Water Isotopes in Spatial Hydrology

Gabe Bowen

gabe.bowen@utah.edu

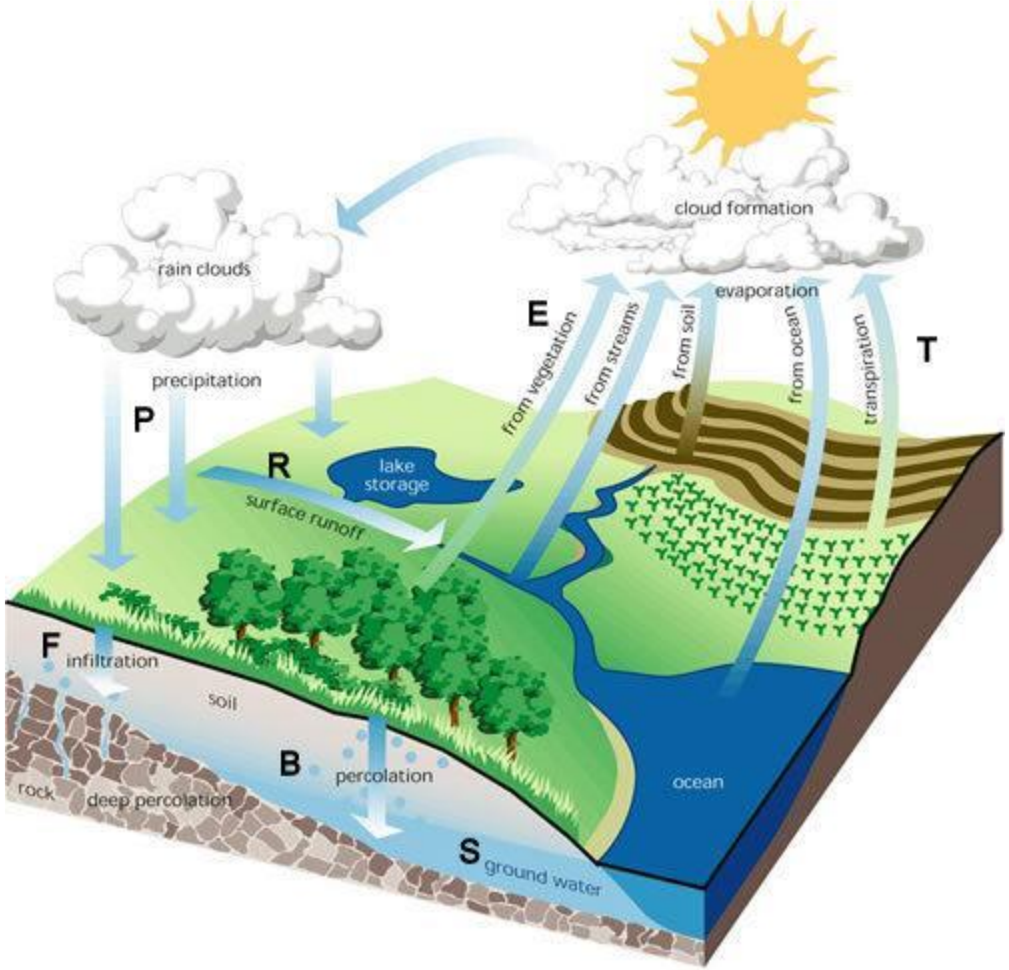
SPATIAL

University of Utah

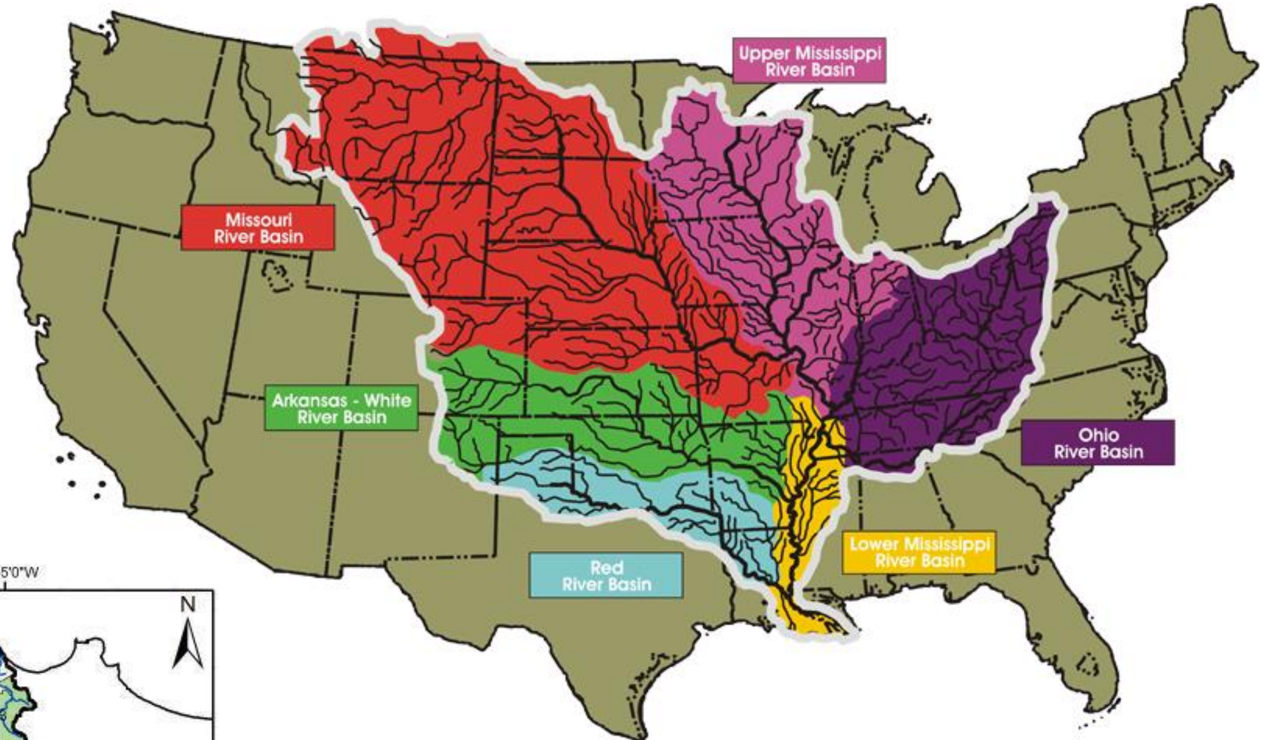
Isotopes can be used to...

