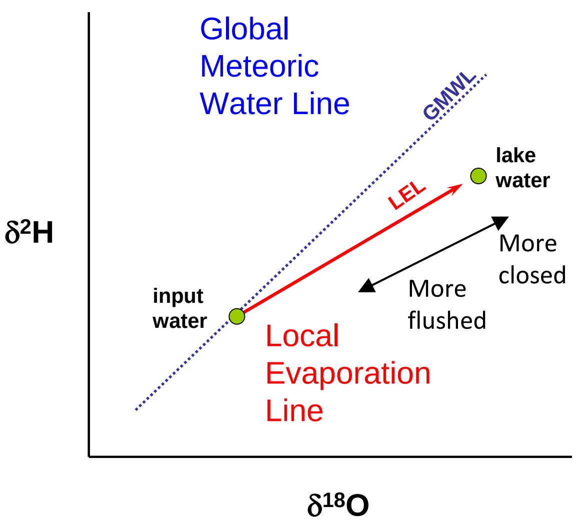
Gibson et al. Hydrol. Process. 2005

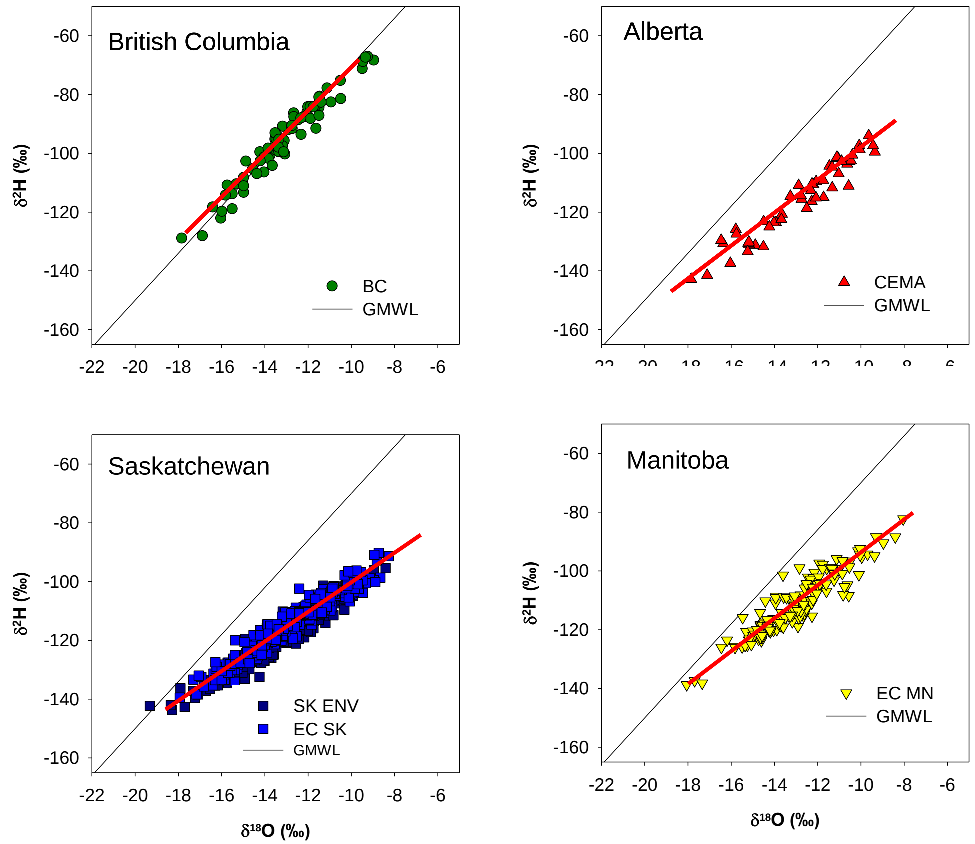
Evaporative enrichment in large lakes



Jasechko et al. 2013 Nature

Evaporative enrichment in networks of small lakes



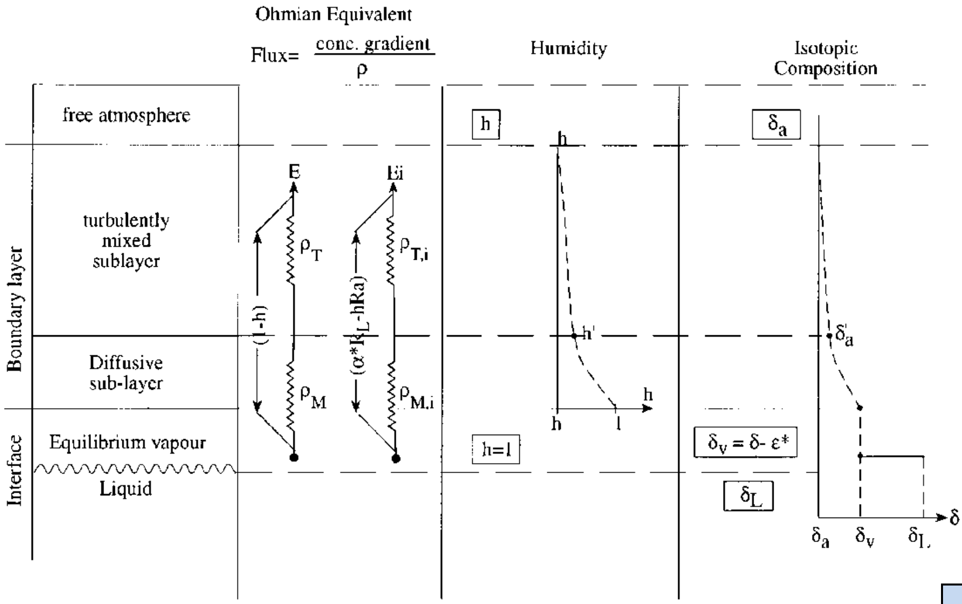


-very systematic isotopic enrichment in lakes used to estimate water balance and runoff to lakes

-information on both lake itself and land area draining to lakes

Isotope exchange at air-water interface:

CRAIG AND GORDON MODEL



Gat, Ann. Rev. Earth Planet Sci.,1996

Atmospheric moisture

Lakewater

equilibrium separation

$$\delta_E = \frac{1}{1-h+\varepsilon_K}\left(\frac{\delta_L - \varepsilon^+}{\alpha^+} - h\delta_A - \varepsilon_K\right)$$

kinetic separation

kinetic separation

Evaporating moisture

Equilibrium fractionation

Majoube, 1971, J. Chim. Phys.

Horita and Wesolowski, 1994, Geochim. Cosmochim. Acta

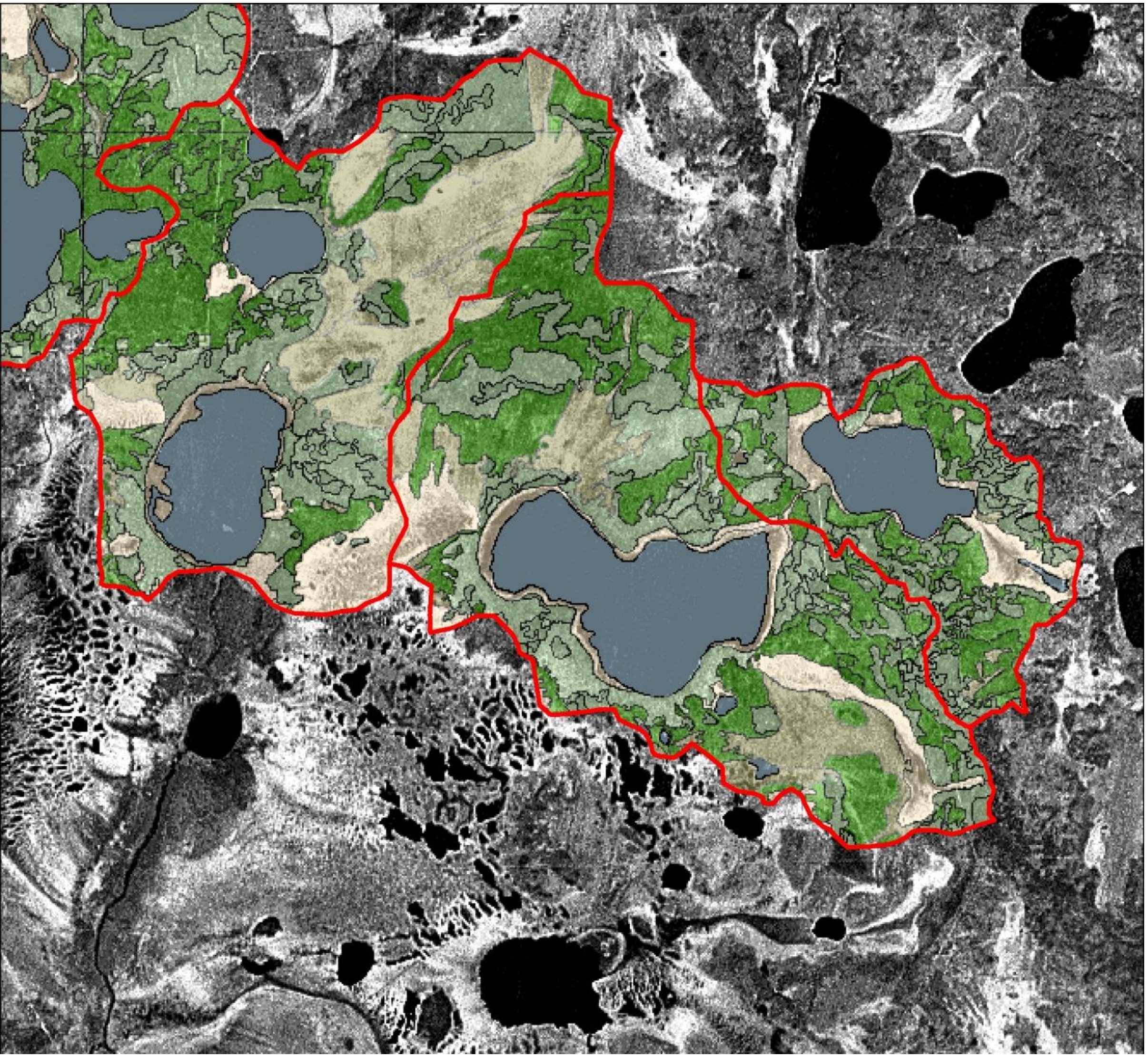
Kinetic fractionation

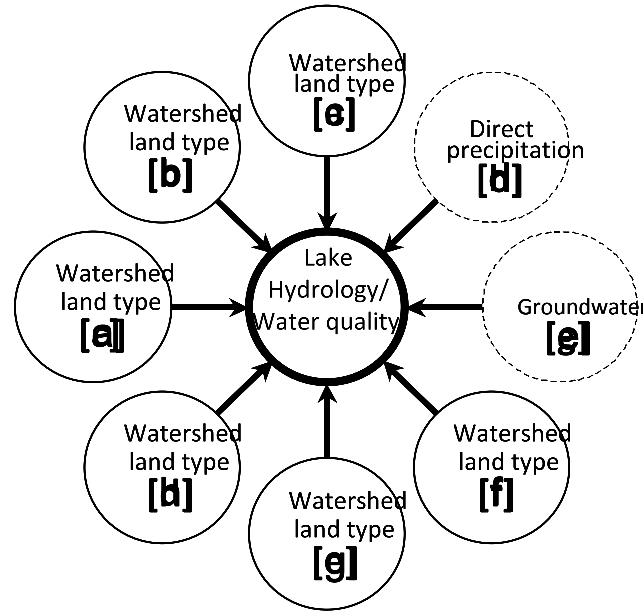
Horita et al. 2008, Isot. Environ. Healt. S. (review)

Cappa et al. 2003, J. Geophys. Res. Atmos. (liquid resistance)

Alternative Rayleigh model: **Merlivat and Jouzel, 1979, J. Geophys. Res. Oceans Atmos. (used by GCM community)**

Runoff Variability: Controlled by Unique Configuration of Watershed Properties/Hydrologic Response Units





$$\left|\begin{array}{cccccccc} \alpha_a & \alpha_b & \alpha_c & \alpha_d & \alpha_e & \alpha_f & \alpha_g & \alpha_h \\ \beta_a & \beta_b & \beta_c & \beta_d & \beta_e & \beta_f & \beta_g & \beta_h \\ \chi_a & \chi_b & \chi_c & \chi_d & \chi_e & \chi_f & \chi_g & \chi_h \\ \delta_a & \delta_b & \delta_c & \delta_d & \delta_e & \delta_f & \delta_g & \delta_h \\ \varepsilon_a & \varepsilon_b & \varepsilon_c & \varepsilon_d & \varepsilon_e & \varepsilon_f & \varepsilon_g & \varepsilon_h \\ \varphi_a & \varphi_b & \varphi_c & \varphi_d & \varphi_e & \varphi_f & \varphi_g & \varphi_h \\ \gamma_a & \gamma_b & \gamma_c & \gamma_d & \gamma_e & \gamma_f & \gamma_g & \gamma_h \\ \eta_a & \eta_b & \eta_c & \eta_d & \eta_e & \eta_f & \eta_g & \eta_h \end{array}\right| \cdot \left|\begin{array}{c} x_a \\ x_b \\ x_c \\ x_d \\ x_e \\ x_f \\ x_g \\ x_h \end{array}\right| = V_L \left|\begin{array}{c} \alpha_L \\ \beta_L \\ \chi_L \\ \delta_L \\ \varepsilon_L \\ \varphi_L \\ \gamma_L \\ \eta_L \end{array}\right|$$

Isotope Mass Balance Models

Water mass balance

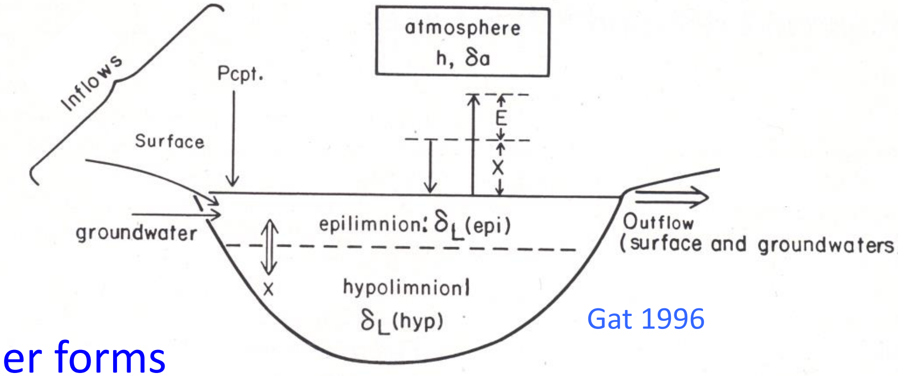
$$\frac{dV}{dt} = I - Q - E$$

Isotope mass balance

$$\delta_L \frac{dV}{dt} + V \frac{d\delta_L}{dt} = \delta_I I - \delta_Q Q - \delta_E E$$

Isotopic and hydrologic steady state

$$\frac{E}{I} = \frac{\delta_I - \delta_L}{\delta_E - \delta_L}$$



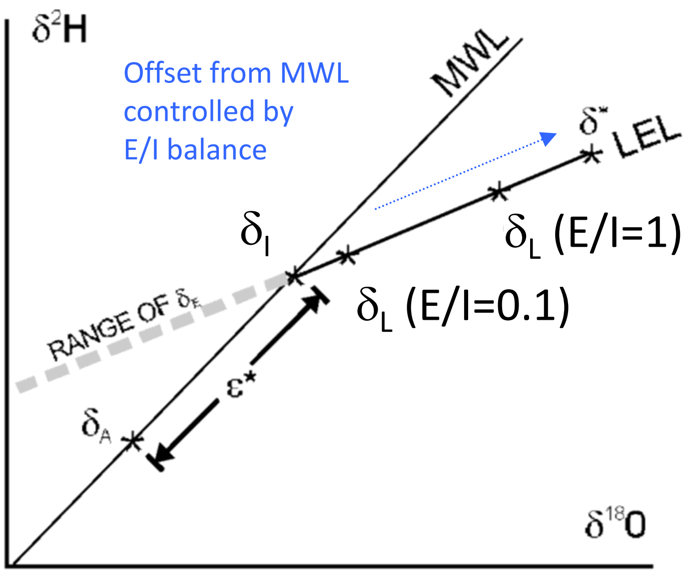
Gat 1996

Other forms

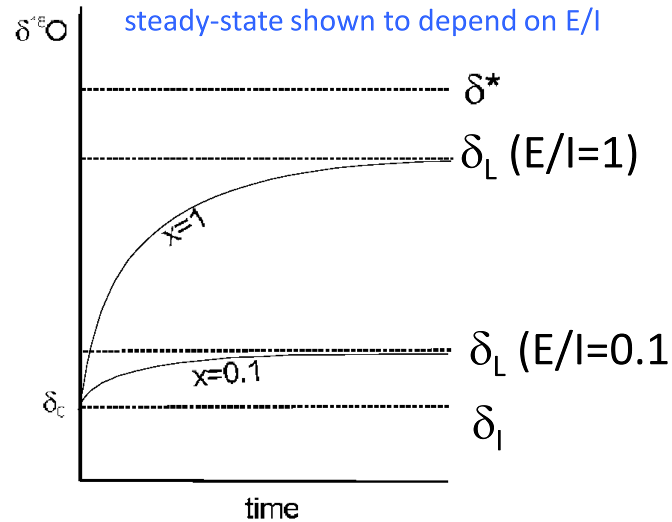
-Volumetric changes $\quad \frac{d\delta_L}{dt} = \frac{I}{V}(\delta_I - \delta_L) + \frac{E}{V}(\delta_L - \delta_E)$

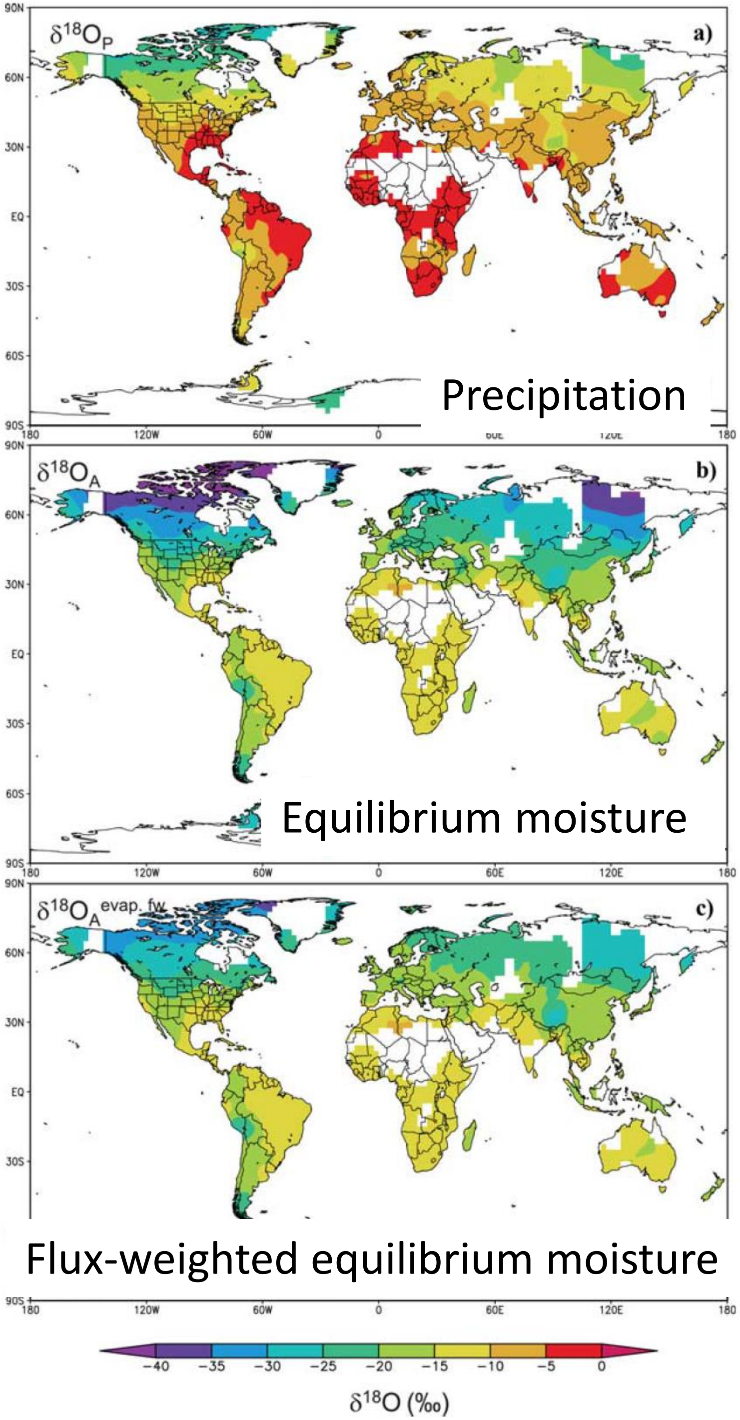
-Isotopic changes $\quad \delta_L = \delta_S - (\delta_S - \delta_0)\exp\left[-(1+mx)\frac{It}{V}\right]$

-Stratified $\quad \ldots + \frac{X(epi - hyp)}{V}\cdot(\delta_{(hyp)} - \delta_L) + \frac{\Delta V}{V}\cdot(\delta_{(hyp)} - \delta_L)$



Temporal enrichment to isotopic steady-state shown to depend on E/I





Atmospheric moisture

<u>**Equilibrium assumption**</u>

-valid for long time-periods

-continental regions

****must be weighted by evaporation flux**

$$\delta_A = \left(\delta_P - \varepsilon^+\right) / \alpha^+$$

<u>**Direct measurement of vapour**</u>

Yamanaka and Shimizu, 2007, Geochim. Cosmochim. Acta

Iannone et al., 2010, J. Geophys. Res. Atmos.

Aemisegger et al., 2012, Atmos. Meas. Tech.

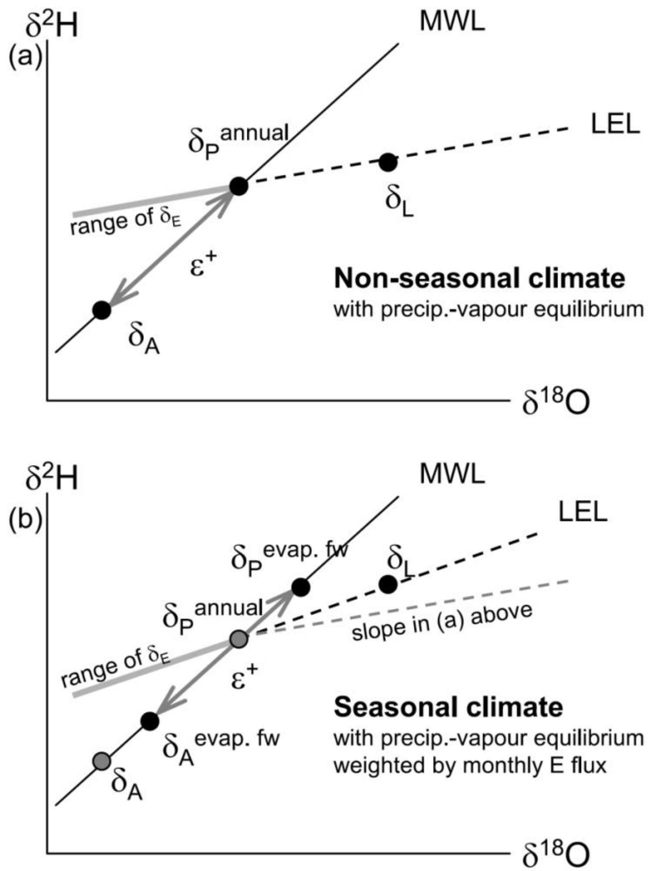
Good et al., 2012, J. Geophys. Res. Atmos.

-laser instrumentation potential

****not yet routinely applied to study lake evaporation**

Gibson et al., 2008, Global Biogeochem. Cycles

Seasonality effect on LEL

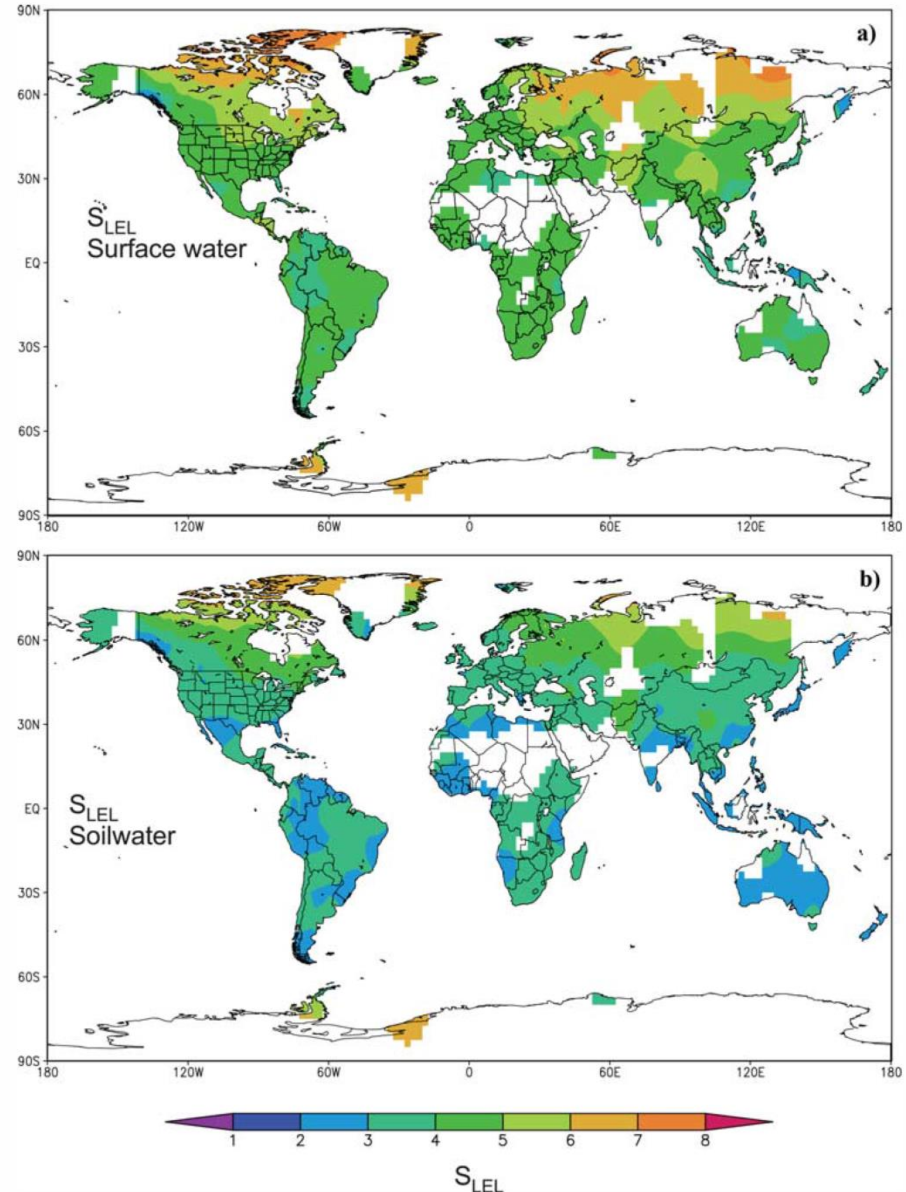


$$S_{LEL} = \frac{\left[\dfrac{h(\delta_A - \delta_P) + (1+\delta_P)(\varepsilon_K + \varepsilon^+ / \alpha^+)}{h - \varepsilon_K - \varepsilon^+ / \alpha^+}\right]_2}{\left[\dfrac{h(\delta_A - \delta_P) + (1+\delta_P)(\varepsilon_K + \varepsilon^+ / \alpha^+)}{h - \varepsilon_K - \varepsilon^+ / \alpha^+}\right]_{18}}$$

Simulated slopes of Local Evaporation Lines

Surface water

Soil water

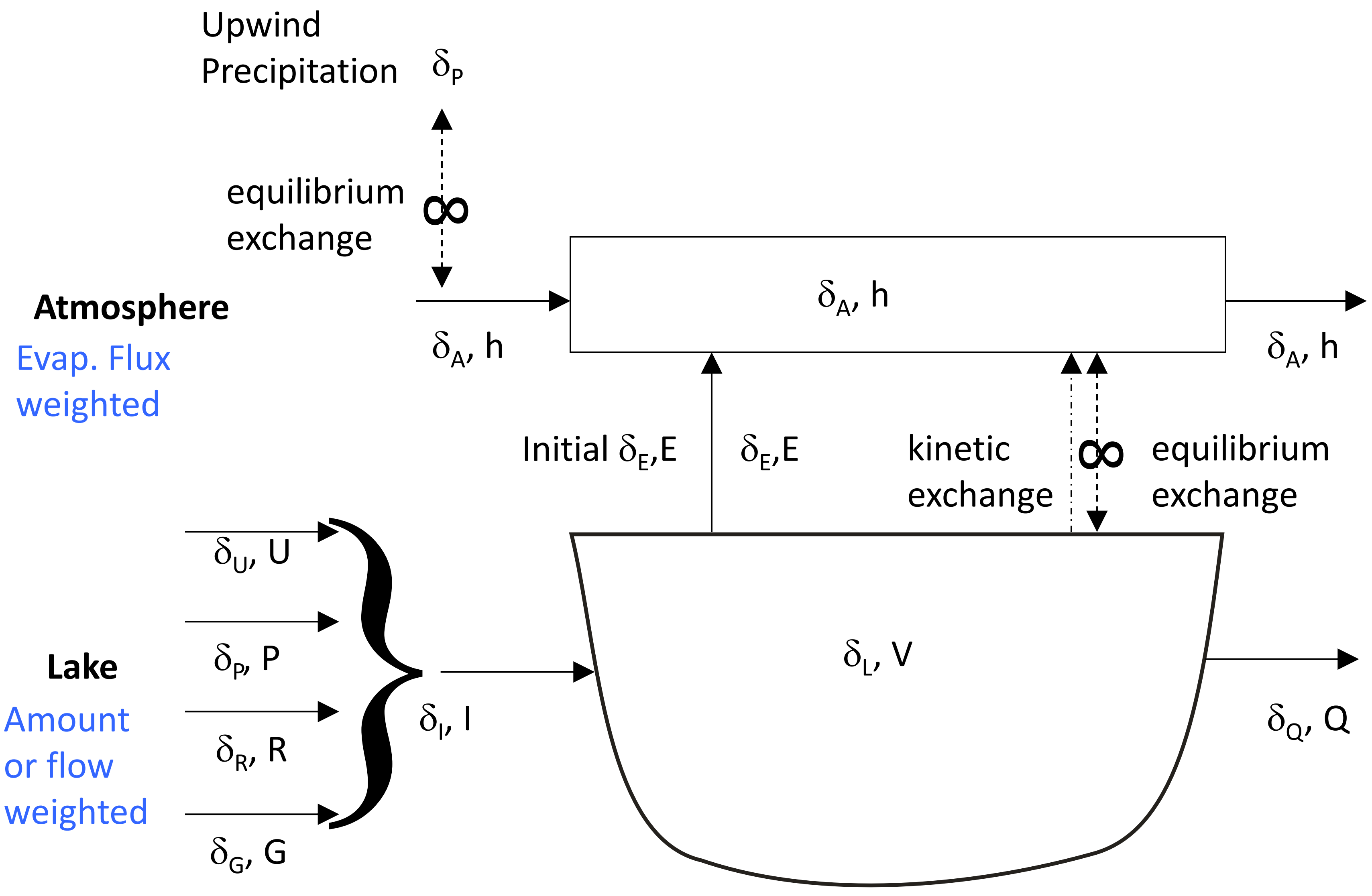


Caveat: due to use of precipitation equilibrium approach, may not be representative for coastal areas strongly influenced by ocean vapour

Gibson et al., 2008, Global Biogeochem. Cycles

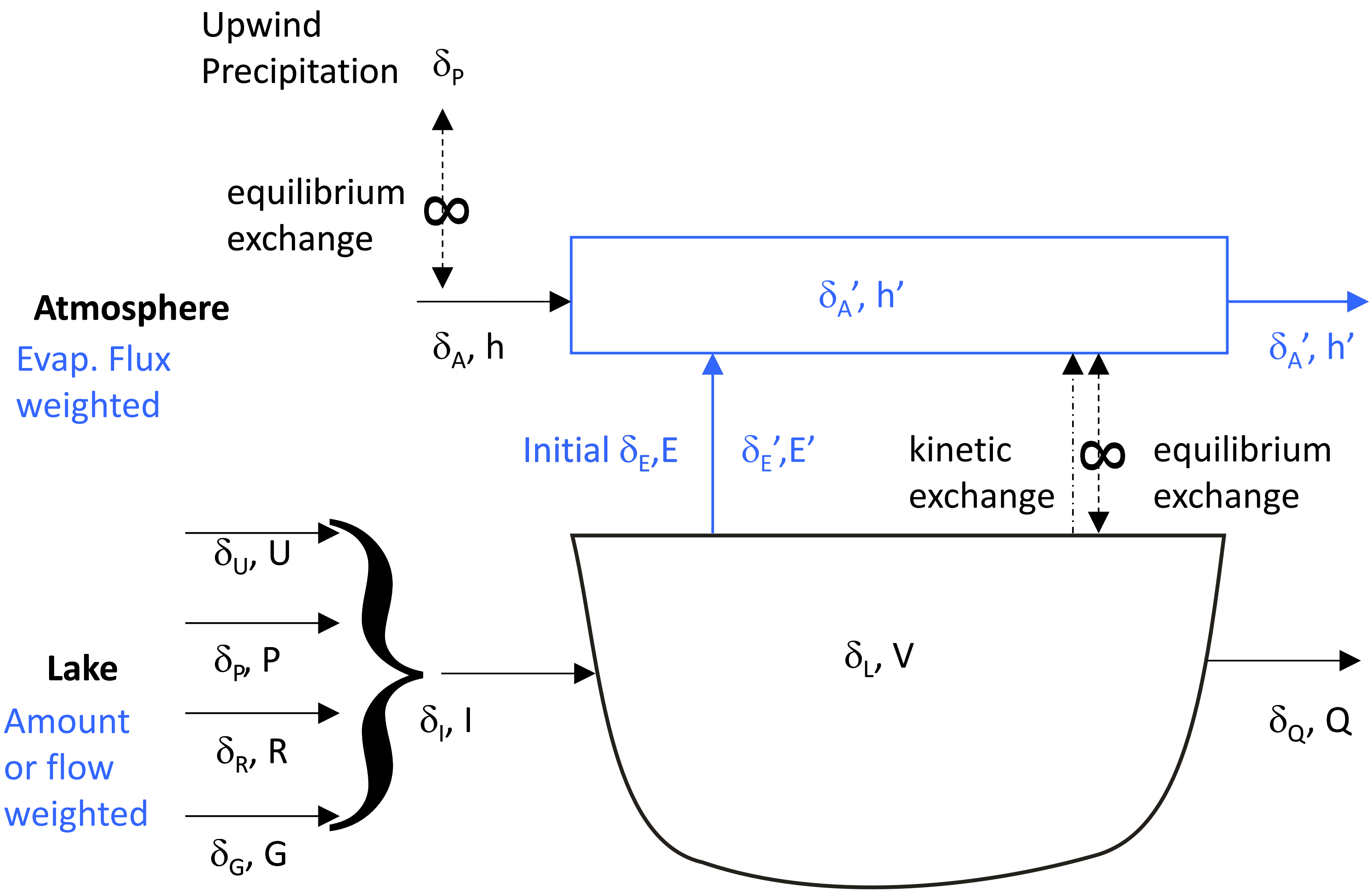
Weighting and Atmospheric Feedback

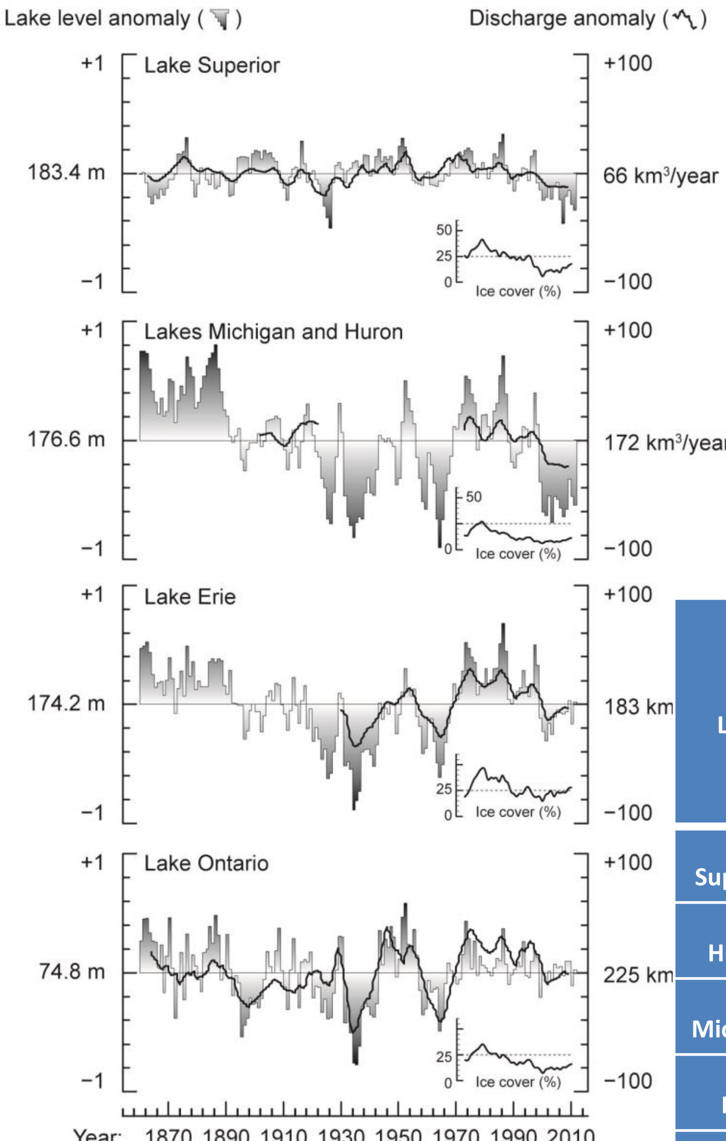
Small Lake – No Atmospheric Feedback



Weighting and Atmospheric Feedback

Large Lake – Atmospheric Feedback





-Lakes Superior, Michigan and Huron are in a 15-year negative lake level anomaly

-longest on record since 1860

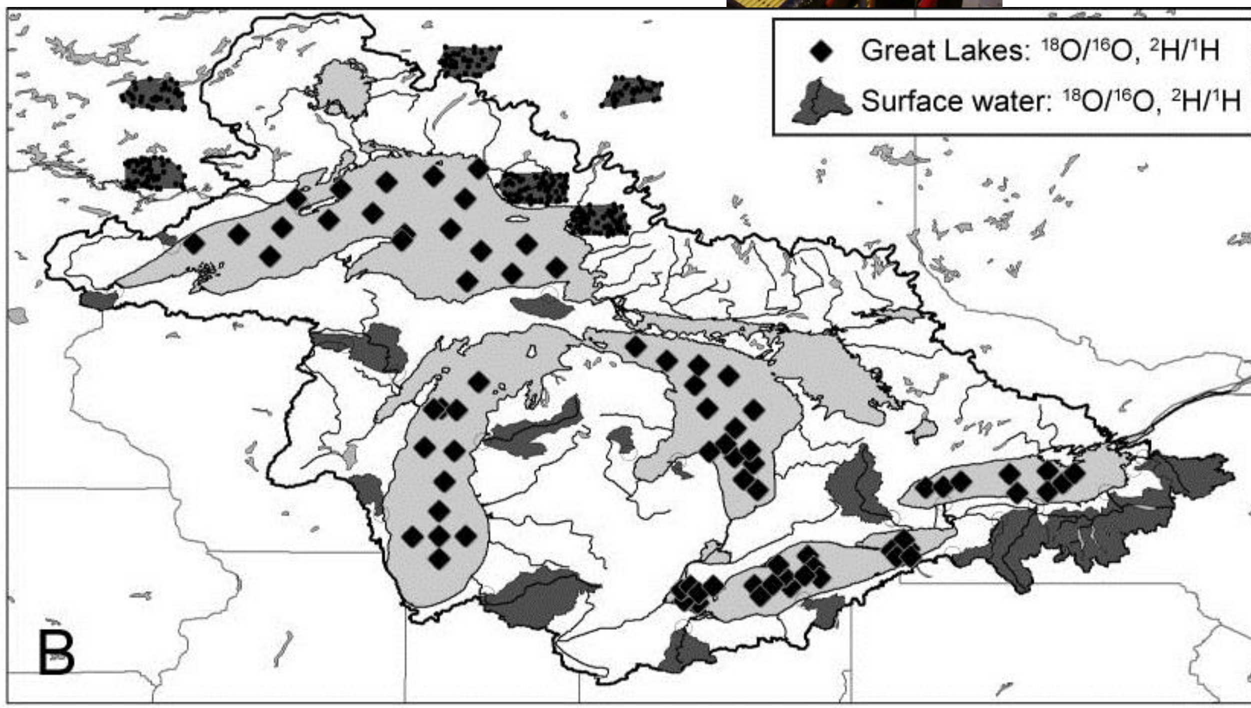
Lake	Lake area (km^2)	Catchment area (km^2)	Lake ÷ catchment area (%)	Level (m.a.s.l.)	Residence time (years)	Volume (km^3)	Depth (m)	
							Avg.	Max.
Superior	82,000	210,000	39	183.4	171	12,000	147	405
Huron	60,000	193,000	31	176.5	21	3,500	59	281
Michigan	58,000	176,000	33	176.5	62	4,900	85	229
Erie	26,000	85,000	31	174.1	2.7	480	19	64
Ontario	19,000	80,000	24	74.8	7.5	1,600	87	244

- International Joint Commission has sponsored number of studies to better constrain water balance (IUGLS)
- Blanken et al. (2011)
  - Surface energy balance using eddy covariance on Lake Superior
  - 70-88% of evaporative heat loss occurred between October and March
  - 464 mm of evaporation for 2008-09, 645 mm for 2009-10
  - Evaporation driven by water temperature, ice cover and ice duration
- Spence et al.(2011)
  - Evaporation rates on Lake Superior, large scale forcing mechanisms, spatially distributed patterns
- Deacu et al. (2012)
  - NWP model development
  - Better evaporation estimates improved 3-day forecast for Ontario
- This study – using stable isotopes – evaporation rates, water balance, lake effect on boundary layer