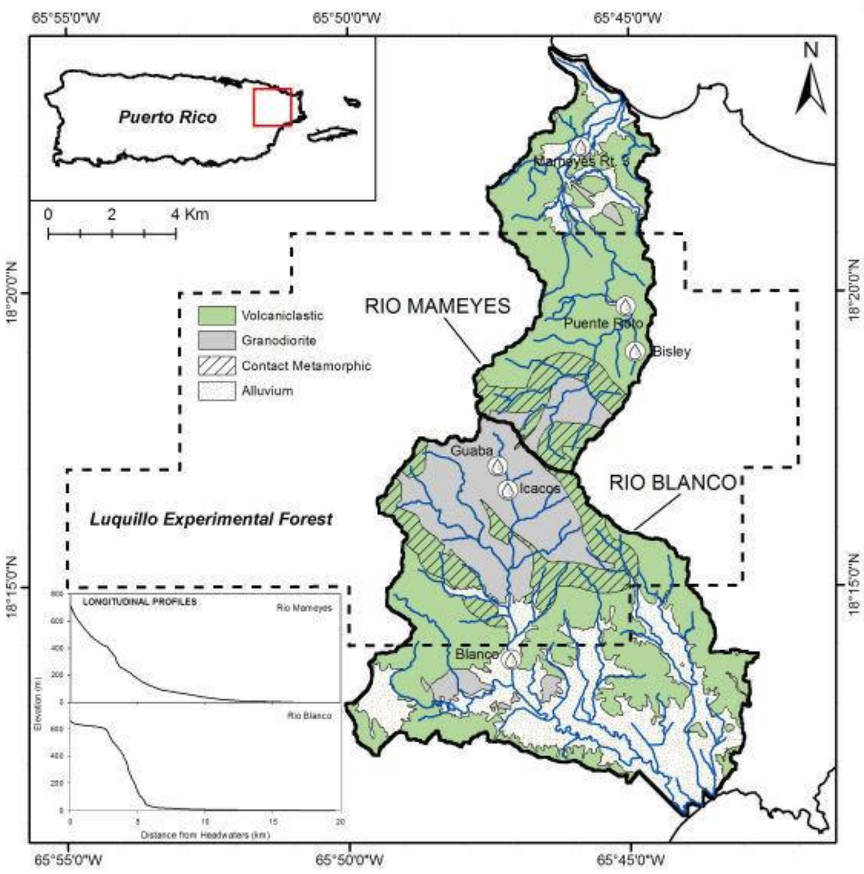
- Trace mass fluxes
- Identify and partition processes
- Infer conditions