- 514 water samples collected in April & August 2007

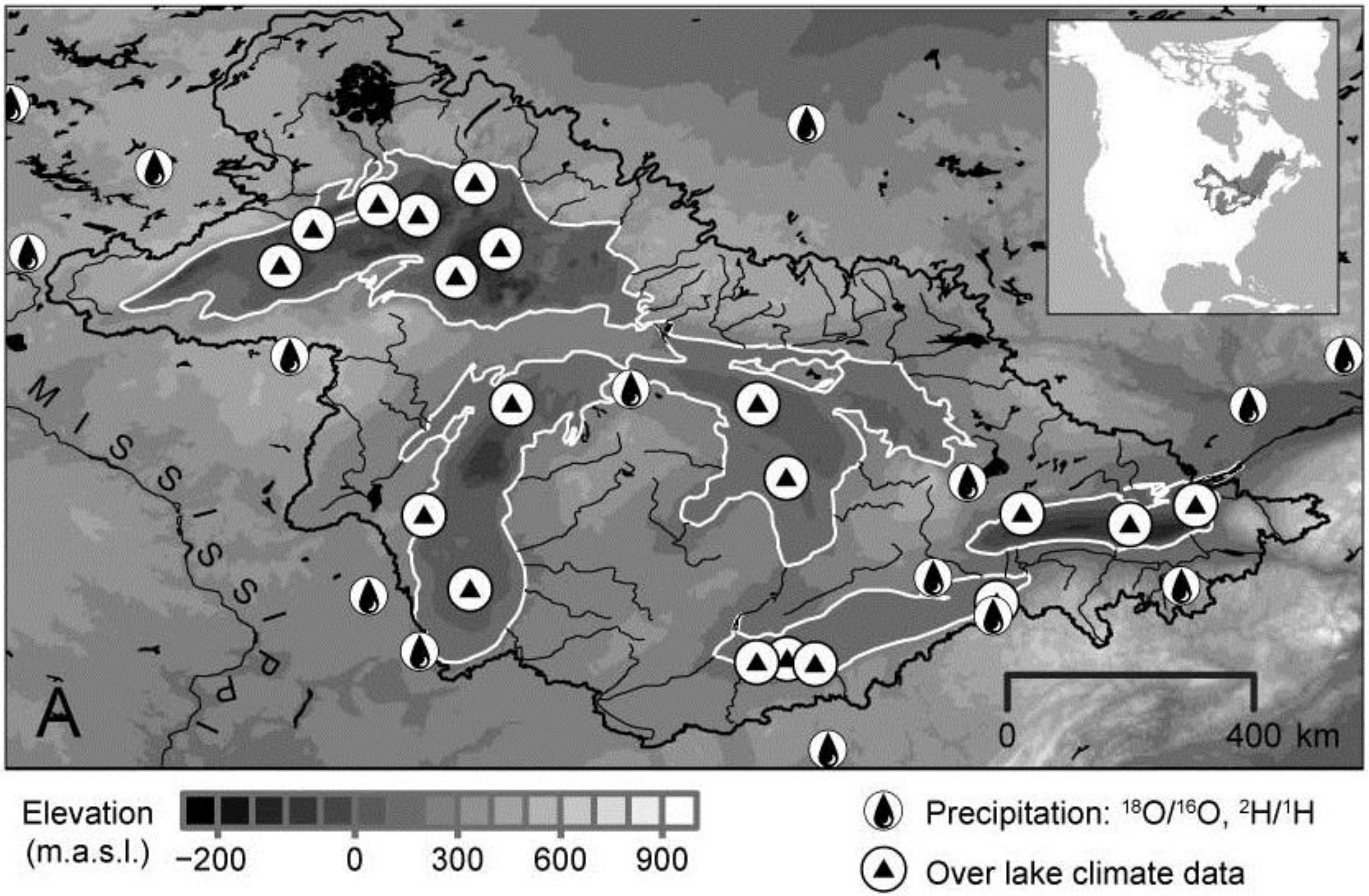
Rosette sampler

EPAs RV Lake Guardian

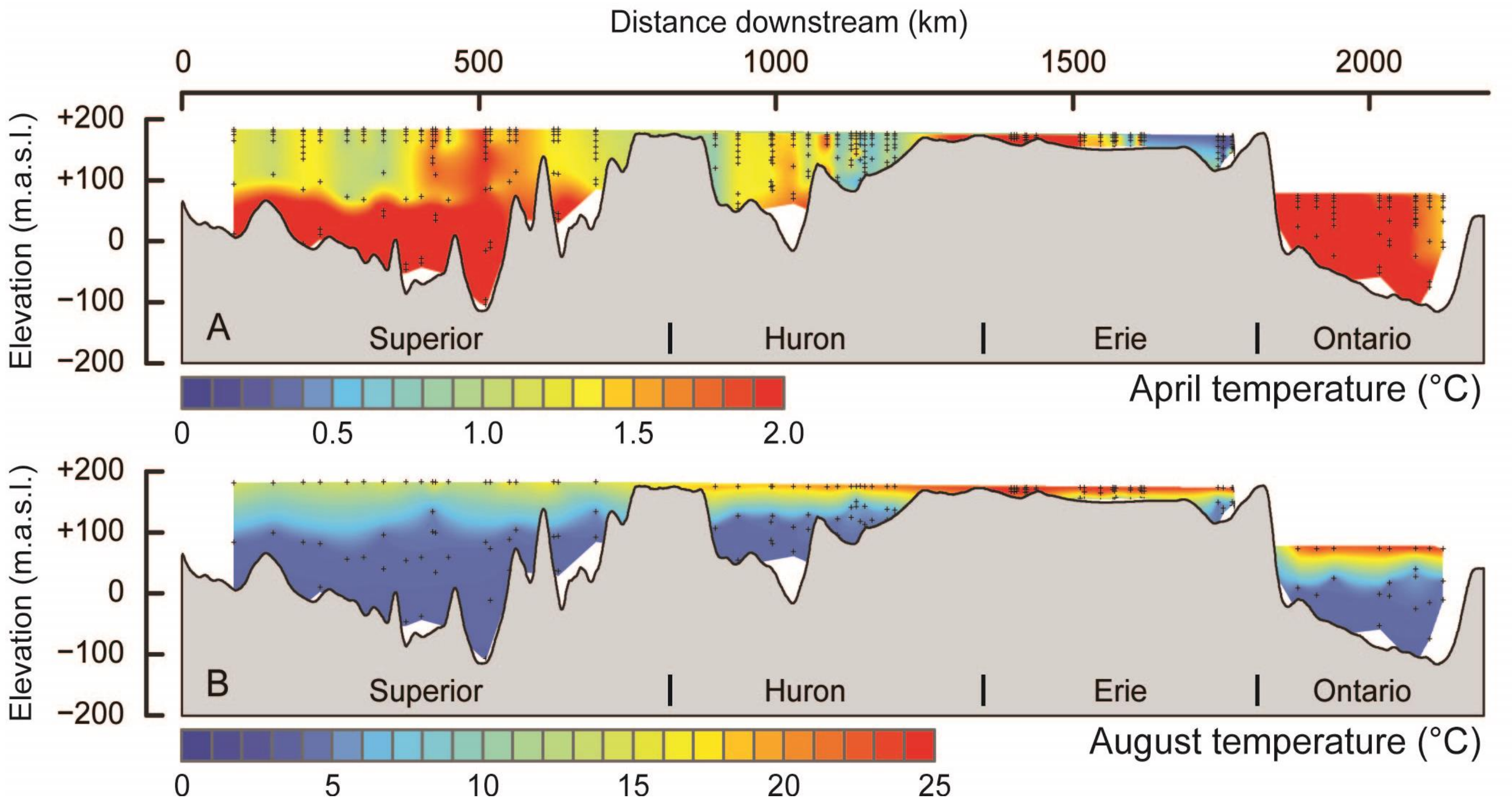


Storm Front

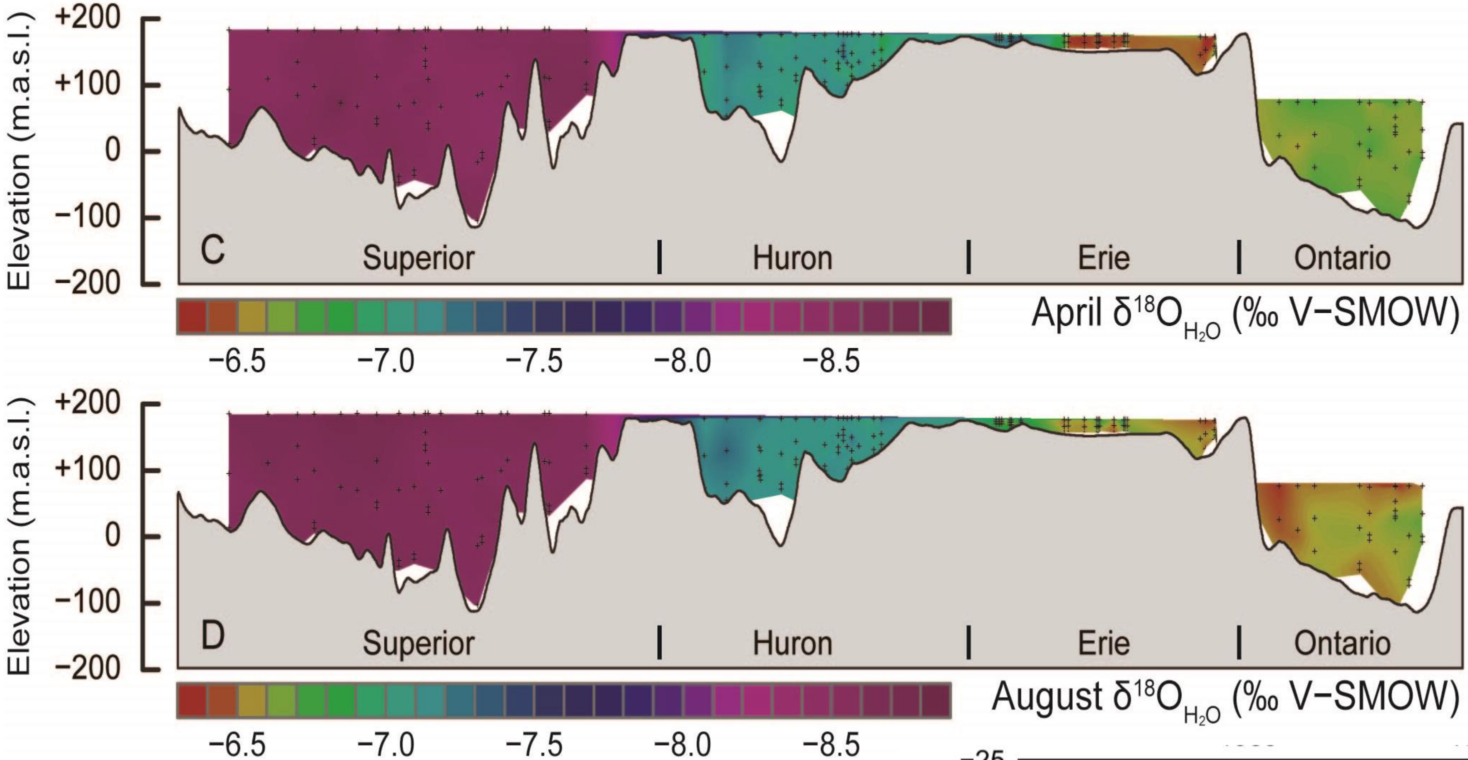
Climate Stations



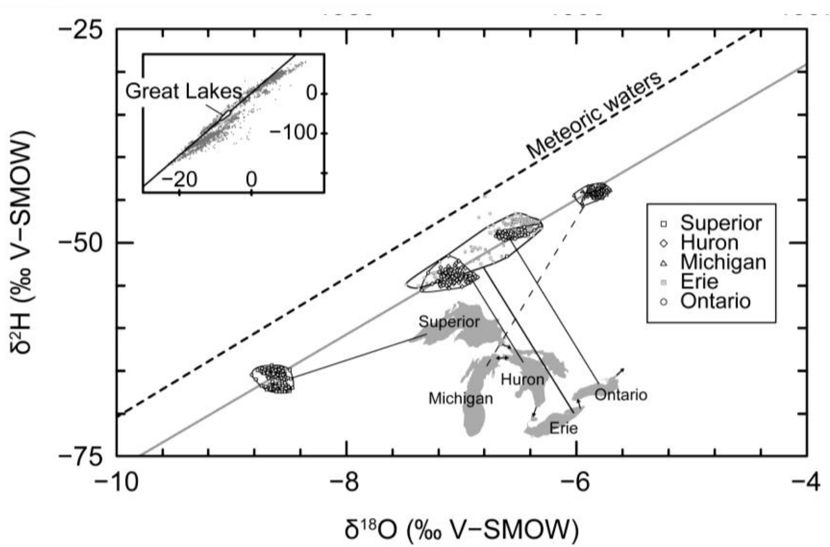
- Thermal stratification



Great Lakes: Isotopic homogeneity



Lake	Samples analyzed			Avg. $\delta^{18}O$	Avg. $\delta^{2}H$	1 s.d. $\delta^{18}O$	1 s.d. $\delta^{2}H$
	Spring	Summer	Total				
Superior	80	60	140	−8.62	−65.8	0.07	0.9
Huron	60	45	105	−7.07	−53.9	0.09	0.7
Michigan	44	36	80	−5.83	−44.2	0.06	0.5
Erie	63	63	126	−6.65	−49.2	0.28	2.4
Ontario	36	27	63	−6.57	−49.1	0.08	0.5



Water mass balance

$$\frac{\mathrm{dV}}{\mathrm{dt}} = \mathrm{I} - \mathrm{Q} - \mathrm{E}$$

Isotope mass balance

$$\delta_L \frac{\mathrm{dV}}{\mathrm{dt}} + \mathrm{V}\frac{\mathrm{d}\delta_L}{\mathrm{dt}} = \delta_I \mathrm{I} - \delta_Q \mathrm{Q} - \delta_E \mathrm{E}$$

Isotopic and hydrologic steady state

$$E = Q \cdot \frac{\delta_I - \delta_L}{\delta_E - \delta_I}$$

Isotope balance equations of inputs

Total Inflow

$$\delta_I = \frac{U\delta_U + P\delta_P + R\delta_R}{U + P + R}$$

Precipitation

$$\delta_{P(aw)} = \frac{\sum_{i=1}^{12} \delta_{P(i)} P_i}{\sum_{i=1}^{12} P_i}$$

Runoff

$$\delta_{R(fw)} = \frac{\sum_{i=1}^{12} \delta_{R(i)} R_i}{\sum_{i=1}^{12} R_i}$$

Liquid outflow ≈ lake water

Precipitation Stations

Station	Network	Lat. (°)	Lon. (°)	Alt. (m. a.s.l.)	Years active	$\delta^{18}O$ * (‰)	$\delta^{2}H$ * (‰)	d (‰)	n	Meteoric water line
Atikokan	IAEA	48.75	−91.62	393	1975 – 1982	−12.61	−91.5	9.4	75	$\delta^2H = 7.84\times\delta^{18}O + 7.5$
Aurora	USNIP	42.73	−76.66	249	1989 – 1994	−8.12	−57.3	7.7	27	$\delta^2H = 7.65\times\delta^{18}O + 10.5$
Bonner Lake	CNIP	49.38	−82.12	245	1993 – 2003	−13.82	−100.7	9.9	121	$\delta^2H = 7.70\times\delta^{18}O + 5.1$
Caldwell	USNIP	39.79	−81.53	276	1989 – 1990		−40.4		30	
Chapais	CNIP	49.82	−74.97	382	1993 – 2003	−13.40	−97.3	9.9	122	$\delta^2H = 7.80\times\delta^{18}O + 8.5$
Chautauqua	USNIP	42.30	−79.40	488	1989 – 1993	−8.36	−55.5	11.4	27	$\delta^2H = 7.05\times\delta^{18}O + 4.3$
Chicago	IAEA	41.78	−87.75	189	1960 – 1979	−6.18	−44.7	4.7	170	$\delta^2H = 6.98\times\delta^{18}O + 0.1$
Coshocton	IAEA	40.37	−81.80	344	1966 – 1971	−7.41	−46.6	12.7	64	$\delta^2H = 7.51\times\delta^{18}O + 8.8$
Douglas Lake	USNIP	45.56	−84.68	238	1989 – 1990	−10.27			23	
Egbert	CNIP	44.23	−79.77	224	1993 – 2003	−10.35	−72.8	10.0	65	$\delta^2H = 6.86\times\delta^{18}O - 2.6$
Exp. Lakes	CNIP	49.67	−93.72	369	1993 – 2003	−12.33	−90.3	8.3	123	$\delta^2H = 7.75\times\delta^{18}O + 5.0$
Gimli	IAEA	50.62	−96.98	223	1975 – 1982	−14.21	−103.7	10.0	73	$\delta^2H = 7.65\times\delta^{18}O + 3.0$
Lake Geneva	USNIP	42.58	−88.50	288	1989 – 1993	−7.51	−52.4	7.7	43	$\delta^2H = 7.20\times\delta^{18}O - 0.1$
Morcell	USNIP	47.53	−93.47	431	1989 – 1994	−11.17	−89.1	0.3	61	$\delta^2H = 8.11\times\delta^{18}O + 11.8$
Ottawa	IAEA	45.32	−75.67	114	1953 – 2007	−10.97	−75.2	12.6	556	$\delta^2H = 7.57\times\delta^{18}O + 7.1$
Penn State	USNIP	40.79	−77.95	393	1989 – 1989		−40.4		26	
Simcoe	IAEA	42.85	−80.27	240	1975 – 1982	−9.27	−62.2	12.0	78	$\delta^2H = 7.80\times\delta^{18}O + 9.4$
Ste. Agathe	IAEA	46.05	−74.28	395	1975 – 1982	−12.55	−87.8	12.6	80	$\delta^2H = 7.75\times\delta 18O + 10.0$
The Pas	IAEA	53.97	−101.1	272	1975 – 1982	−16.55	−125.8	6.6	70	$\delta^2H = 7.57\times\delta 18O - 0.4$
Trout Lake	USNIP	46.05	−89.65	501	1989 – 1991	−9.06	−67.3	5.2	31	$\delta^2H = 8.12\times\delta 18O + 14.9$

River discharge stations

River	Lake catchment	Station number	Lat. (°)	Lon. (°)	Alt. (m.a.s.l.)	Catchment (km^2)	$\delta^{18}O$ * (‰)	δ^2H * (‰)	d ** (‰)	n	Q (km^3/y)
Baptism R.	Superior	4014500	47.34	−91.20	187	360	−10.14	−73.3	7.8	10	0.11
Nemadji R.	Superior	4024430	46.63	−92.09	191	1090	−12.03	−84.3	11.9	11	0.39
Tahquamenon R.	Superior	4045500	46.58	−85.27	212	2050	−12.31	−85.2	13.2	10	0.89
Washington Ck.	Superior	4001000	47.92	−89.15	184	30	−12.42	−87.2	12.2	11	0.01
Pigeon R.	Huron	4159010	43.94	−83.24	183	320	−10.81	−73.9	12.5	10	0.26
Rifle R.	Huron	4142000	44.07	−84.02	198	830	−11.13	−77.7	11.3	9	0.61
Manistee R.	Michigan	4126520	44.25	−86.32	184	5180	−10.83	−73.9	12.7	16	2.6
Menominee R.	Michigan	4067500	45.32	−87.66	192	10180	−10.80	−76.3	10.1	8	3.2
Milwaukee R.	Michigan	4087000	43.10	−87.91	185	1800	−10.24	−69.8	12.1	9	0.95
Popple R.	Michigan	4063700	45.76	−88.46	429	360	−10.77	−75.7	10.5	11	0.08
St. Joseph R.	Michigan	4101500	41.83	−86.26	193	9500	−7.98	−52.9	10.9	16	3.9
Cattaraugus Ck.	Erie	4213500	42.46	−78.94	225	1130	−10.62	−70.6	14.4	11	0.9
Grand R. (Canada)	Erie	At York	43.02	−79.89	190	6500	−10.70	−74.0	11.5	72	1.8
Grand R. (U.S.A.)	Erie	4212200	41.74	−81.27	177	1820	−9.25	−60.2	13.9	7	1.4
Sandusky R.	Erie	4198000	41.31	−83.16	191	3240	−8.01	−50.7	13.3	12	0.92
Black R.	Ontario	4260500	43.99	−75.93	114	4850	−11.12	−75.7	13.3	17	3.0
Genesee R.	Ontario	4232006	43.22	−77.62	105	6360	−8.95	−60.8	10.7	4	1.9
Oswego R.	Ontario	4249000	43.45	−76.51	75	13210	−9.46	−65.7	9.9	11	4.8
Sandy Ck.	Ontario	4250750	43.81	−76.08	160	330	−11.51	−77.0	15.1	17	0.21
Tonawanda Ck.	Ontario	4217000	43.00	−78.19	267	440	−11.04	−74.2	14.2	7	0.18