Catchment water balance



$$P = R + E + T + \Delta S$$

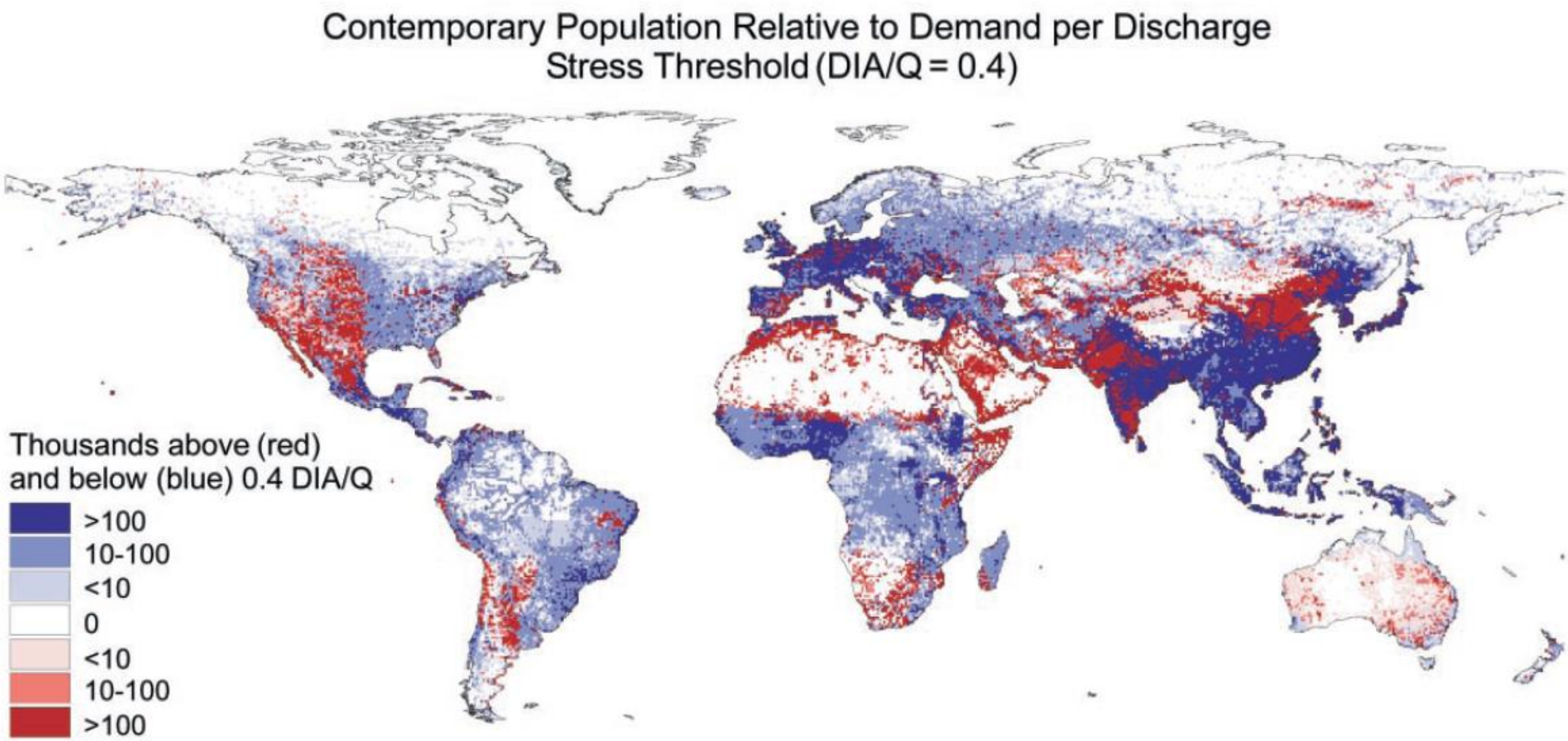

Upper Mississippi
River Basin
Missouri
River Basin
Arkansas - White
River Basin
Ohio
River Basin
Red
River Basin
Lower Mississippi
River Basin


65°55'0"W
65°50'0"W
65°45'0"W
18°20'0"N
18°15'0"N
N
Puerto Rico
0
2
4 Km
Volcaniclastic
Granodiorite
Contact Metamorphic
Alluvium
RIO MAMEYES
RIO BLANCO
Luquillo Experimental Forest
Mameyes Rt. 3
Puente Roto
Bisley
Guaba
Icacos
Blanco
LONGITUDINAL PROFILES
Rio Mameyes
Rio Blanco
Elevation (m)
Distance from Headwaters (km)

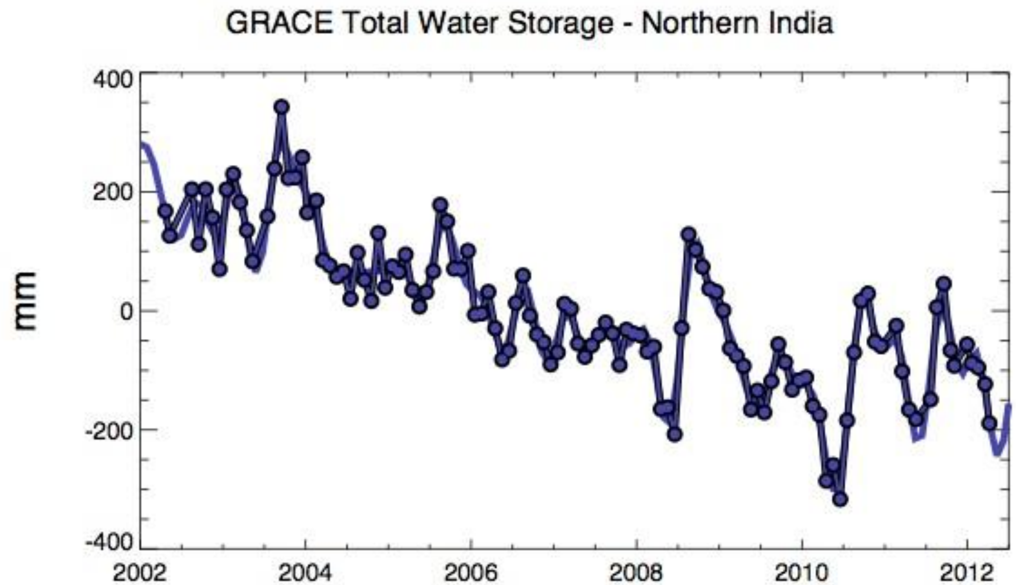
9 ideas

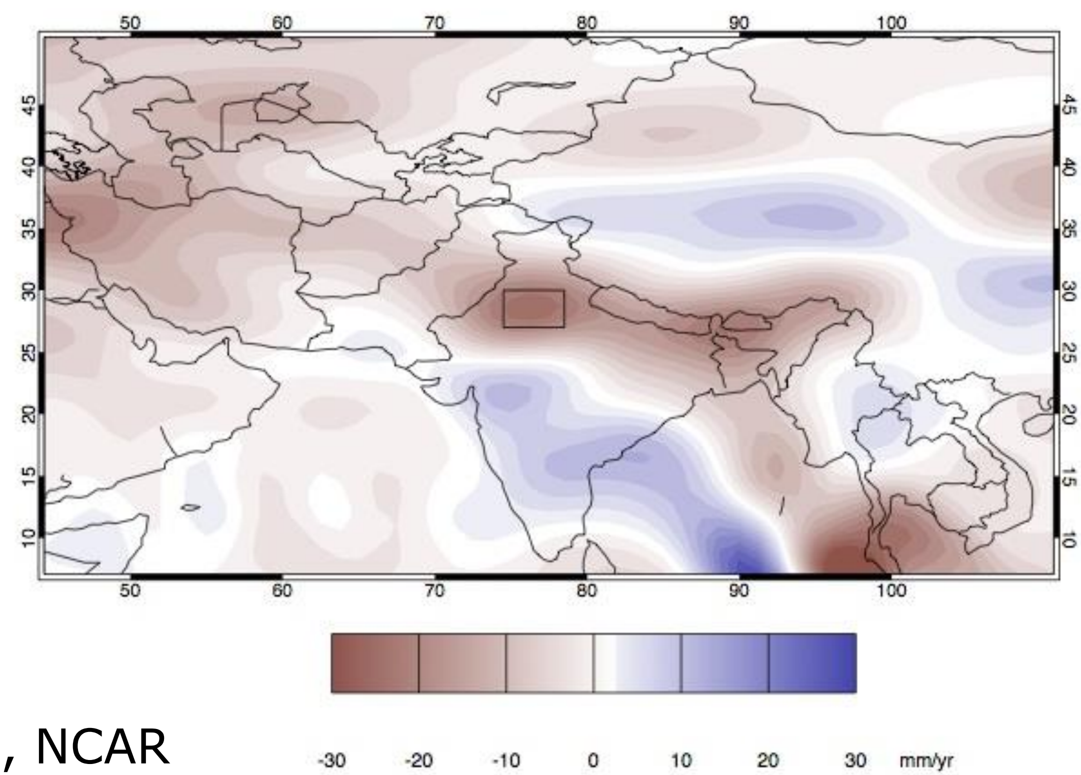
1. Water balance matters
2. It all starts with precipitation (isoscapes)
3. Interpolating in space and time
4. Most headwater catchments export old water
5. Urban and agricultural systems do not (always)
6. Groundwater looks like local precipitation, except when it isn't
7. Regional water balance trends are easy to extract from rivers
8. Lake basins evaporate, but even more they transpire
9. The water we drink often comes a long way to reach us