- Isotopic Inputs

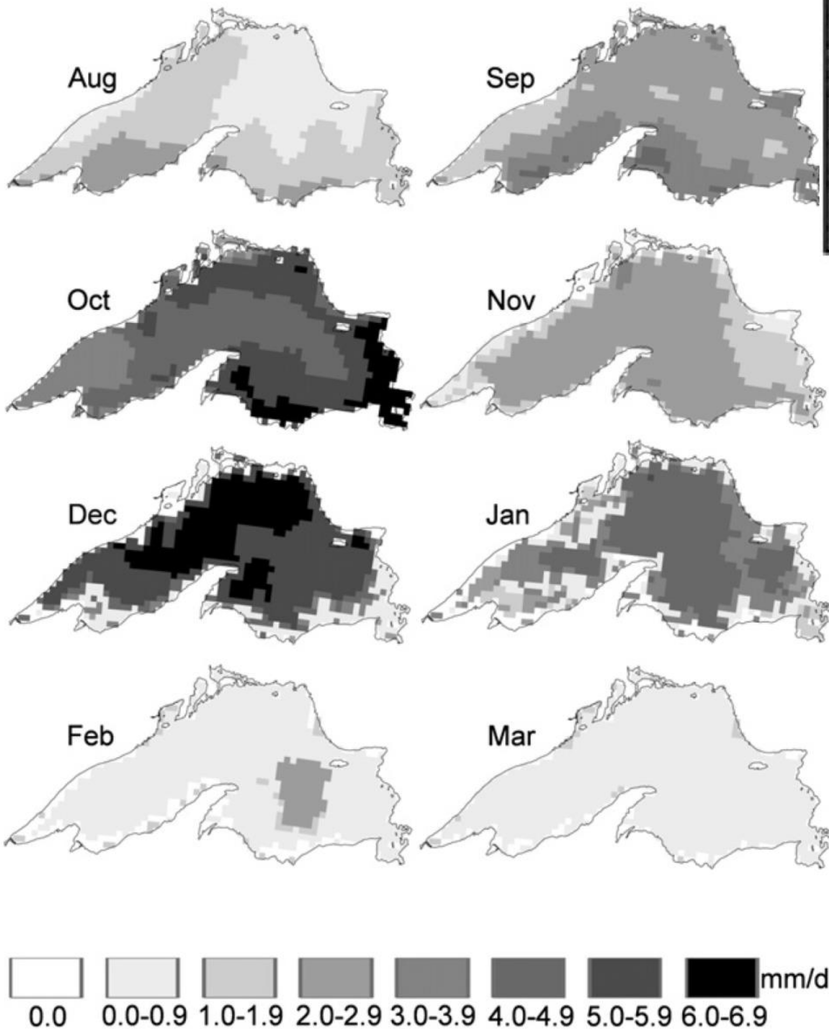
Lake	δ_U		δ_P		δ_R		δ_A	
	$\delta^{18}O$	δ^2H	$\delta^{18}O$	δ^2H	$\delta^{18}O$	δ^2H	$\delta^{18}O$	δ^2H
Superior	-	-	−11.74±1	−84.9±9	−12.50±1	−91.1±9	−24.3±1	−182±9
Huron	−7.09±0.5	−54.0±4	−10.33±1	−70.3±9	−10.80±1	−74.0±9	−22.1±1	−162±9
Michigan	−7.07±0.7	−53.9±6	−9.06±1	−62.1±9	−9.35±1	−64.3±9	−20.9±1	−155±9
Erie	−7.07±0.3	−53.9±2	−8.86±1	−57.4±9	−8.82±1	−57.4±9	−19.5±1	−127±9
Ontario	−6.52±0.3	−48.3±2	−10.15±1	−67.0±9	−10.53±1	−69.9±9	−21.1±1	−148±9

- Hydroclimatic inputs

Lake	U (km³/year)	P (km³/year)	R (km³/year)	Q (km³/year)	T_L (°C)	T_A (°C)	e (hPa)
Superior	-	64±19	50±12	66±7	4.9±1	0.3±1	4.7±0.2
Huron	146±33	52±16	49±12	208±26	6.4±1	6.5±1	7.6±0.3
Michigan	36±12	55±16	36±9	88±18	9.0±1	5.8±1	6.9±0.3
Erie	172±17	23±7	19±5	183±13	15.0±1	11.8±1	10.3±0.4
Ontario	183±13	16±5	34±8	225±4	9.4±1	6.5±1	7.4±0.3

- Timing and lake effect

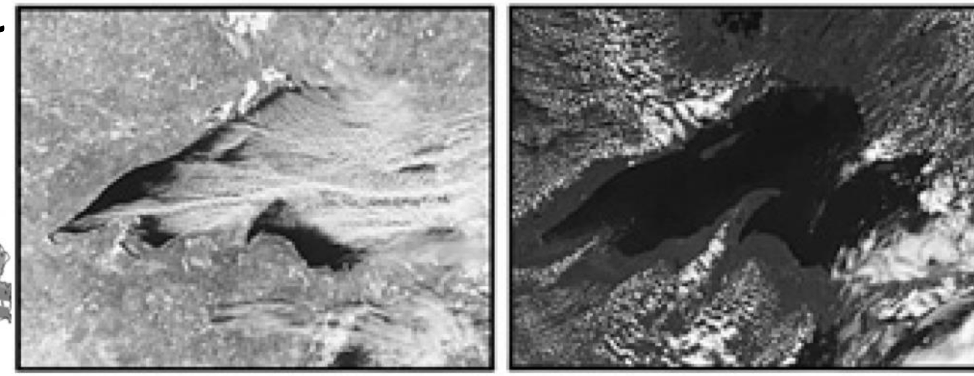
2008/2009 Evaporation rates



Spence et al. 2011

Winter

Summer



Winter

Isotope balance model for evaporate

Evaporate

$$\delta_{E'} = \frac{(\delta_L - [\alpha_{l \cdot v}{}^* - 1])/\alpha_{l \cdot v}{}^* - h\delta_{A'} - (C_k[1-h])}{1 - h + (C_k[1-h])}$$

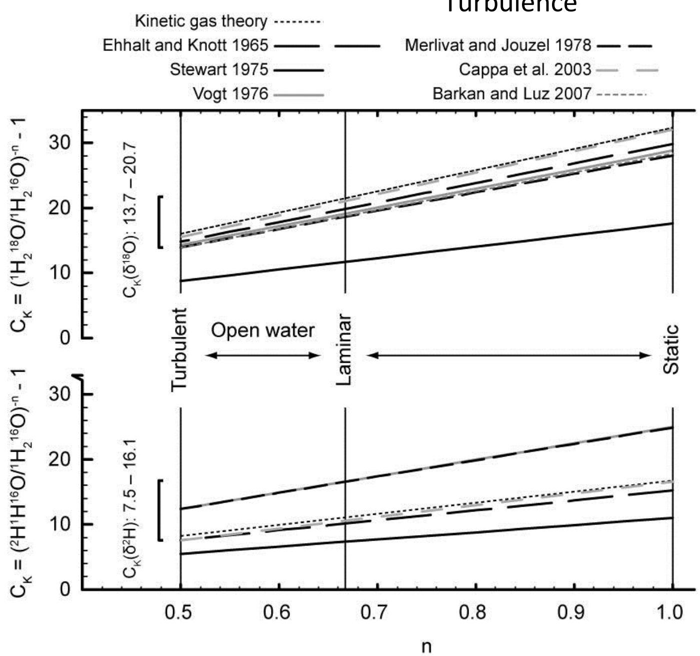
Atmospheric Feedback (lake effect)

$$\delta_{A'} = (1-x)\delta_A + x\delta_{E}{'}$$

Controls
- Fetch
- Evaporation rate

C_K values

Controls
- Boundary Layer Turbulence



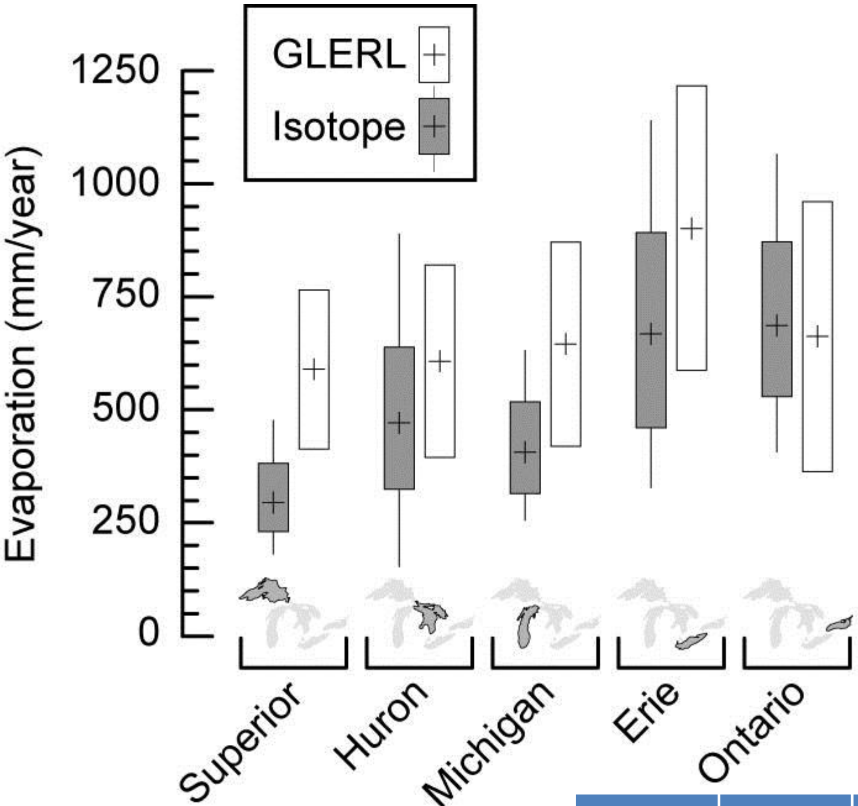
Convergence in our model

Lake	x
Huron	15%
Ontario	27%
Michigan	33%
Erie	40%
Superior	41%

Other studies (Gat et al. 1996): Western Mediterranean 30%

Eastern Mediterranean 69%-125%

Great Lakes: Results



-Lakes with long residence time have lower evaporation rates
-cooler climate in past?

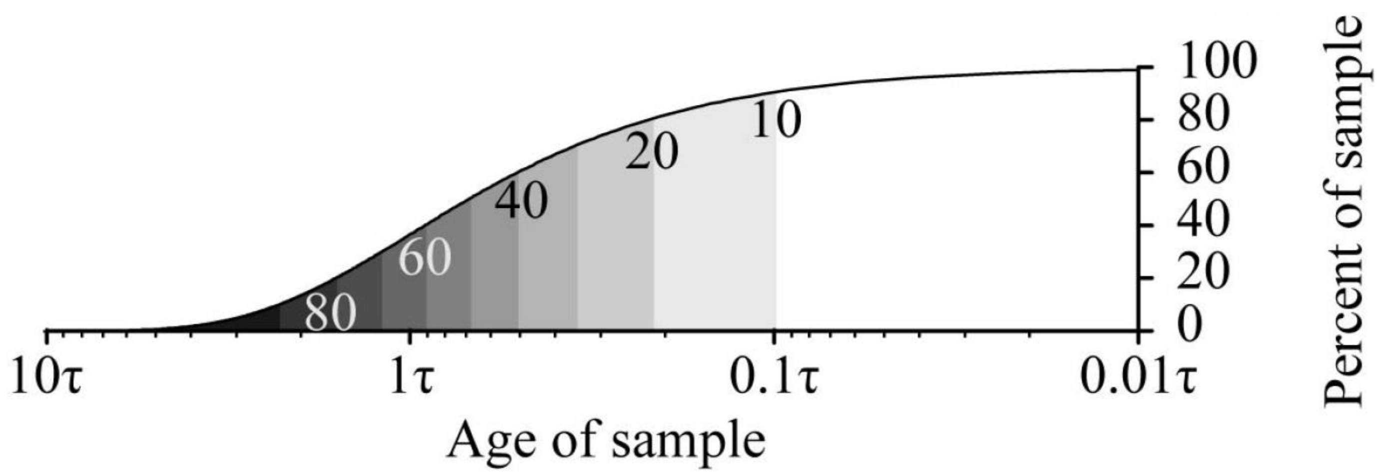
-Lake effect ranged from 15% for Lake Huron to 41% for Lake Superior

Table 7. Great Lake evaporation rates
•75th and 25th percentiles of Monte Carlo analysis
•shown for isotope-based uncertainties

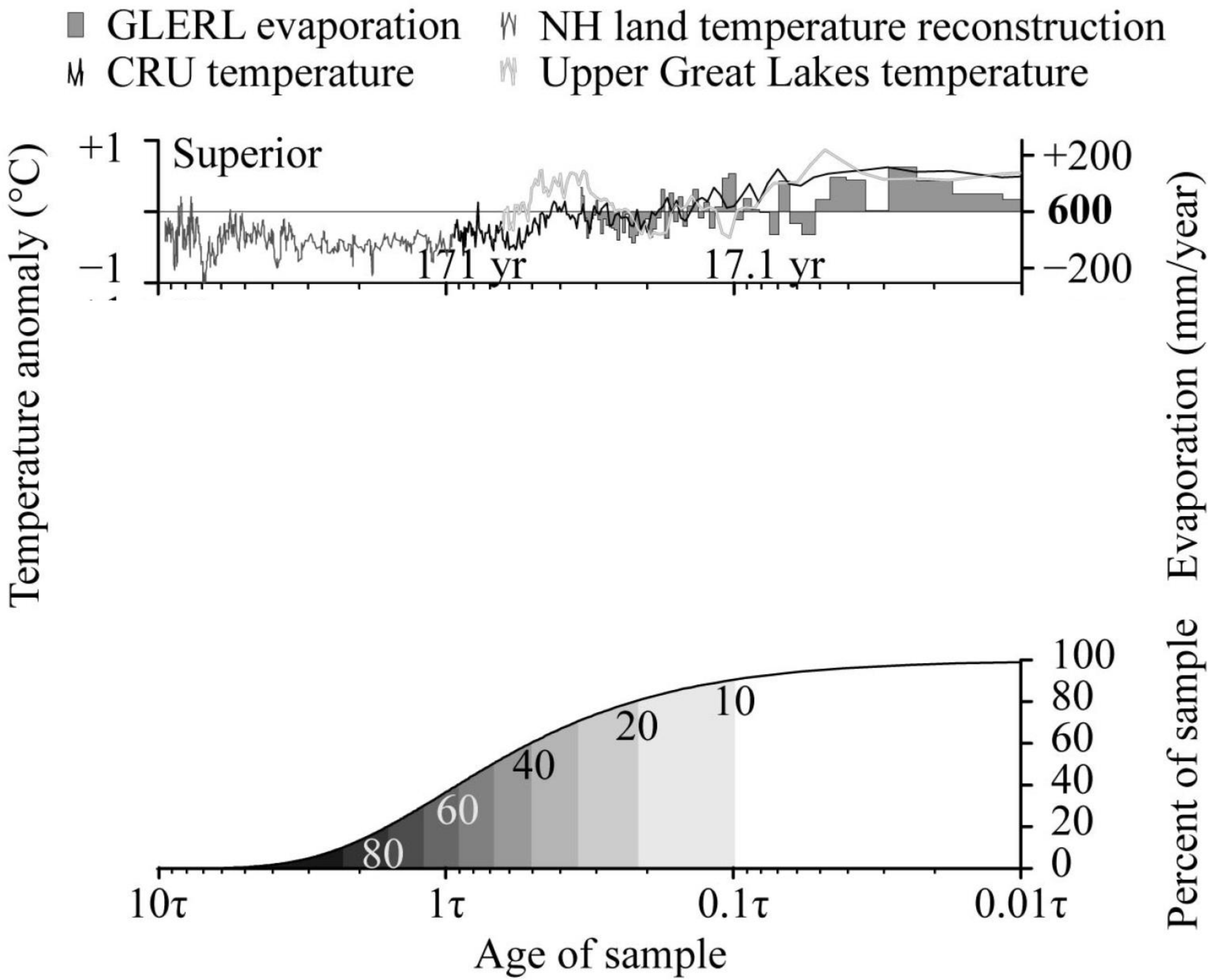
	Isotope	GLERL	Morton, 1967	Schertzer, 1973	Derecki, 1981	Lofgren and Zhu, 2000	Blanken et al., 2011
Superior	306±76	590±177	541	516	483	423	464, 645
Huron	483±157	609±213				521	
Michigan	418±101	646±226				445	
Erie	678±215	903±316			676	633	
Ontario	701±171	663±298	813			482	