1. Water balance matters



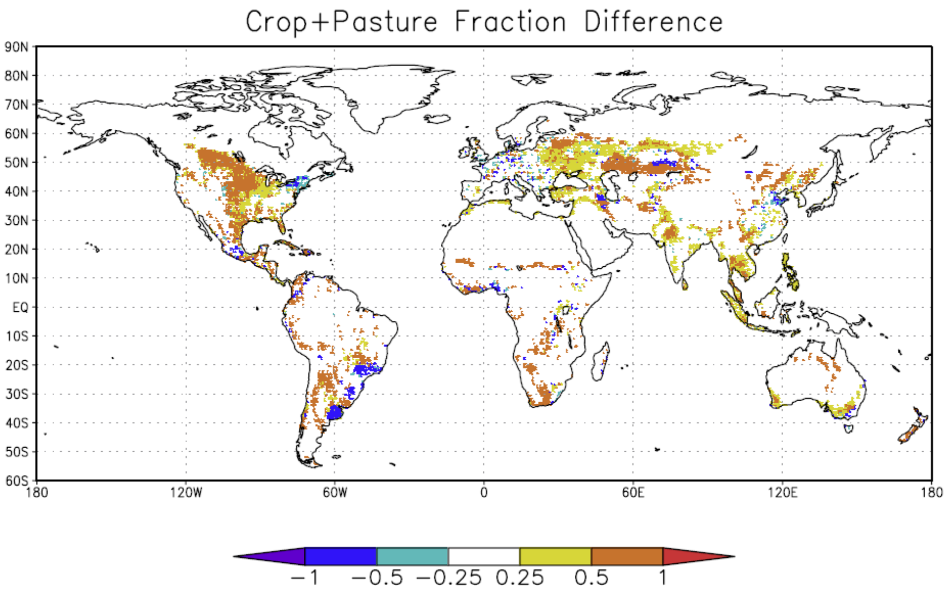
Vorosmarty et al., 2000, *Science*

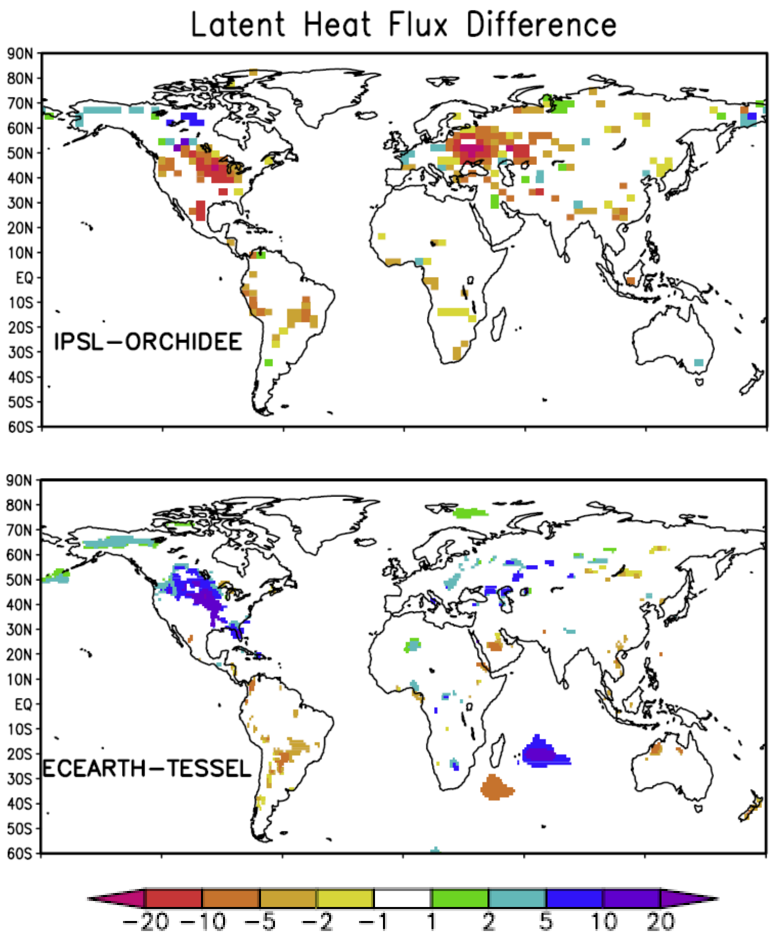




Sean Swenson, NCAR

Water balance matters





Pitman et al., 2009, *GRL*

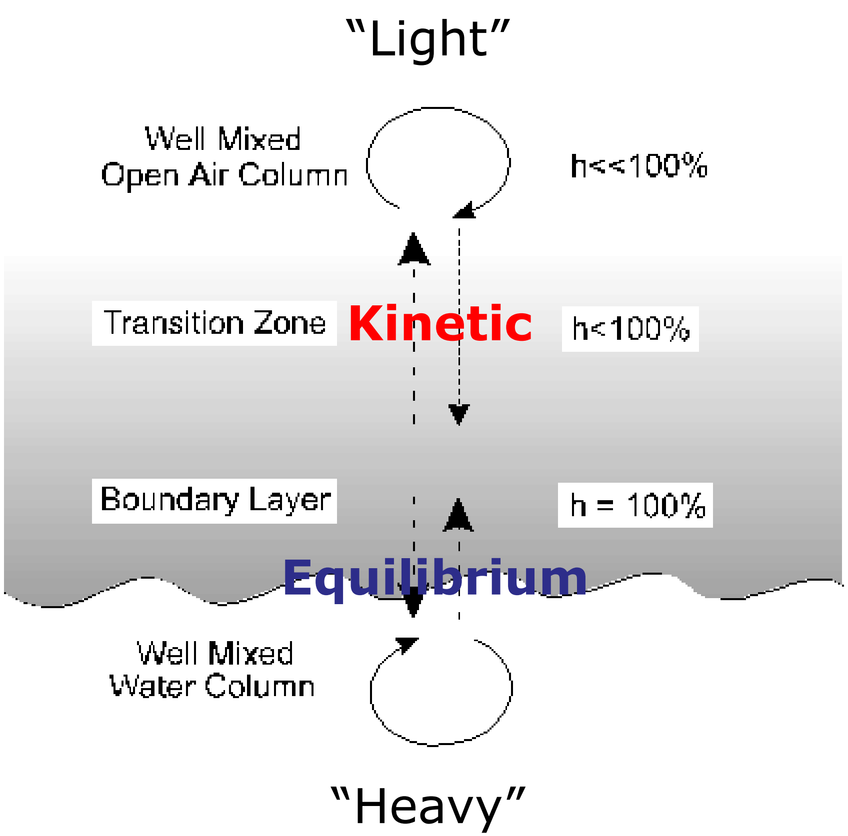
2. It all starts with precipitation (isoscapes)

- First, some fundamentals!
- What is the most important process leading to H and O isotope variation in water?

1. Evaporation (condensation)
2. Transport

Phase Change Reaction: Craig-Gordon

- Open air
  - Well-mixed
  - Large
- Transition zone (TZ)
  - Turbulently mixed
  - Decreasing humidity upwards
- Boundary layer (BL)
  - Thin, well-mixed layer
  - 100% RH