Jasechko et al., 2014, in press, JGLR

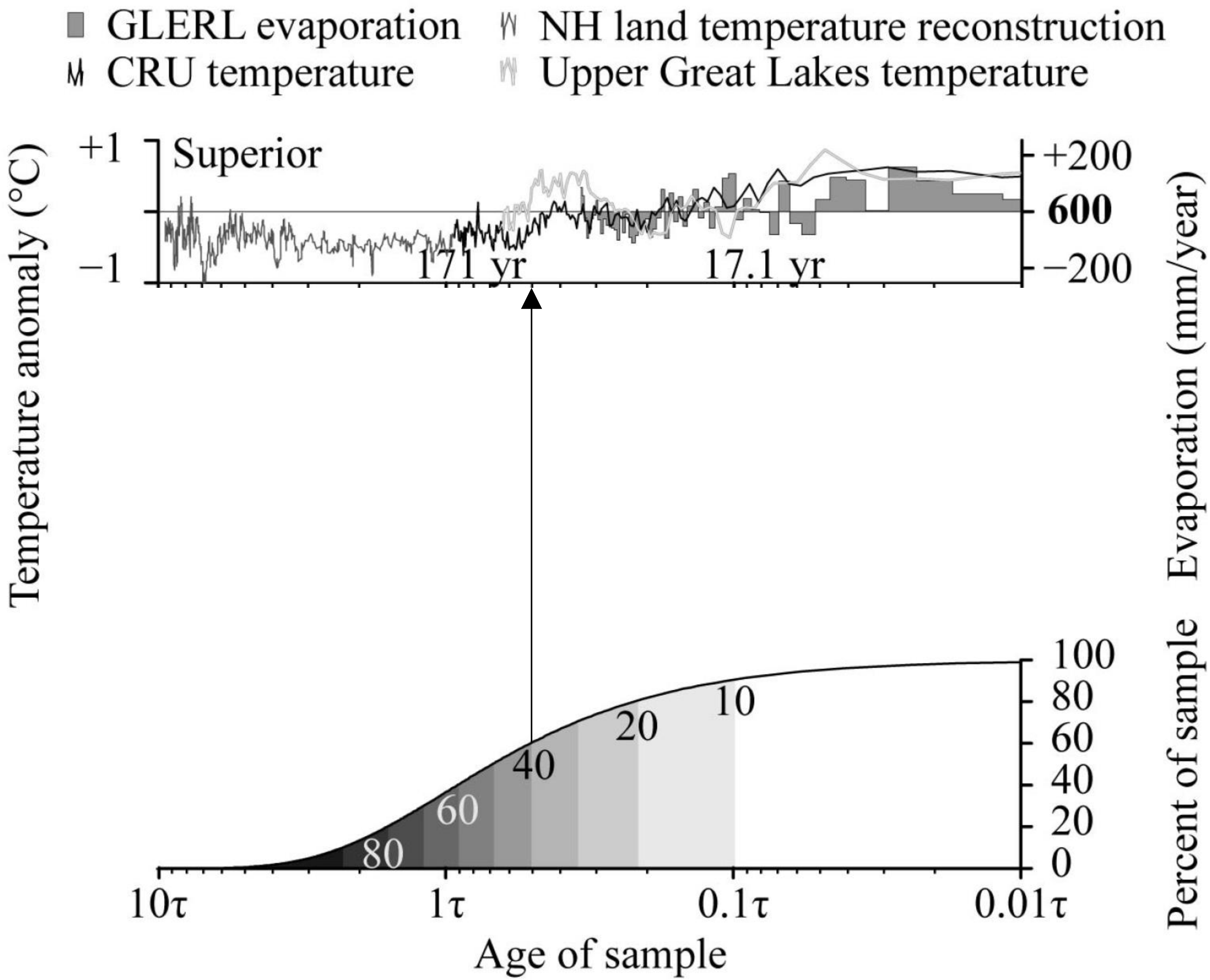
Residence time and climate



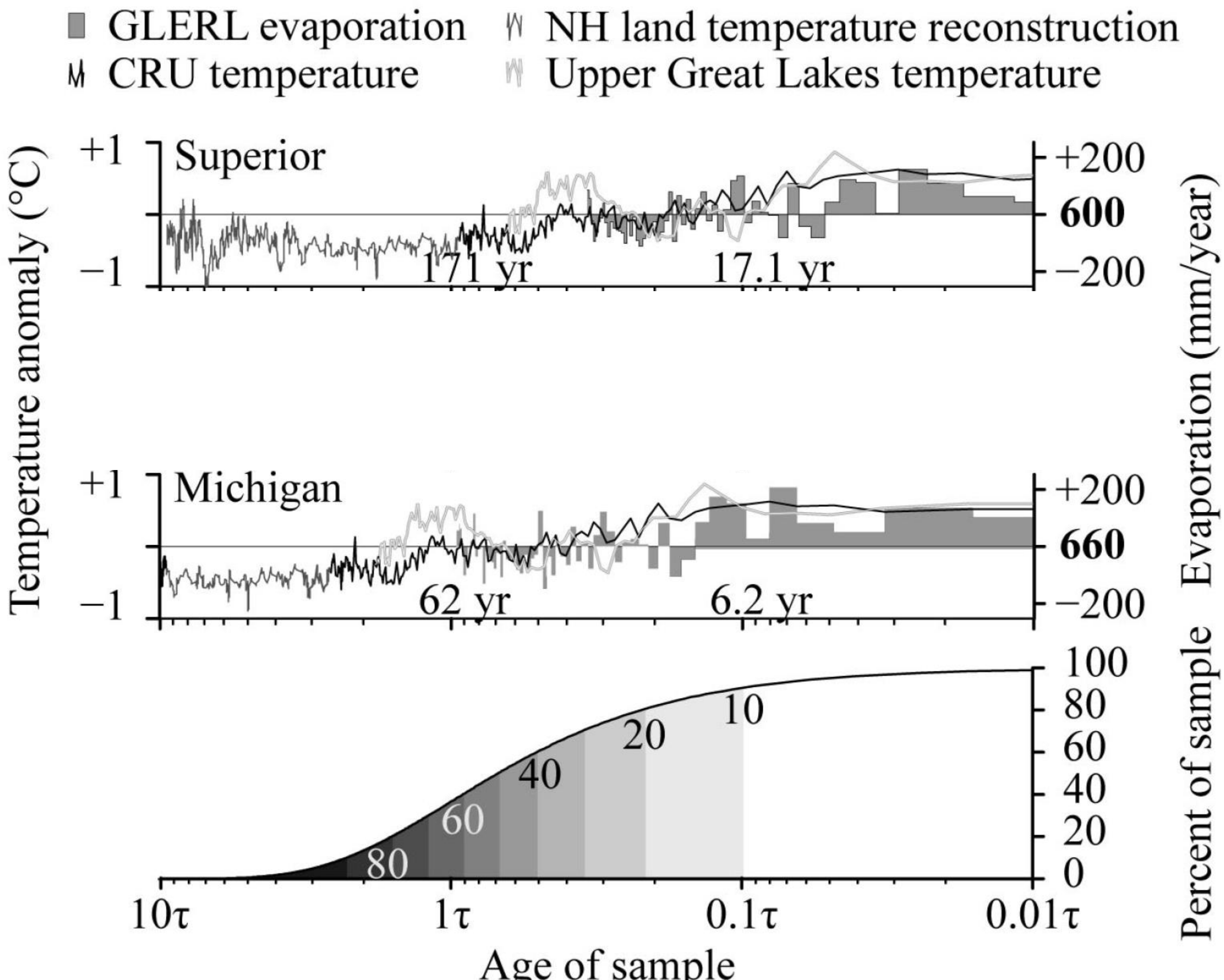
Residence time and climate



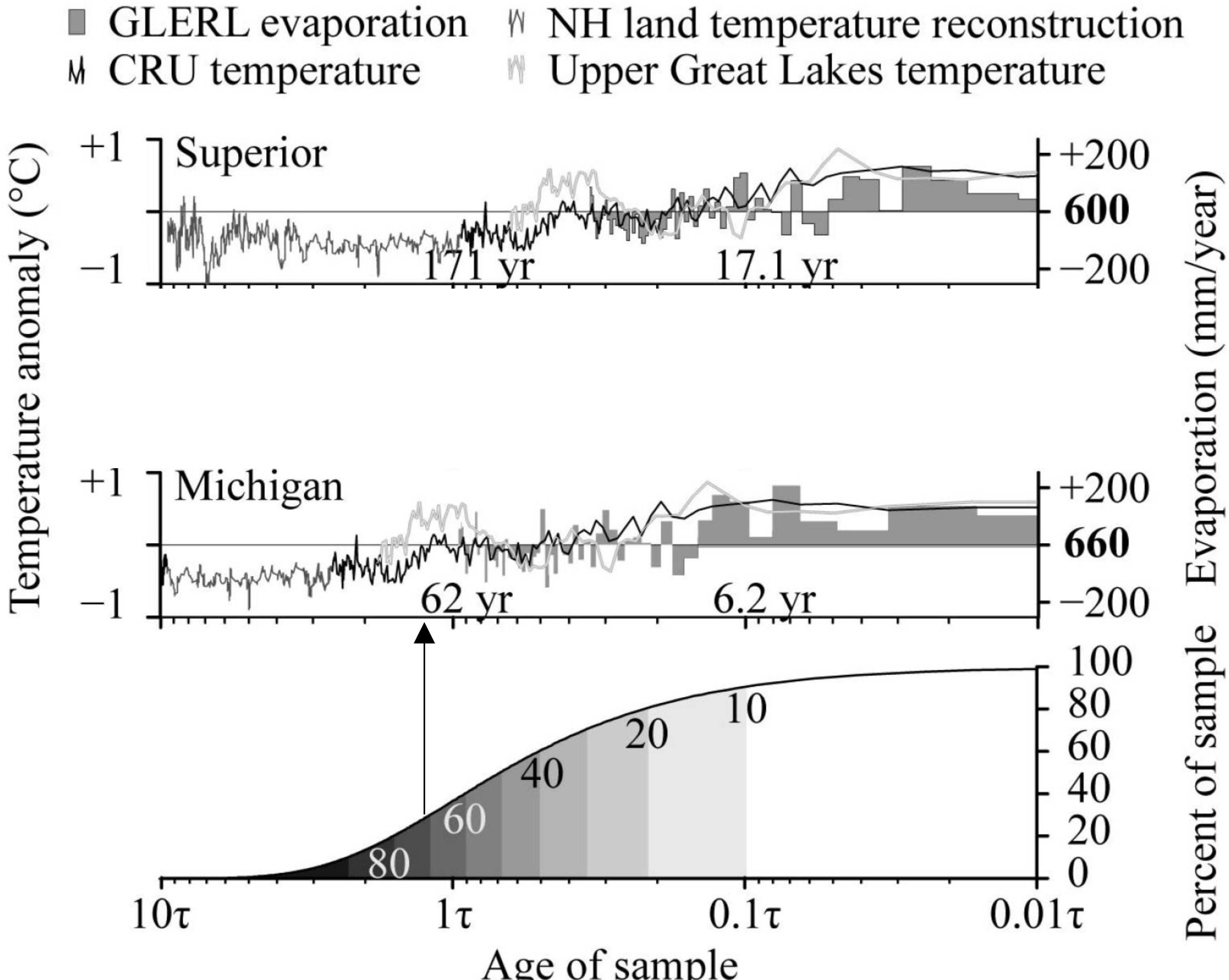
Residence time and climate



Residence time and climate



Residence time and climate

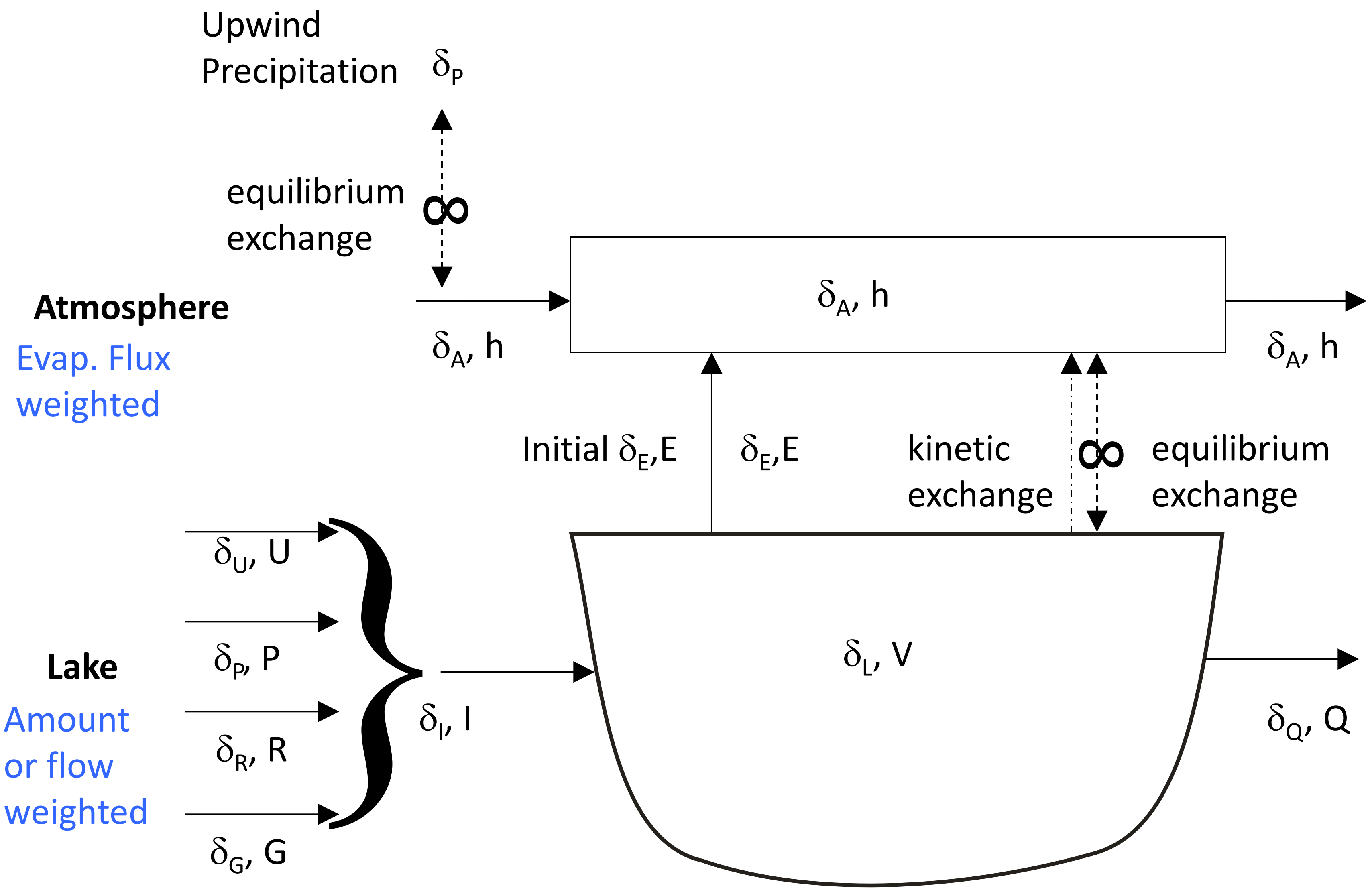


Conclusions: Great Lakes

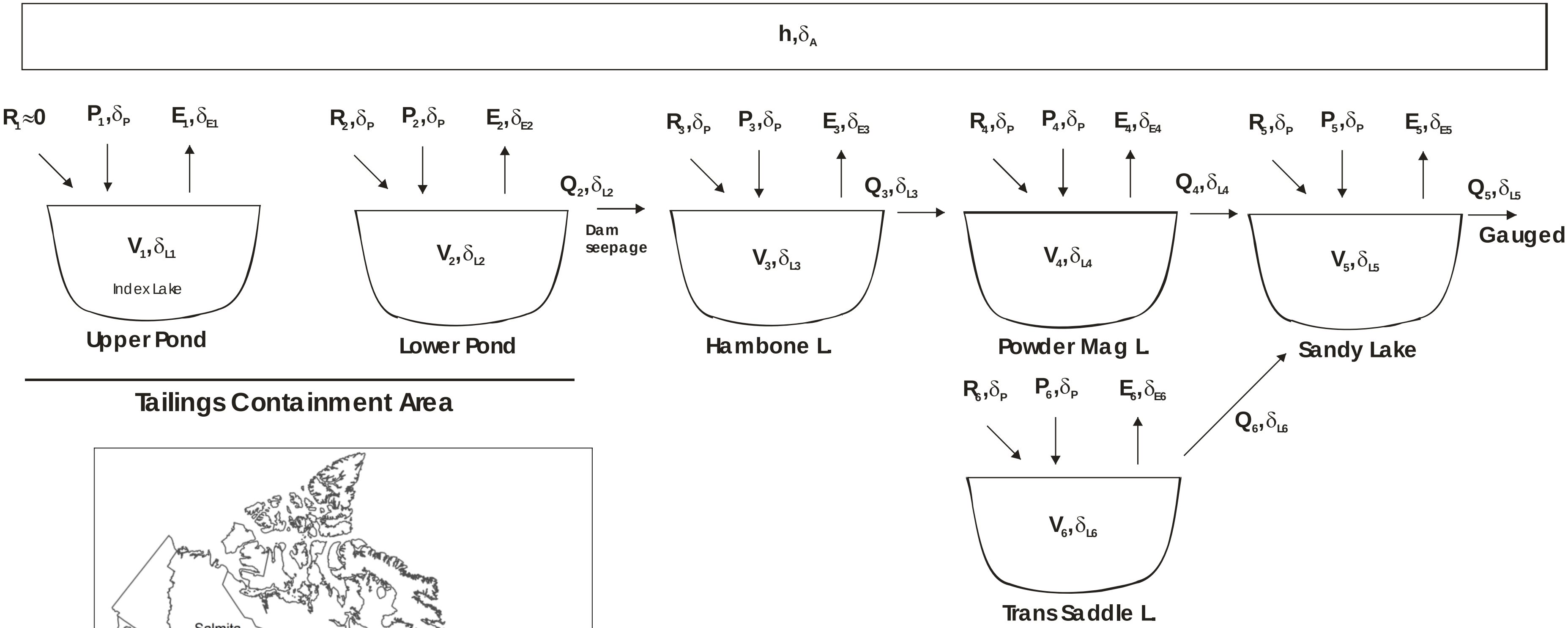
- New isotope dataset- best available spatial/temporal data for Great Lakes
- IMB method developed for large lakes allows simultaneous solution of:
  - lake effect, isotopic composition of evaporate, and evaporation rate
- Lake effect on boundary layer ranges from 15% (Huron) to 41% (Superior)
- Isotope-based evaporation rates range from 306 mm/year (Superior) to 701 mm/year (Ontario)
- Longer residence time lakes have lower isotope-based E relative to GLERL estimates
- Evidence that historical rates of evaporation were lower especially in lakes Superior and Michigan