- Liquid
  - Large (ocean) or small (droplet) body of water
  - Mixed or stratified



$$\delta_e = \frac{\alpha^* \delta_l + \varepsilon^* - h\delta_a - \Delta\varepsilon}{1 - h}$$

Gat, 1996

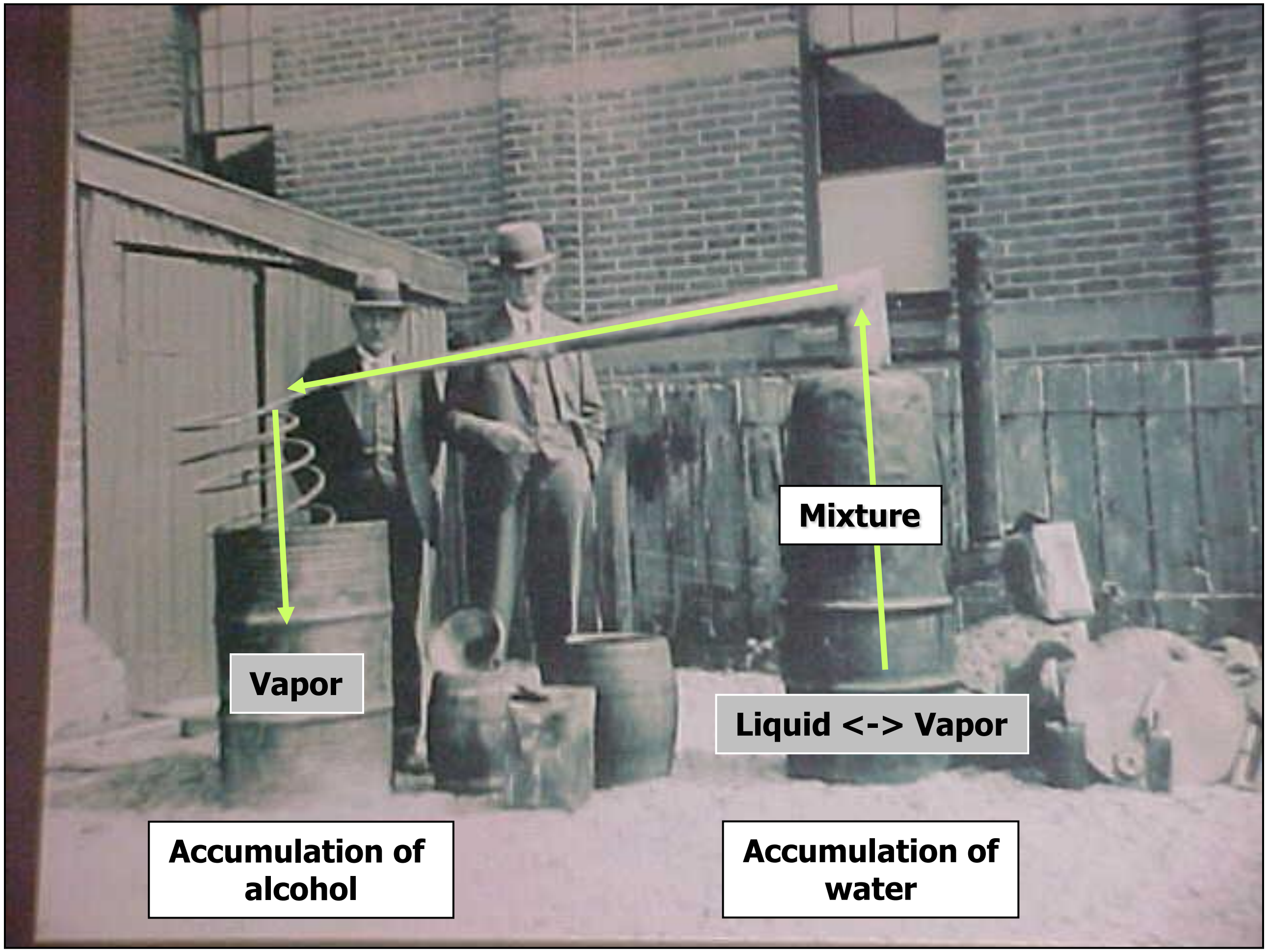
Rayleigh Distillation

- A processes by which fractionation (of isotopes, elements, molecules, elephants) leads to a change in 2-component reactant mixture
- Is it Rayleigh Distillation?
  - Open system
    - No addition of material
    - Rapidly and continuous removal of product
  - Product is fractionated relative to the reactant
- The Rayleigh equation describes the composition of the reactant pool as a function of reaction progress:

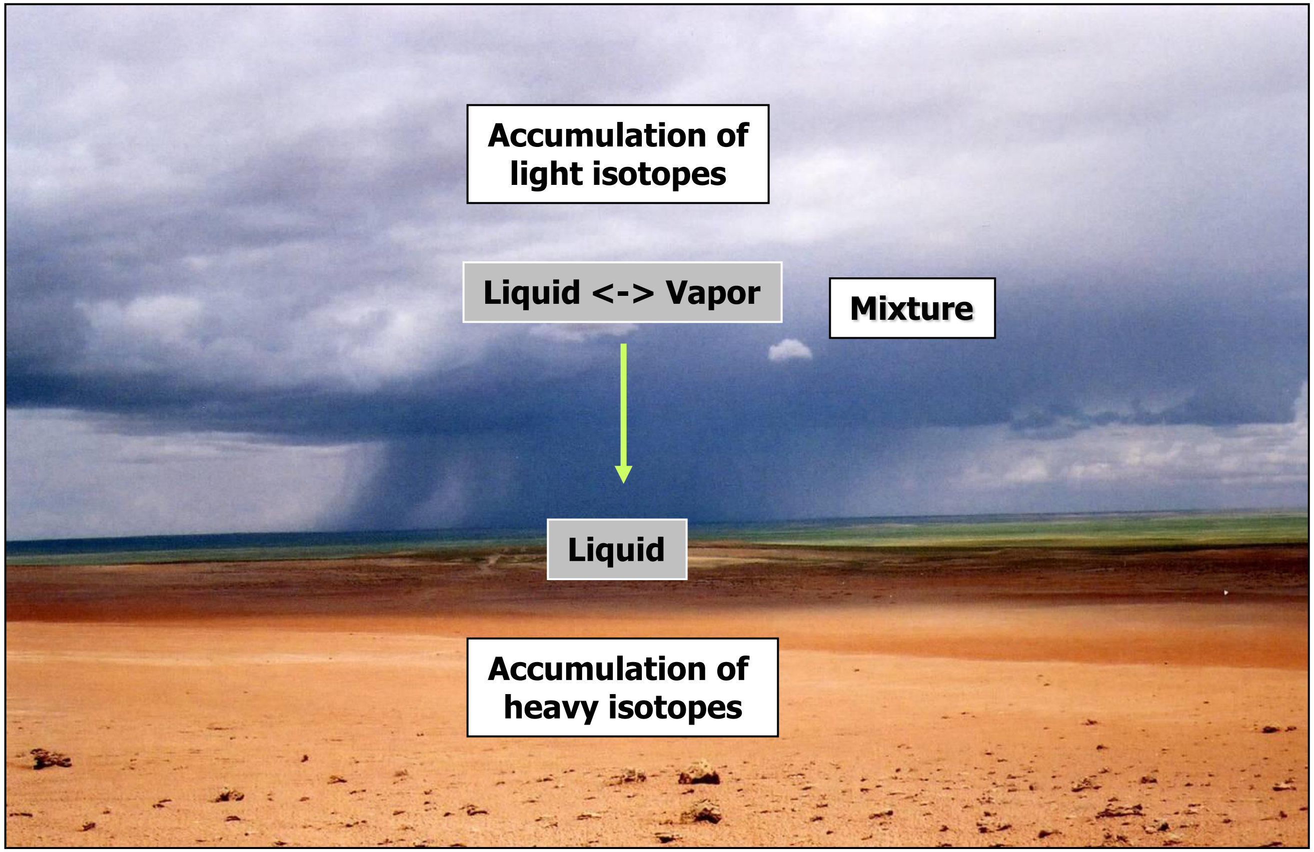
$$R = R_0 f^{(\alpha - 1)}$$

R and R_0 are current and initial isotope ratios
f is fraction of reactant remaining