Weighting and Atmospheric Feedback

Small Lake – No Atmospheric Feedback

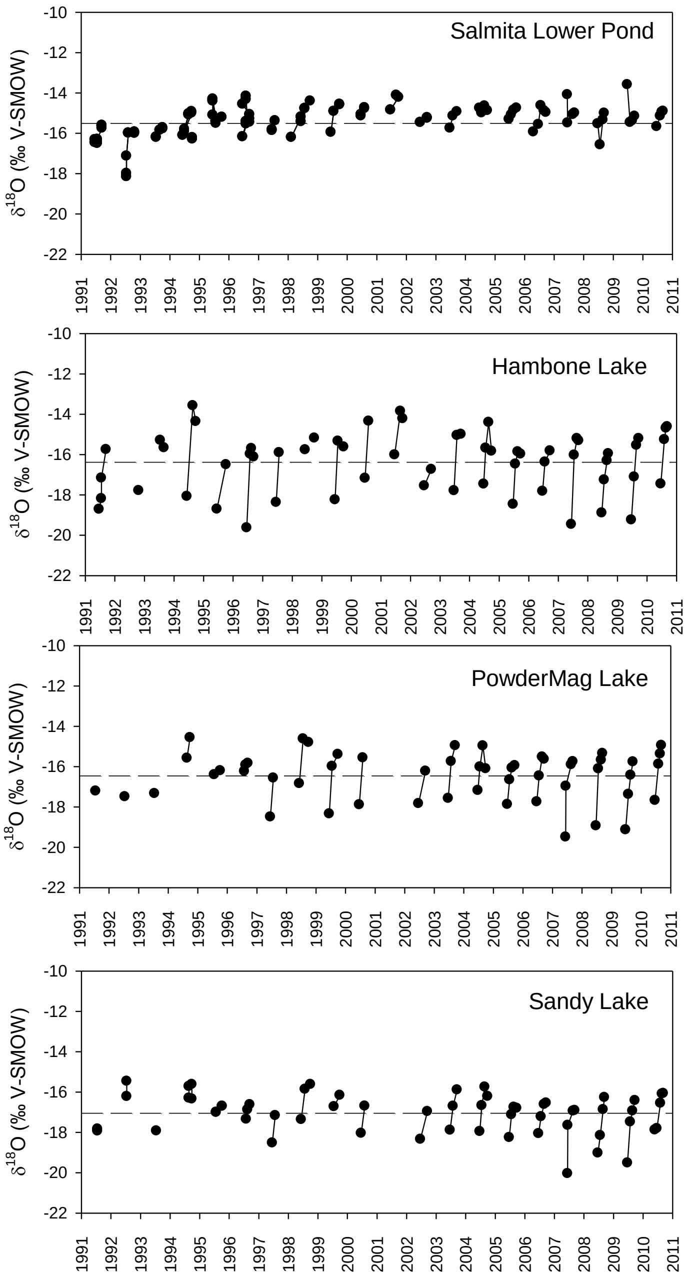


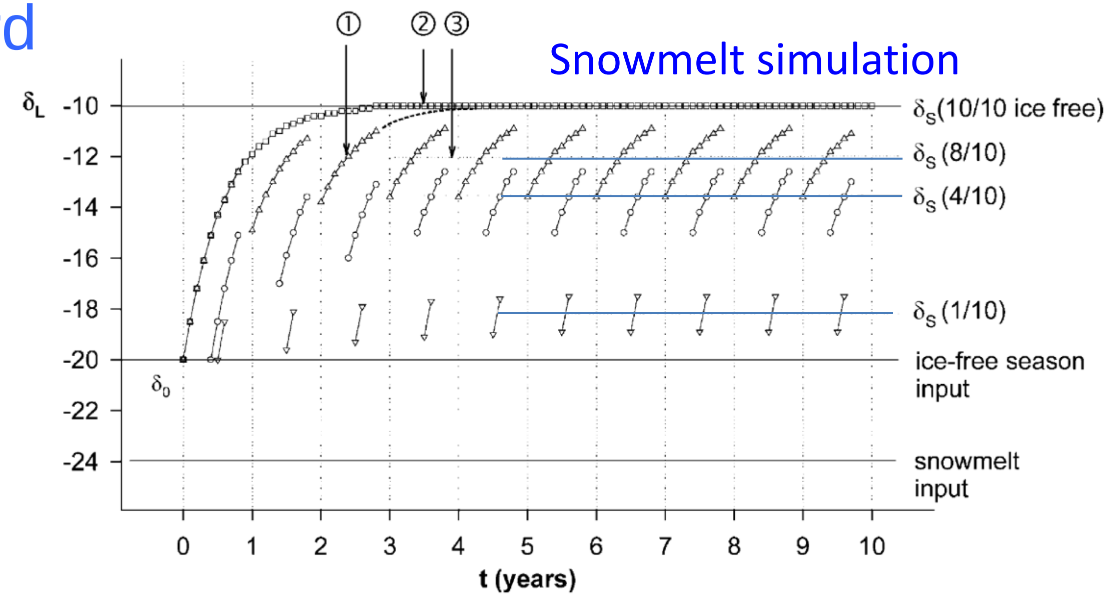
Salmita: Chain-of-lakes model

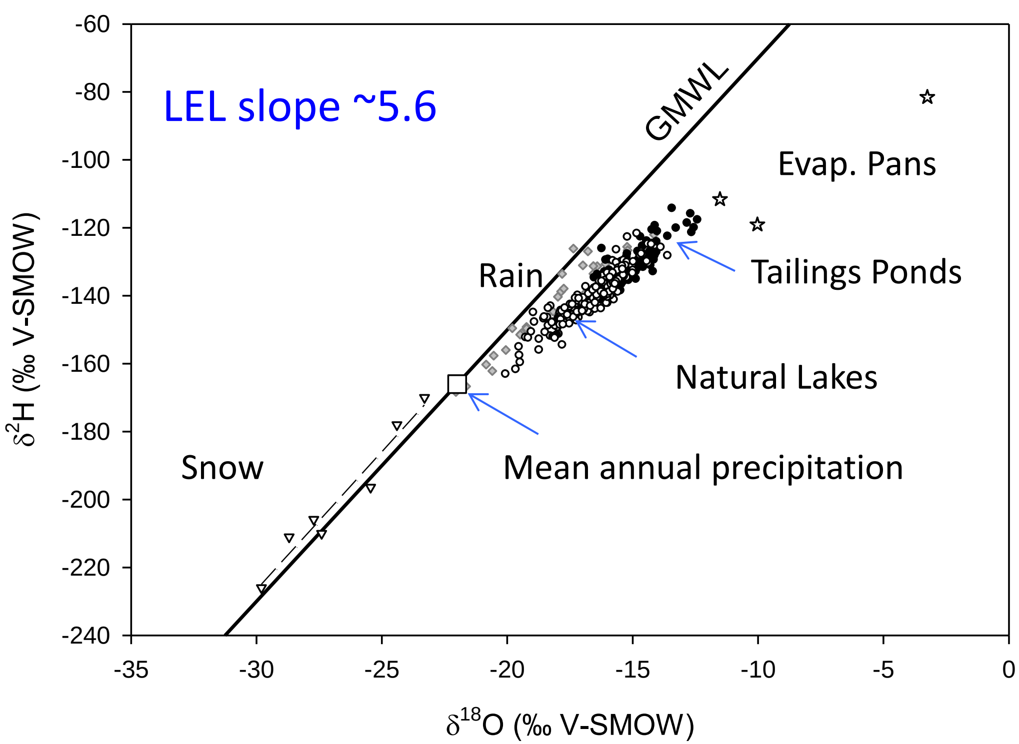


- a decommissioned mine site
- 64°N, continuous permafrost, tundra

Salmita: a 20-year record

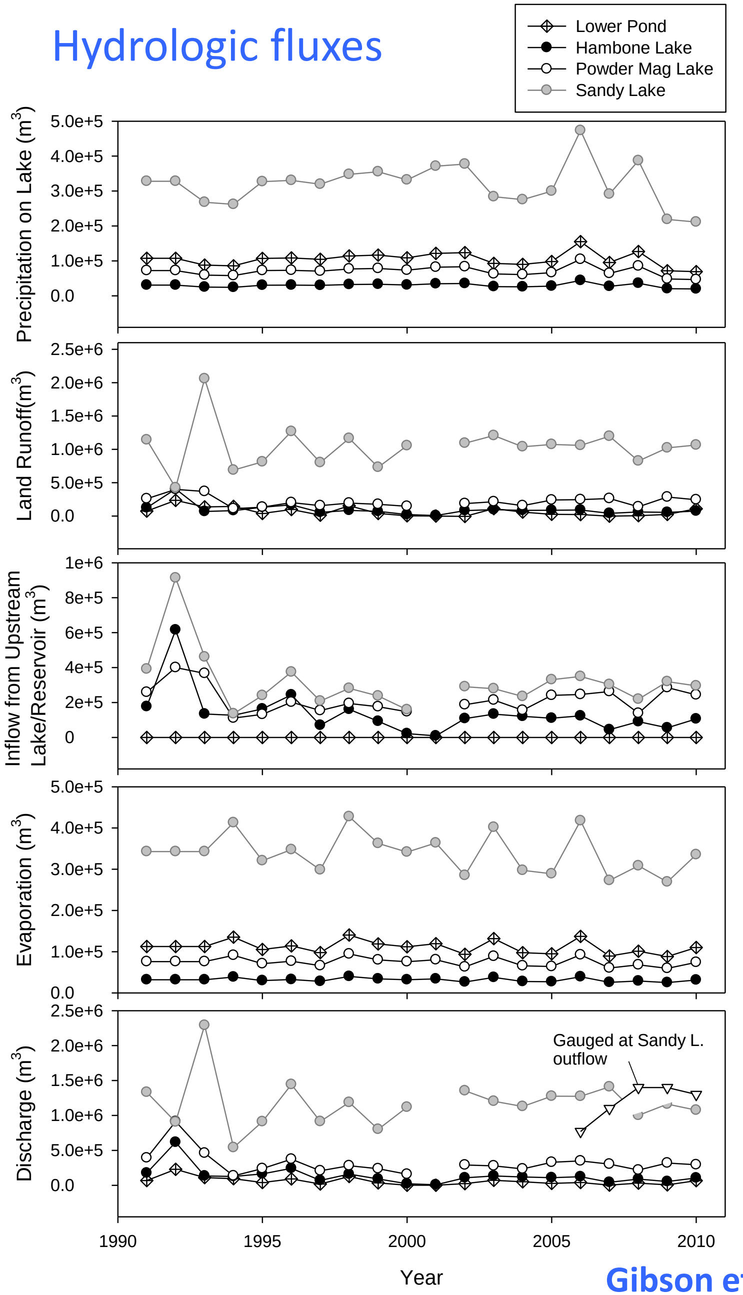




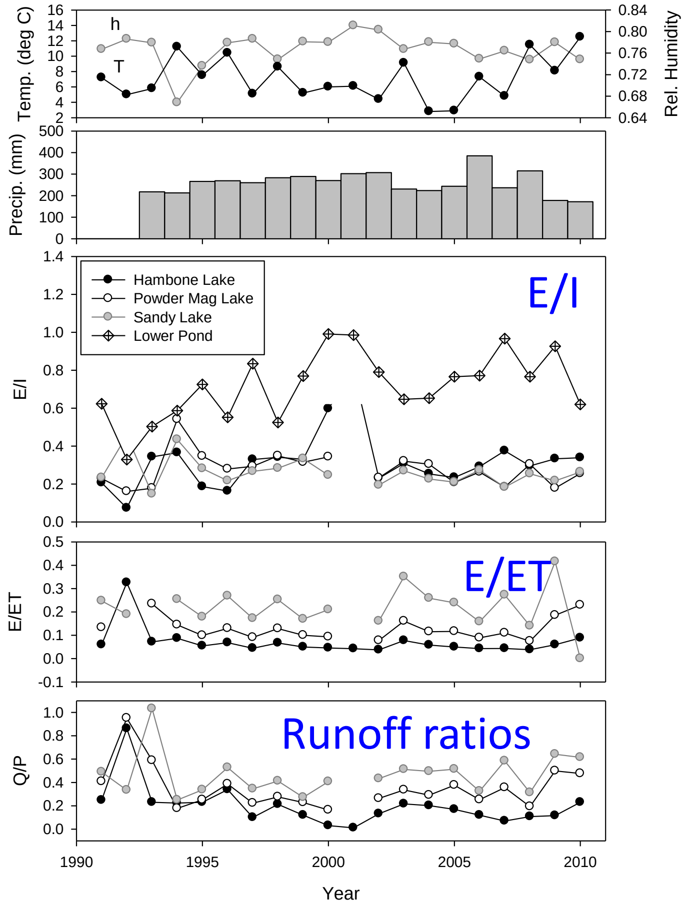


Salmita: Results

Hydrologic fluxes

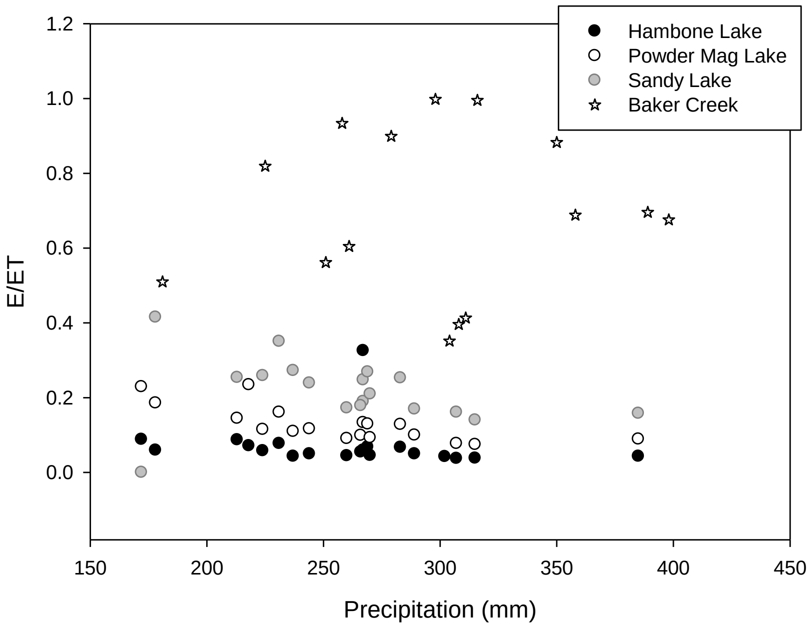


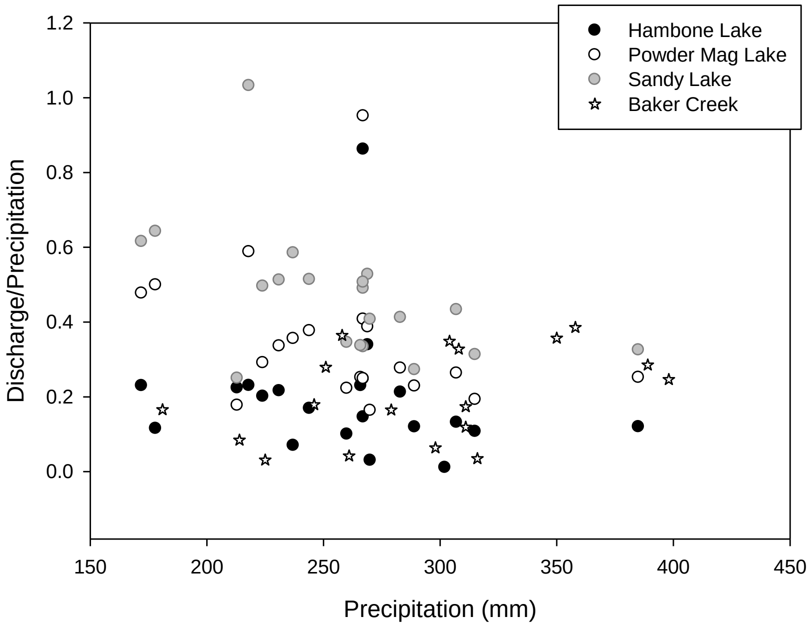
Key indicators



Gibson et al., in review

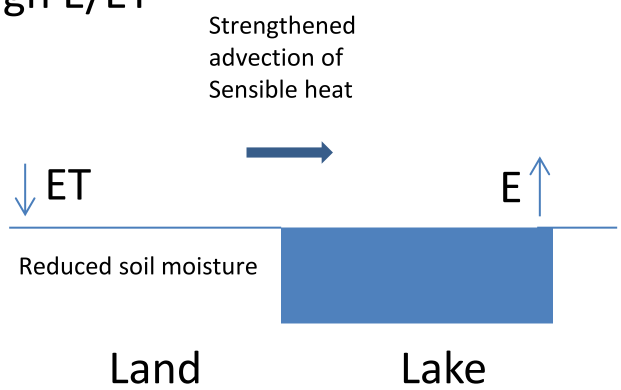
Salmita: Results



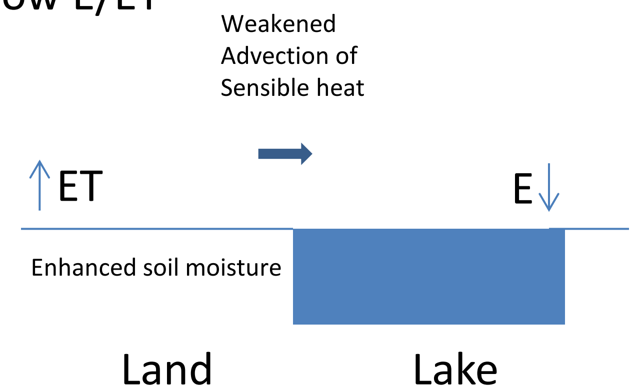


Conclusions: Salmita

DRY: high E/ET



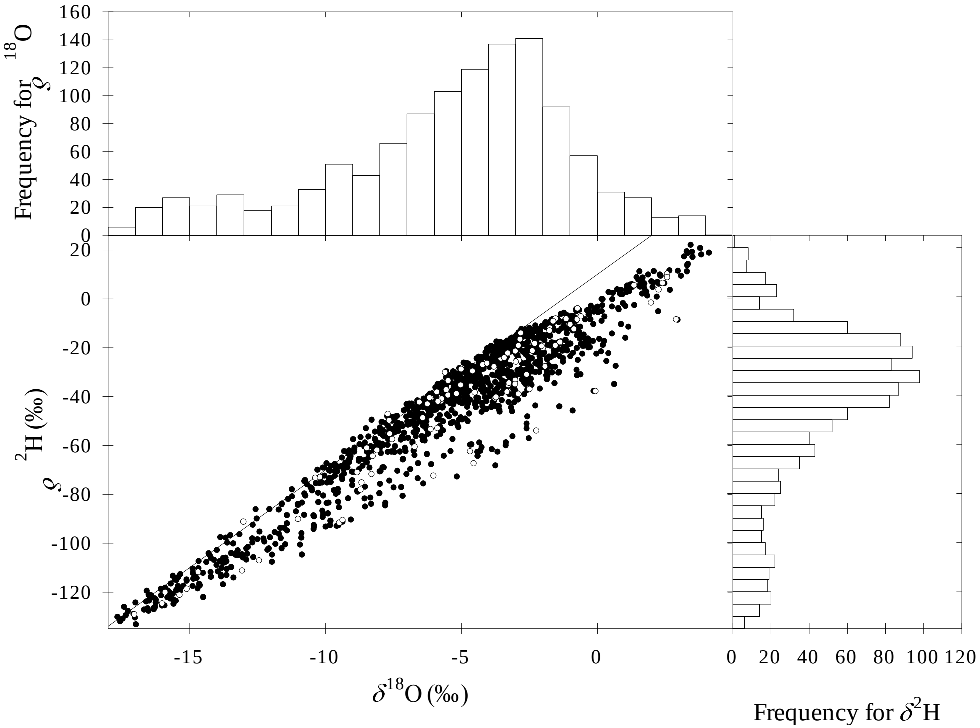
WET: low E/ET

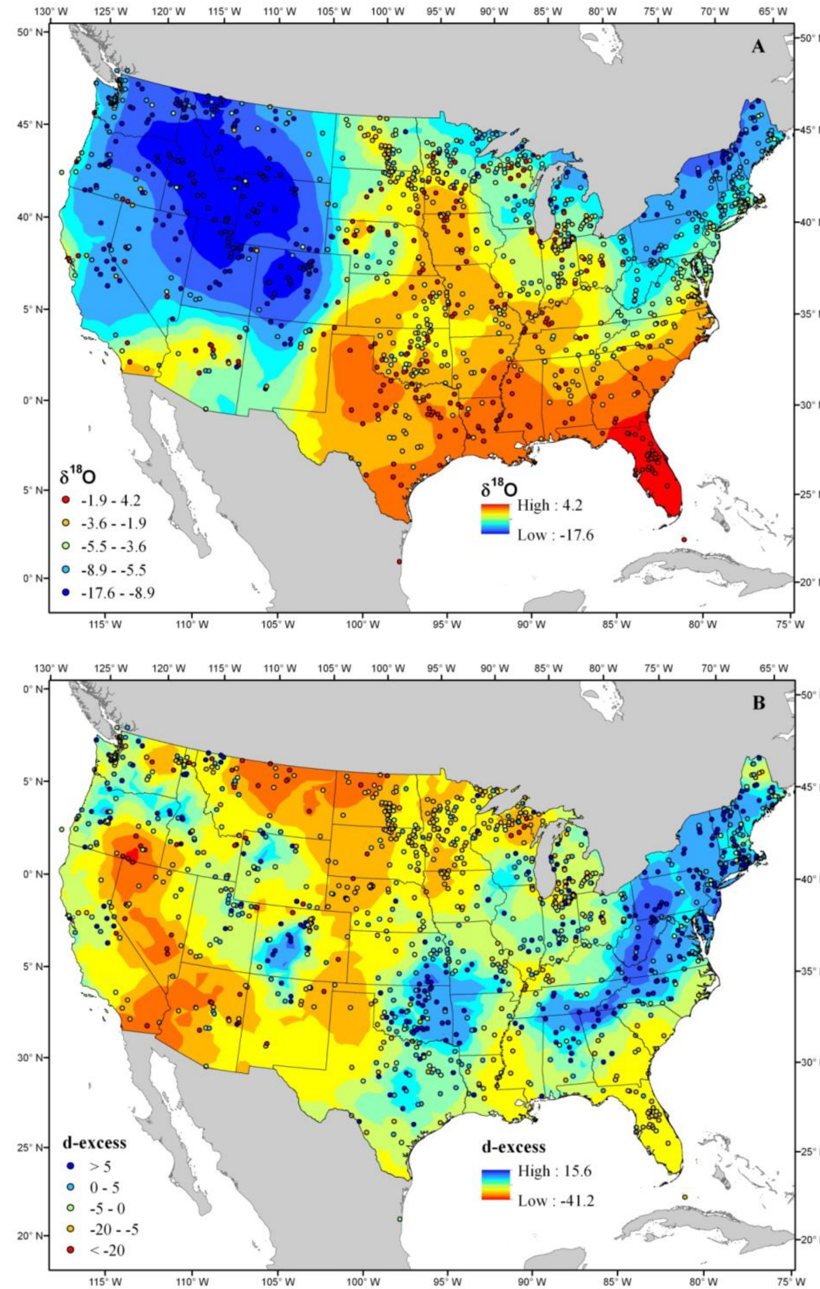


- E/ET patterns attributed to land-lake advection and soil moisture conditions
- Runoff ratios higher in low precipitation years due to active layer storage effects
- Natural lakes evaporate 25-30% of inputs
- Mine-tailings ponds evaporate 72-100% of input but still are leaky
- Evaporation is not a complete solution to acid mine drainage in region

EPA survey:1000+ lakes

2007 US Environmental Protection Agency's National Lakes Assessment (NLA)

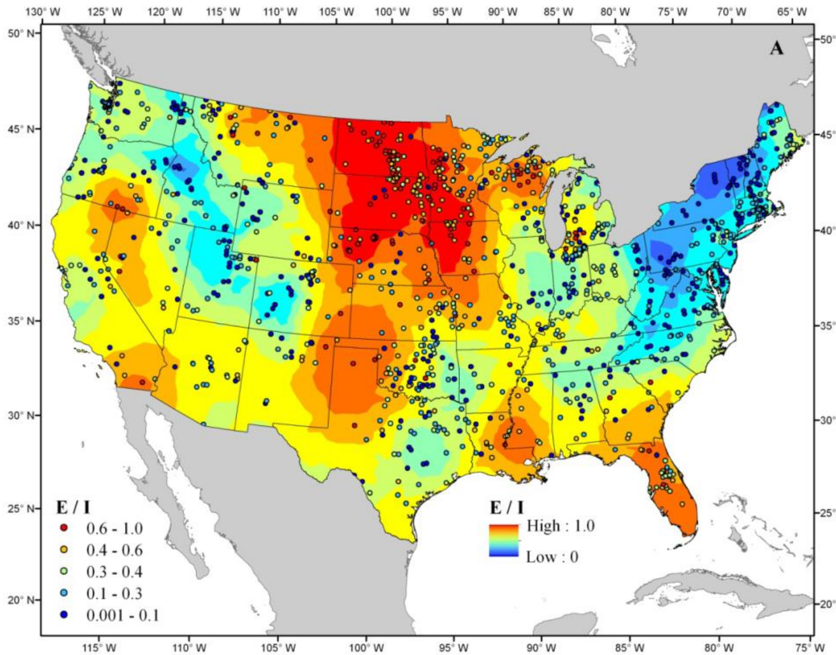


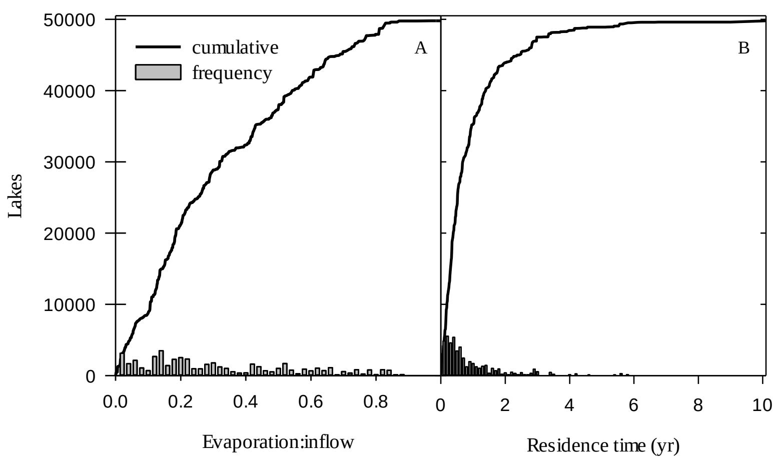


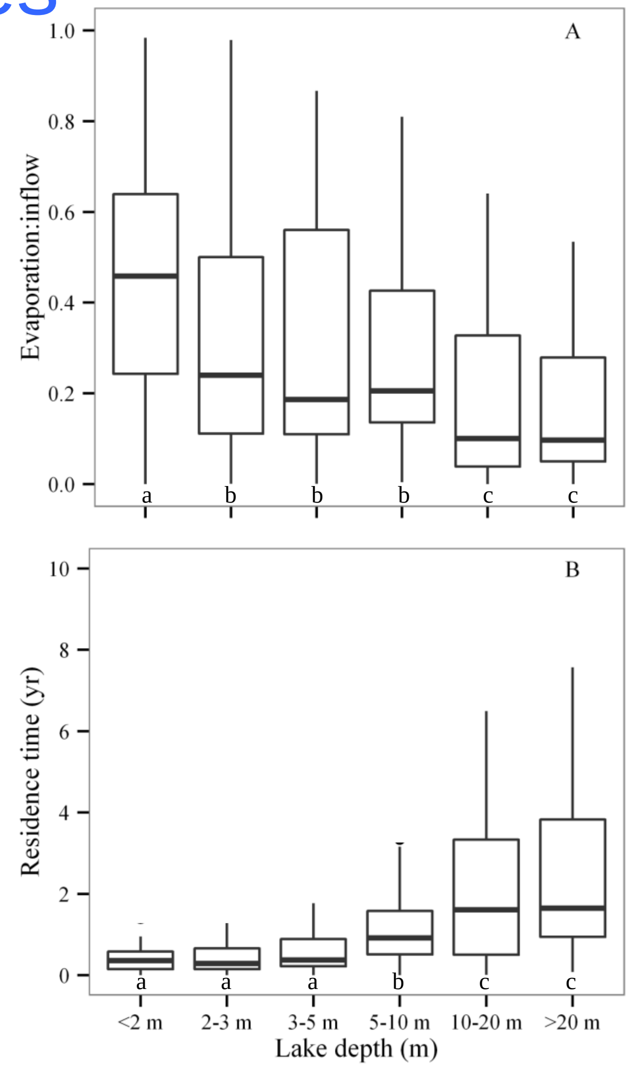
-systematic isotopic enrichment in lakes applied to estimate E/I and residence time