Rayleigh Distillation

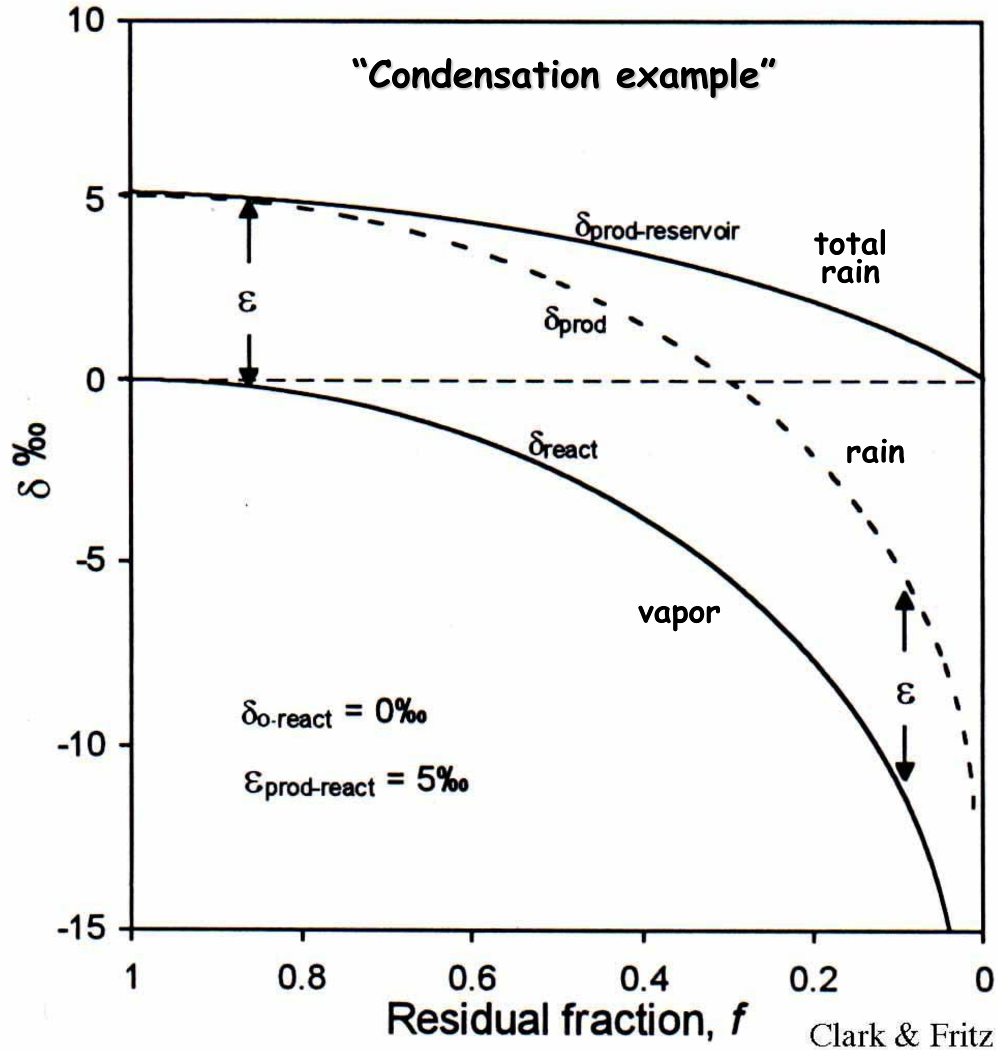


Rayleigh Distillation



Rayleigh Distillation and Precipitation

- Precipitation formed from condensation of cloud vapor
- Equilibrium process (free atmosphere RH ≈ 100%)
    - Equilibrium fractionation
- **But one element of complexity…**



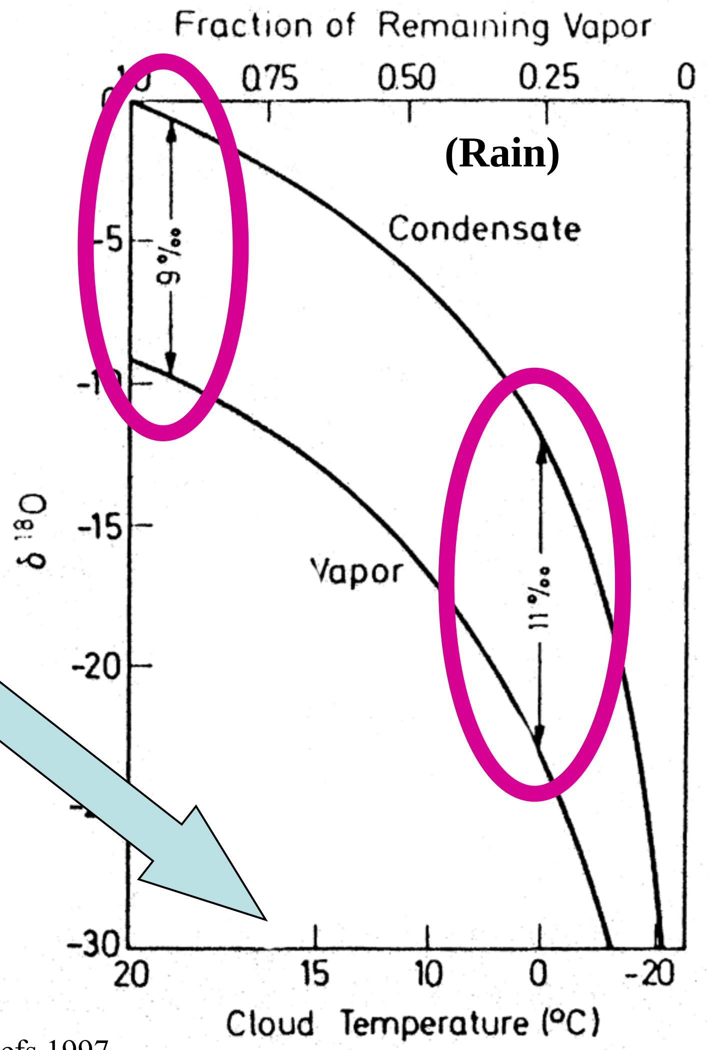
Clark & Fritz 1997

Rayleigh Distillation and Precipitation

!!! This does not cause the 'temperature effect', but it contributes (slightly) to it !!!

As condensation proceeds, the temperature of the remaining cloud decreases.

Thus, α increases, resulting in a greater difference between cloud and rain H_2O



Hoefs 1997

Spatial Patterns and Rayleigh Distillation

- Rayleigh distillation causes precipitation isotope ratios to get **lower** as air gets **drier**