Brooks et al., in review

EPA survey:1000+ lakes



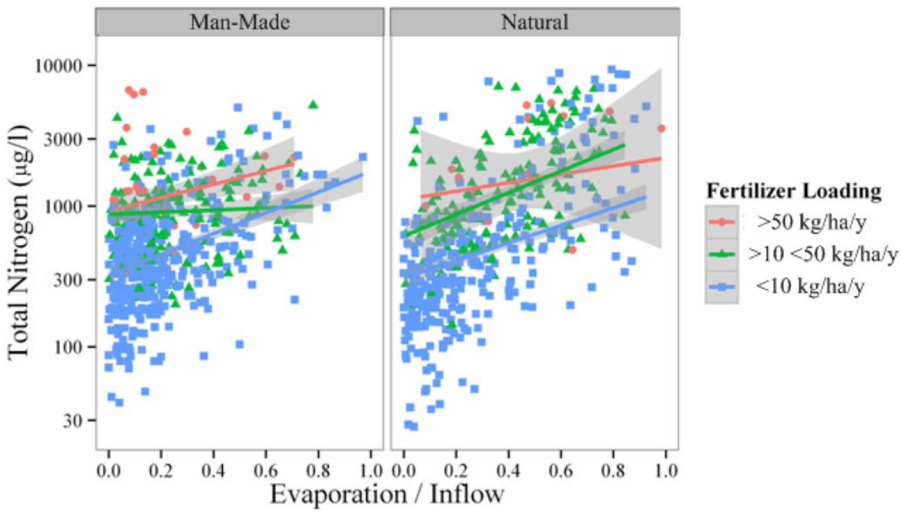


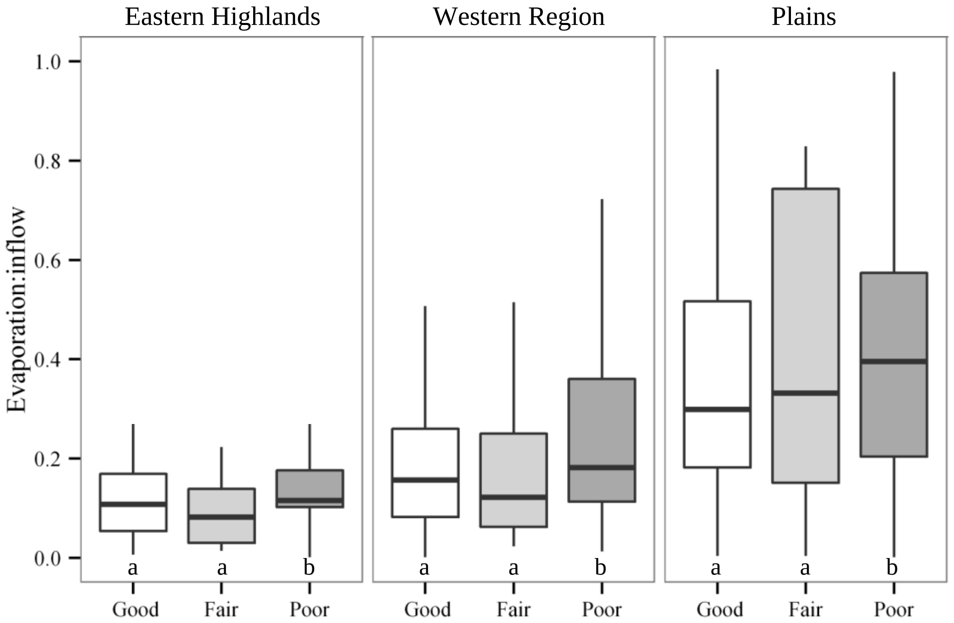


Brooks et al., in review

-climate is main driver of lake water balance
-climatic versus local factors

EPA survey:1000+ lakes



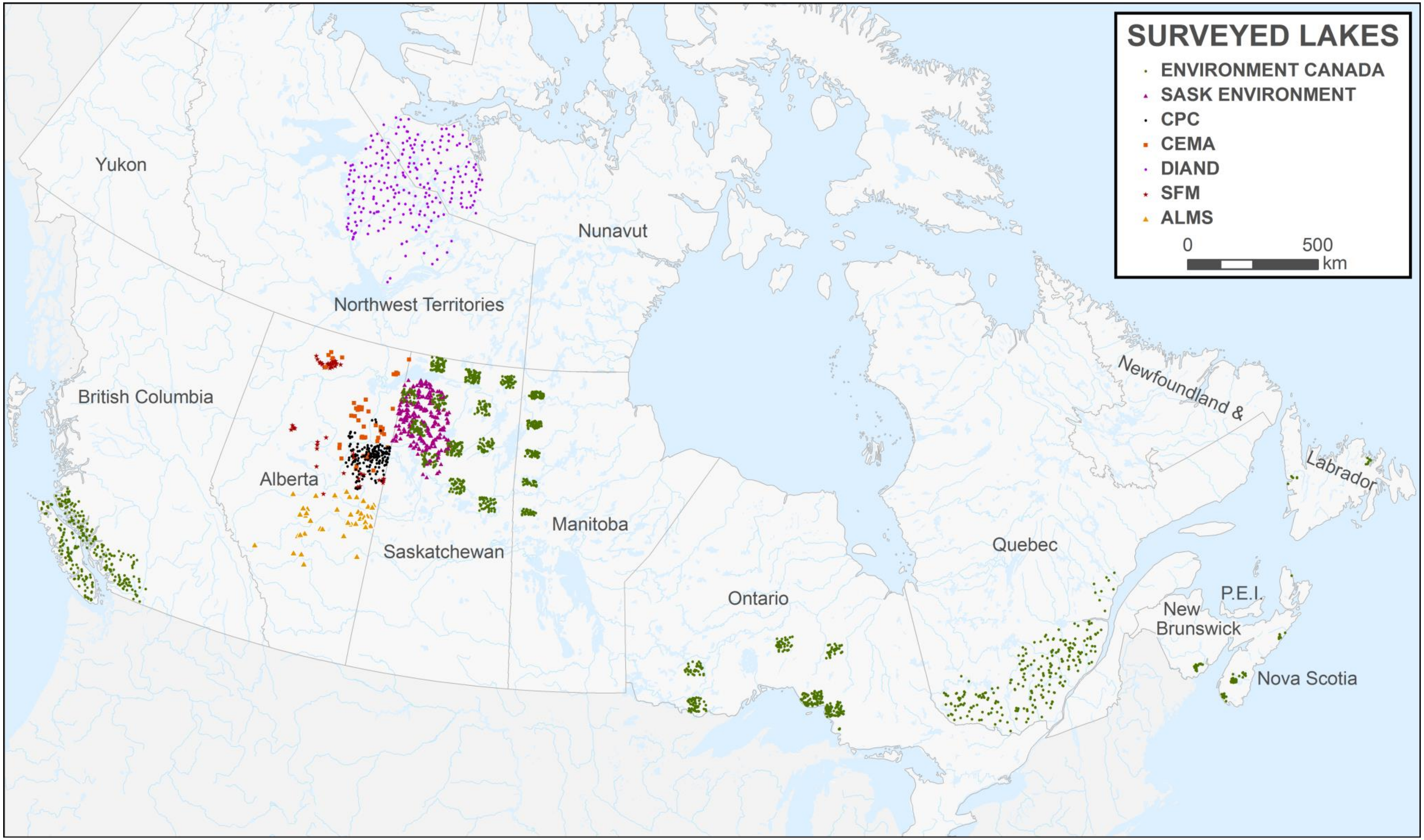


Brooks et al., in review

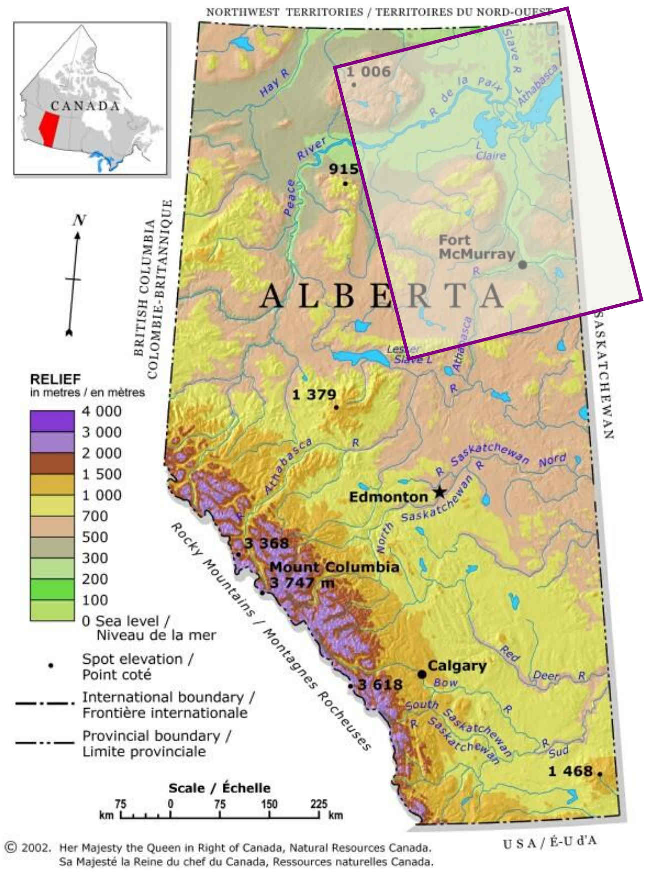
Conclusions: EPA survey

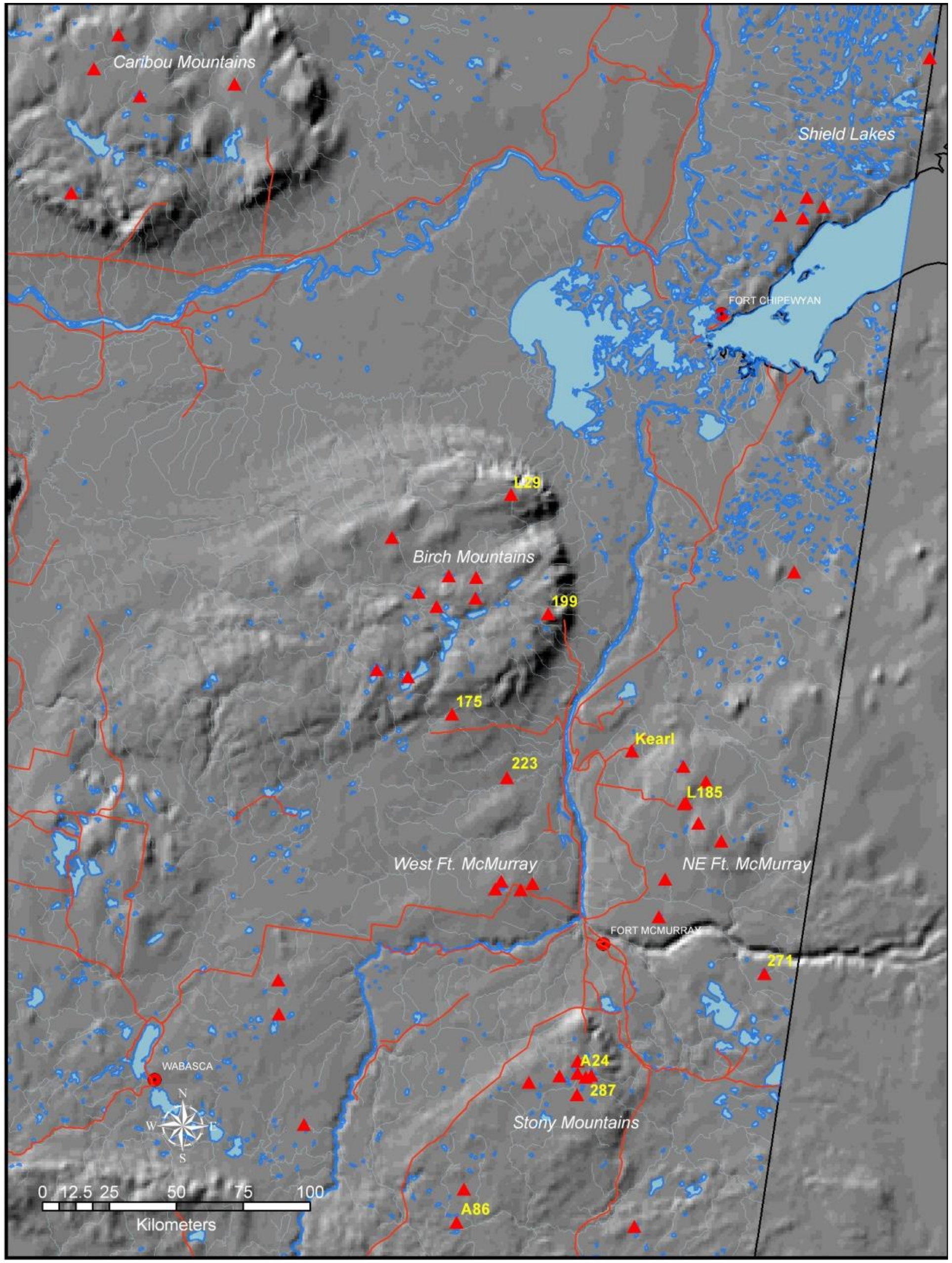
- In general deep lakes have lower E/I and longer residence times than shallow lakes
- E/I is correlated with hydrochemistry and TN
- lakes in poor biological condition (based on phytoplankton and zooplankton taxon loss) tended to have higher E/I
- whether TN pattern due to throughput (flushing) or groundwater influence was not determined
- Use in national lake assessments allows better understanding of water quantity-water quality relationships

Lake surveys across Canada mainly for acid sensitivity assessment



LOCATION:


NORTHWEST TERRITORIES / TERRITOIRES DU NORD-OUEST
CANADA
ALBERTA
BRITISH COLUMBIA
COLOMBIE-BRITANNIQUE
SASKATCHEWAN
Fort McMurray
Edmonton
Calgary
Mount Columbia
3 747 m
Rocky Mountains / Montagnes Rocheuses
RELIEF
in metres / en mètres
4 000
3 000
2 000
1 500
1 000
700
500
300
200
100
0 Sea level / Niveau de la mer
Spot elevation / Point coté
International boundary / Frontière internationale
Provincial boundary / Limite provinciale
Scale / Échelle
USA / É-U d'A
© 2002. Her Majesty the Queen in Right of Canada, Natural Resources Canada.
Sa Majesté la Reine du chef du Canada, Ressources naturelles Canada.


Caribou Mountains
Shield Lakes
FORT CHIPEWYAN
Birch Mountains
L29
199
175
Kearl
223
L185
West Ft. McMurray
NE Ft. McMurray
FORT MCMURRAY
271
WABASCA
A24
287
Stony Mountains
A86
0 12.5 25 50 75 100
Kilometers

Isotope Mass Balance

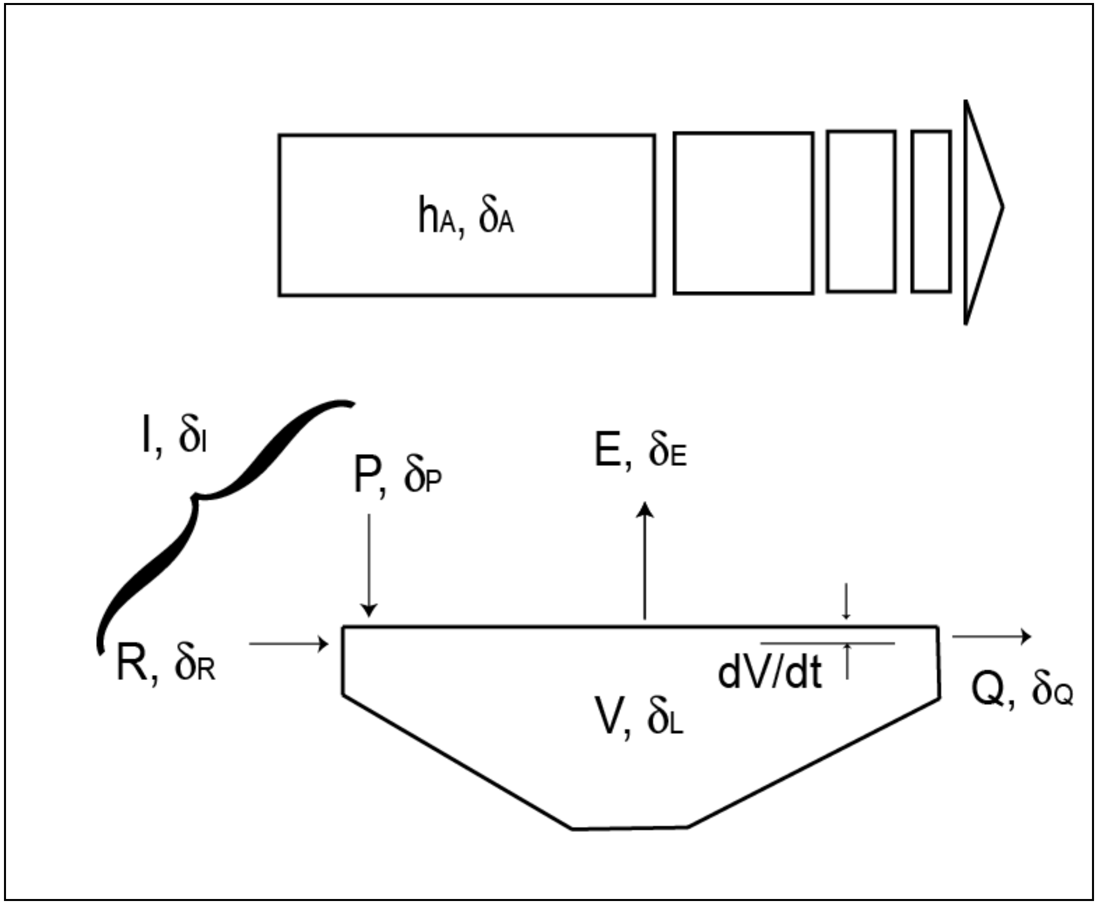
-using: $^{18}O/^{16}O$ in H_2O
$^{2}H/^{1}H$ in H_2O

Mass Balance

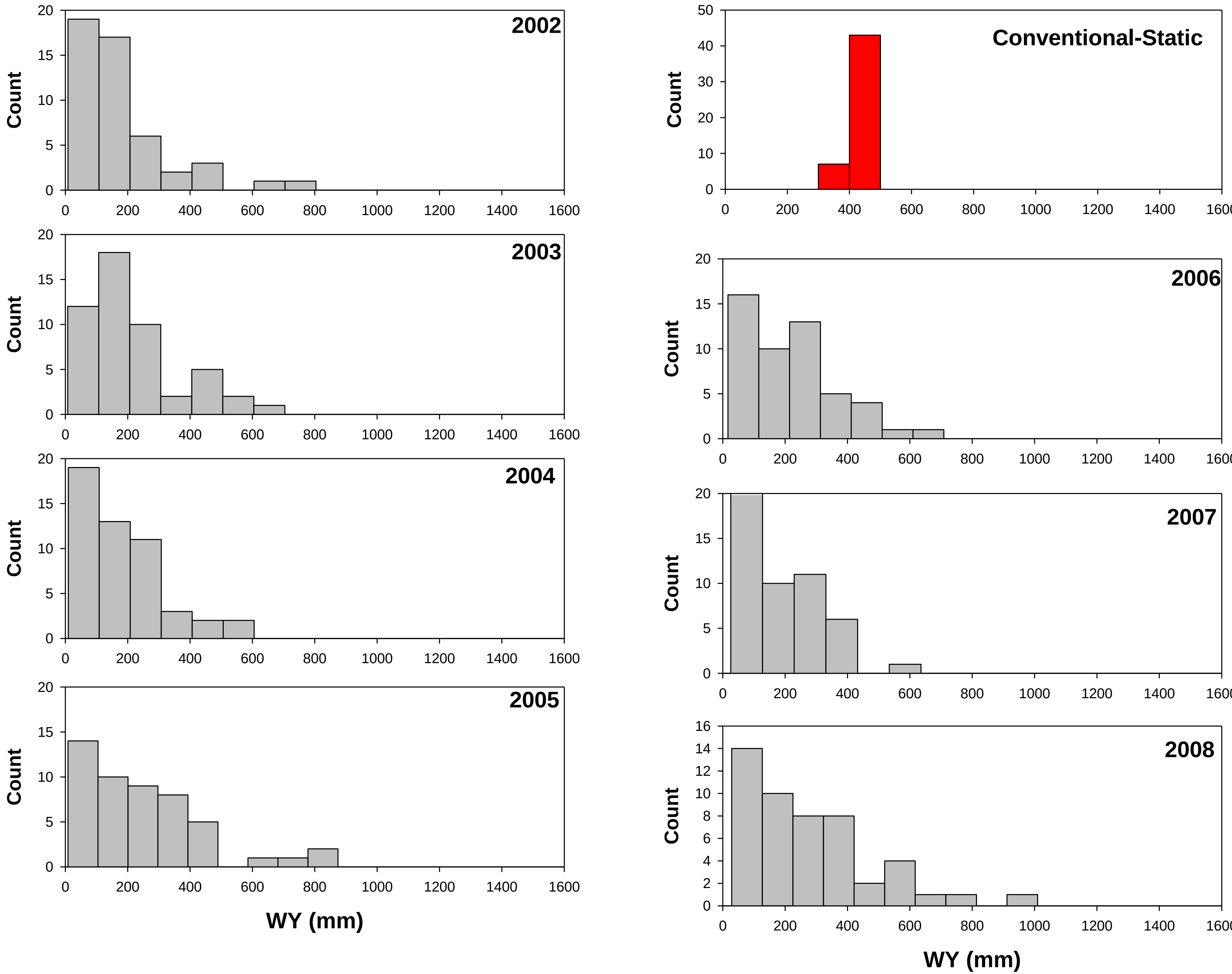
$$dV/dt = I - Q - E$$

Isotope Balance

$$\frac{d(V\delta_L)}{dt} = I\delta_I - Q\delta_Q - E\delta_E$$



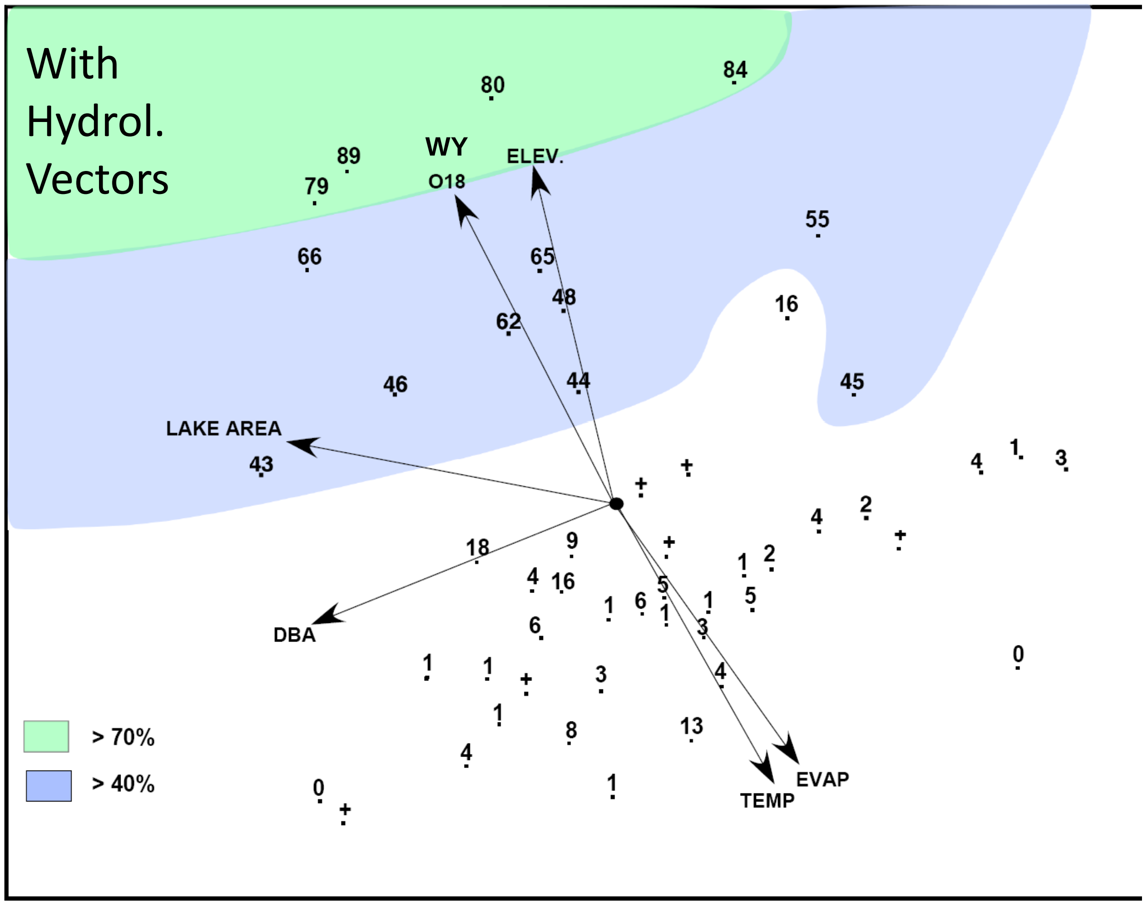
-throughflow/flushing rate   x = E/I
-residence time   V/I
-catchment water yield   R
=> $CL = [BC^*_0 - ANC_{lim}]\ R$



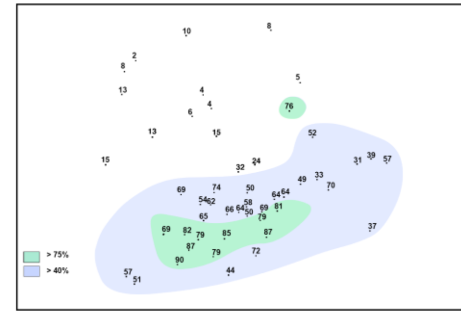
2002
2003
2004
2005
Conventional-Static
2006
2007
2008
Count
WY (mm)
0
200
400
600
800
1000
1200
1400
1600

NMDS Ordination Analysis

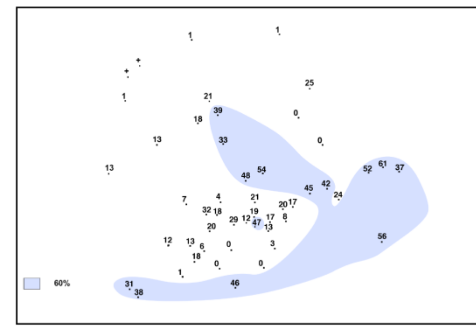
Bog % Cover



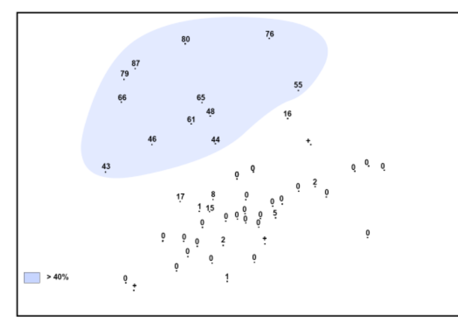
Fen % Cover



Uplands % Cover



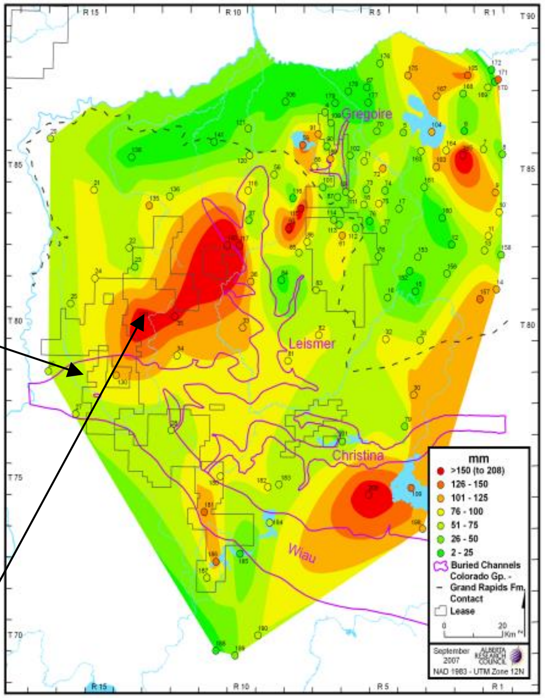
Permafrost % Cover



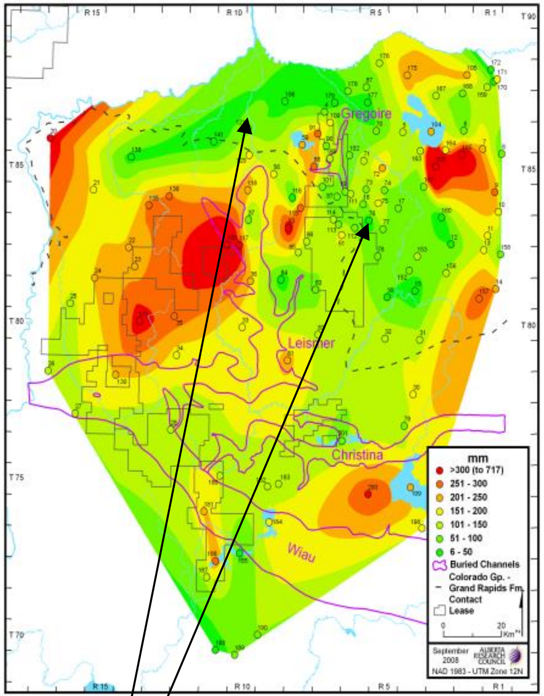
-non-metric multidimensional scaling analysis – ordination/gradient analysis technique

Runoff mapping potential

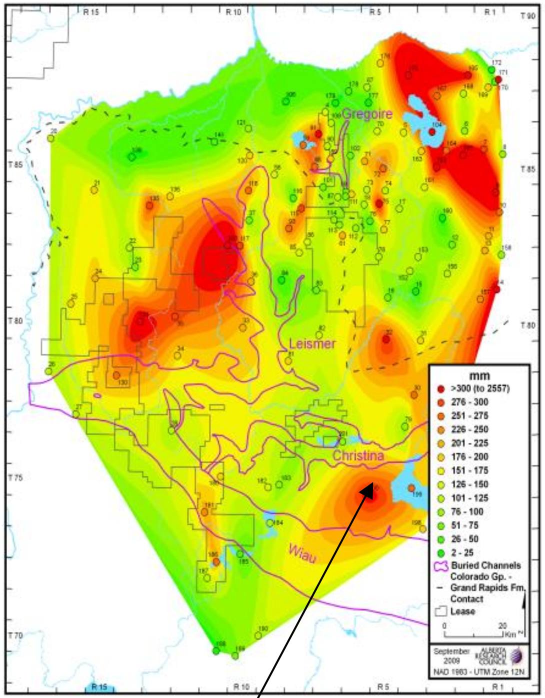
2007



2008



2009



Quaternary channels tend to occur in zones of transitional runoff

Stony Mountains (higher runoff to lakes due to higher precip., abundant ribbed wetlands, shale substrate)

Christina/Hangingstone Valley (lower runoff to lakes due to incised river capture)

Mostoos Uplands (higher runoff due to higher slope)

Conclusions: Alberta studies

- Bogs especially permafrost bogs important drivers of runoff
- Mapable variations across SAOS show influence of incised and buried channels
- Demonstrated to be useful for acid sensitivity assessments and design of monitoring/research networks

Summary

- Benefits:
  - enrichment signals are robust and models work fairly well
  - oxygen/hydrogen isotopes are both systematic i.e. LEL slopes are meaningful
  - Allows scaling-up of water balance and ET partitioning studies
  - Better understanding of present allows for improved quantitative interpretation of paleoclimate/paleohydrology proxies

- Challenges and limitations:
  - still lack comparative datasets of isotopes in gauged lake basins
  - errors in E/I can be 30% or more without δ_L of upstream lake
  - few (if any) laser-based studies conducted of lake boundary layer, and

  as such Craig and Gordon model has not been significantly improved

- Future applications and research
  - Integration within water quantity/quality research programs at regional and national scale (e.g. WSC, LTRN)
  - Establishing physical drivers of water balance and underlying causes of water cycle variability
  - Quantifying moisture feedback of large lakes to the climate system
  - Study of the role of lakes in continental runoff
  - Integration of radon-222 to enable partitioning of surface/groundwater pathways

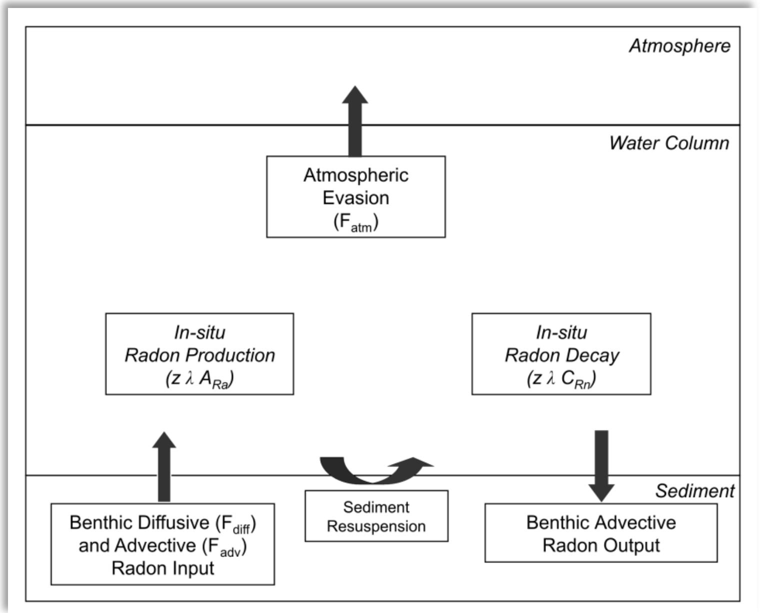
New technique: Radon-222 mass balance

- radon-222 is a colourless, odourless noble gas
- produced by decay of radium in soil/rock

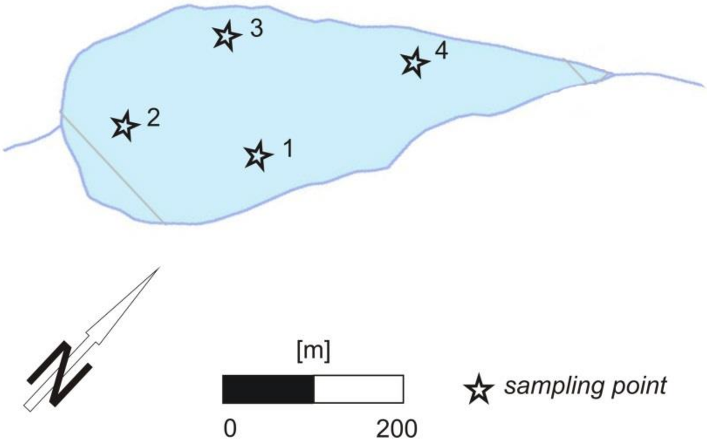
$^{226}Ra \rightarrow {}^{222}Rn \rightarrow {}^{218}Po$

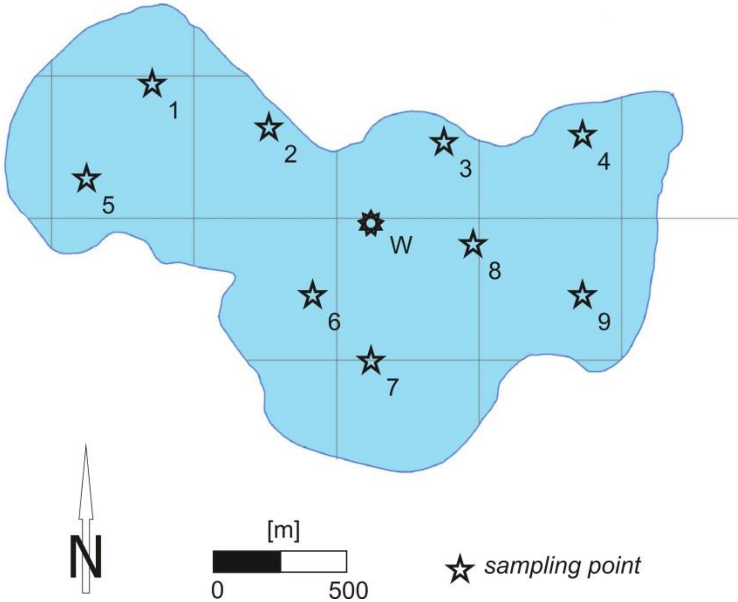
half-life: 1601 years, 3.8 days

- High contrast between radon-222 levels in surface water and groundwater in AOSR
- Allows for tracing of groundwater inputs



RAD7 portable radon monitor





NE07 Lake

ID	Radon [Bq/m³]		
M-1	1.27	±	0.90
J-1	1.10	±	0.44
J-2	1.03	±	0.36
J-3	0.53	±	0.48
J-4	0.75	±	0.61

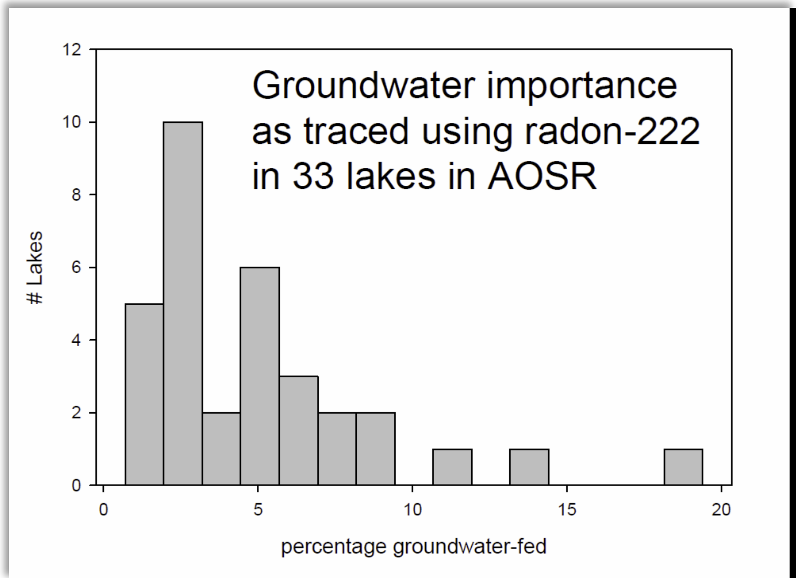
Shallow Groundwater

ID	Radon [Bq/m³]		
P7	5,500	±	1,628
P8	4,561	±	1,494
P2	3,243	±	1,223
P1	2,306	±	1,123

SM08 Lake

ID	Rn [Bq/m³]		
M-1	72.8	±	16.7
J-1	13.8	±	2.5
J-2	36.6	±	9.7
J-3	33.2	±	6.5
J-4	15.5	±	3.8
J-5	11.2	±	2.6
J-6	17.7	±	2.0
J-7	12.1	±	1.4
J-8	12.7	±	2.9
J-9	20.9	±	2.8

- Better understanding of the role of groundwater for lakes and rivers
- Detection of both fresh and saline groundwater inputs
- Surface/groundwater interaction mapping
- Understanding sensitivity to climate variability and change
- Understanding sensitivity to development impacts
- Understanding changes in aquatic ecosystems



Hydrol. Earth Syst. Sci., 14, 79–89, 2010
www.hydrol-earth-syst-sci.net/14/79/2010/

Hydrology and Earth System Sciences

The contribution of groundwater discharge to the overall water budget of two typical Boreal lakes in Alberta/Canada estimated from a radon mass balance

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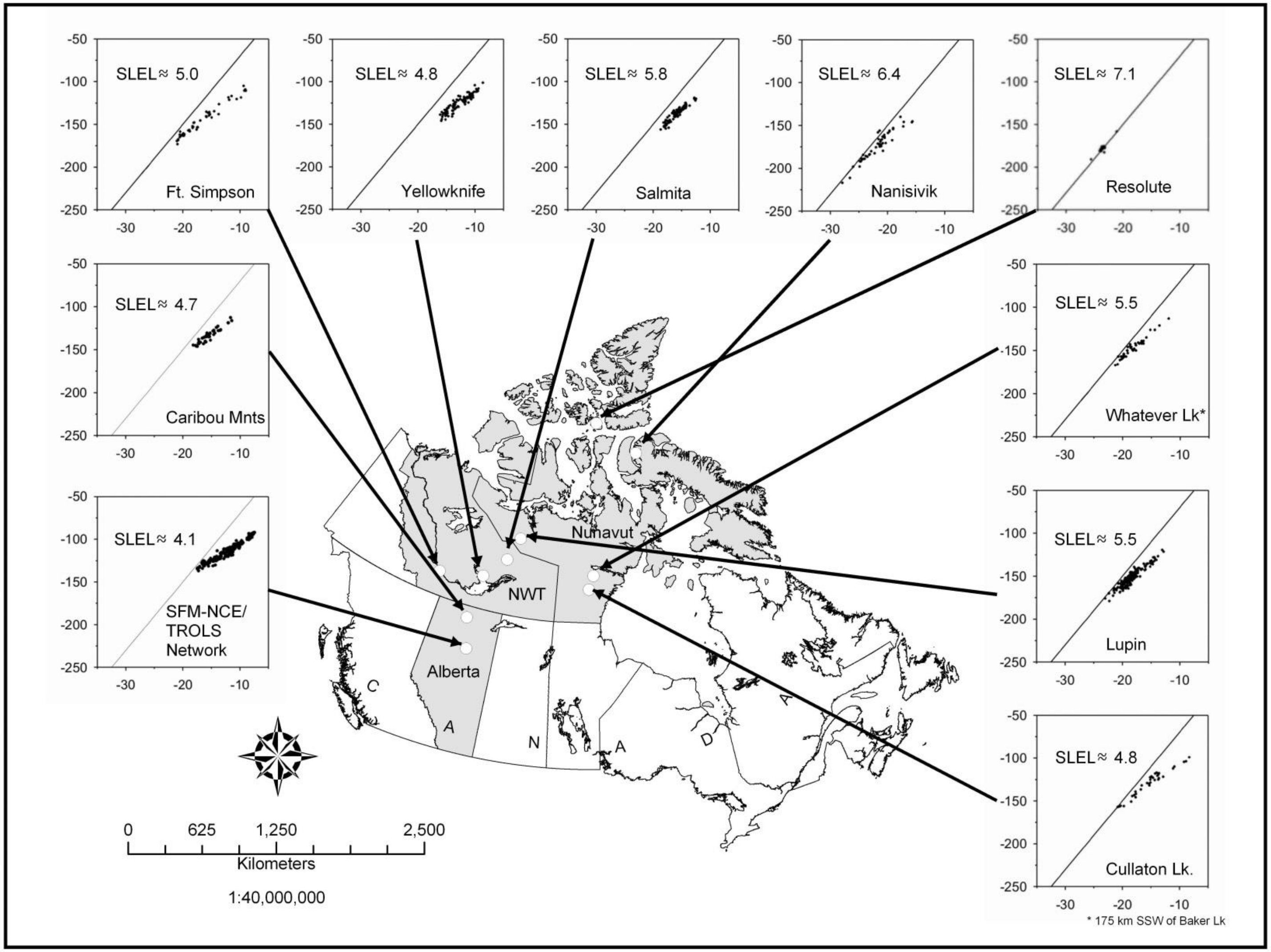
Received: 10 July 2009 – Published in Hydrol. Earth Syst. Sci. Discuss.: 21 July 2009
Revised: 27 November 2009 – Accepted: 16 December 2009 – Published: 14 January 2010

Abstract. Radon-222, a naturally-occurring radioisotope with a half-life of 3.8 days, was used to estimate groundwater discharge to small lakes in wetland-dominated basins in the vicinity of Fort McMurray, Canada. This region is under significant water development pressure including both oil sands mining and in situ extraction. Field investigations were carried out in March and July 2008 to measure radon-222 distributions in the water column of two lakes as a tracer of groundwater discharge. Radon concentrations in these lakes ranged from 0.5 to 72 Bq/m^3, while radon concentrations in groundwaters ranged between 2000 and 8000 Bq/m^3. A radon mass balance, used in comparison with stable isotope mass balance, suggested that the two lakes under investigation had quite different proportions of annual groundwater inflow (from 0.5% to about 14% of the total annual water inflow). Lower discharge rates were attributed to a larger drainage area/lake area ratio which promotes greater surface connectivity. Interannual variability in groundwater proportions is expected despite an implied seasonal constancy in

1 Introduction

Northeastern Alberta is the centre of oil sand mining in Canada. The intense mining activities in the vicinity of the City of Fort McMurray were established some decades ago. The processes of oil extraction, upgrading and refinement require significant inputs of water, some of which is withdrawn from local aquifers.For in situ mining purposes, groundwater is pumped from the available aquifer system to the surface where it is heated up and re-injected as steam into the oil bearing sands. The resultant decrease in the viscosity of the bitumen allows its pumping to the surface. This practice may trigger considerable changes in the local groundwater flow patterns. One concern related to this process is the potential ecological effect on hydraulically connected surface water bodies.

Water exchange between surface waters and connected aquifer systems generally provide major pathways for the transfer of dissolved matter (Burnett et al., 2006; Santos et



ISOTOPIC ENRICHMENT IN SURFACE WATER, N. CANADA

Gibson et al. Hydrol. Process. 2005