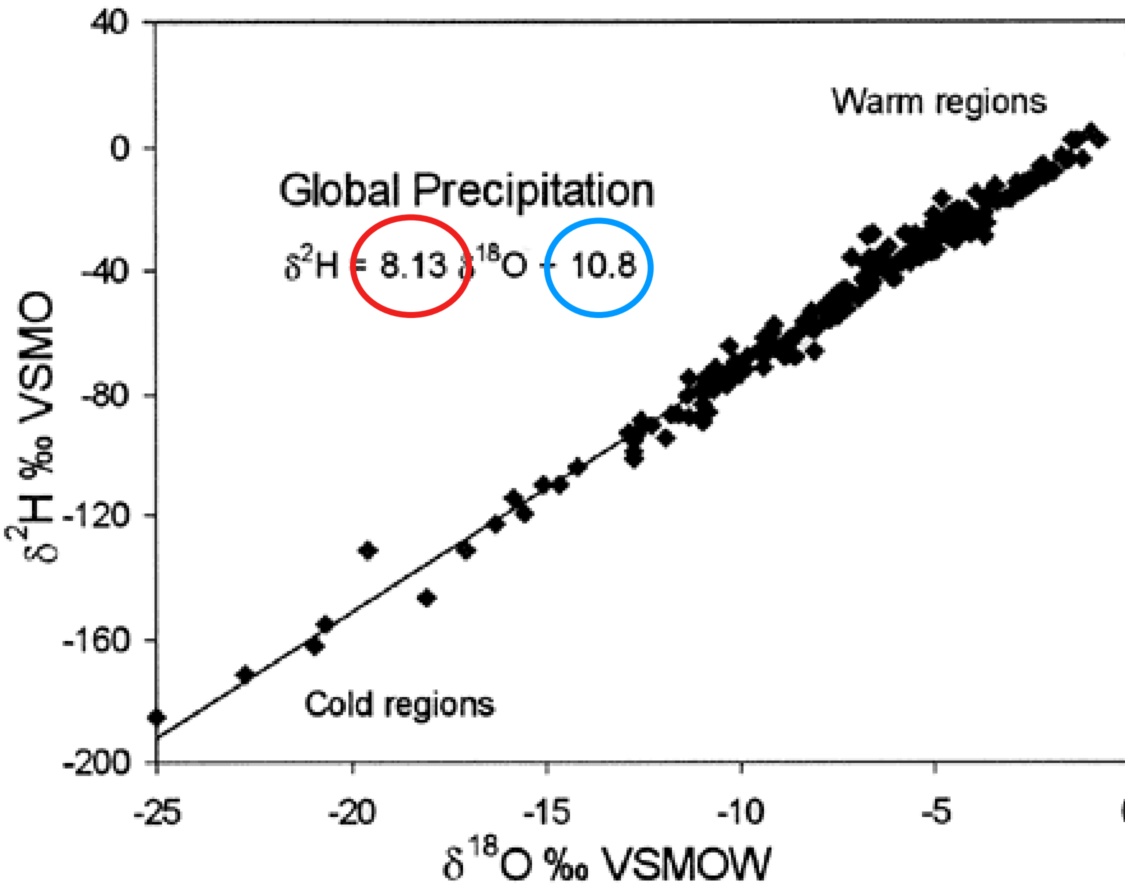
What does this imply about the spatial distribution of precipitation isotope ratios?

Equilibrium fractionation factors for water isotopes

- at 20° C
  - $\varepsilon^2H = 74‰$
  - $\varepsilon^{18}O = 9.2‰$
  - $\varepsilon^2H / \varepsilon^{18}O = 8.0$
- at 80° C
  - $\varepsilon^2H = 38‰$
  - $\varepsilon^{18}O = 4.5‰$
  - $\varepsilon^2H / \varepsilon^{18}O = 8.4$

Equilibrium enrichment factors for H isotopes are ~8 x those for O isotopes

The Global Meteoric Water Line



Condensation
is an equilibrium process

so

Most precipitation δ values lie along a Global Meteoric Water Line (GMWL) of slope 8

(ε^2H / $\varepsilon^{18}O$ = 8)

The intercept of the GMWL is +10‰

Clark and Fritz, 1997; GMWL defined by Craig, 1961

Equilibrium and kinetic enrichment factors

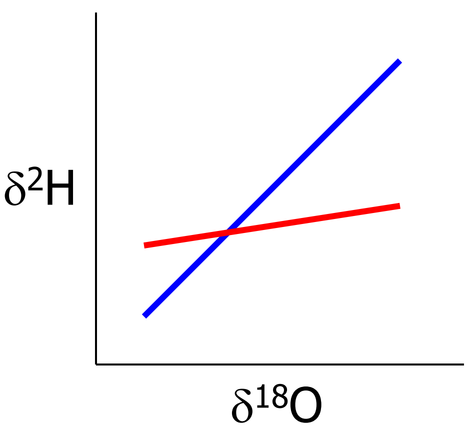
Q: What was the relationship between $\varepsilon_e{}^2H$ and $\varepsilon_e{}^{18}O$?

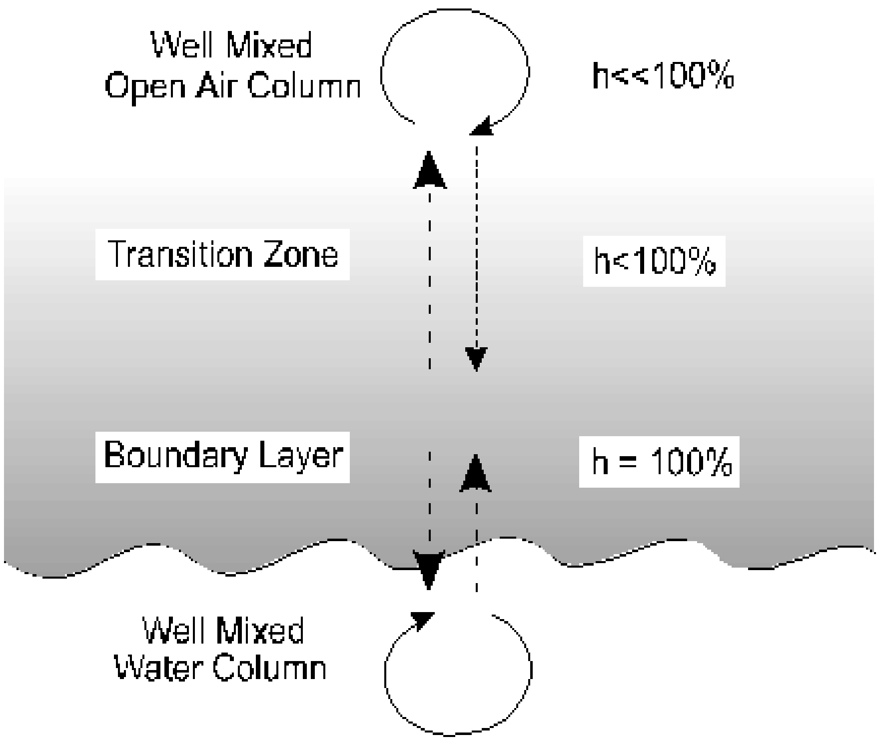
A: $\varepsilon_e{}^2H / \varepsilon_e{}^{18}O = 8$

$\Delta\varepsilon^2H$ and $\Delta\varepsilon^{18}O$ give us a different relationship

Kinetic
$\alpha^2H \approx \alpha^{18}O$

Equilibrium
$\alpha^2H = 8*\alpha^{18}O$

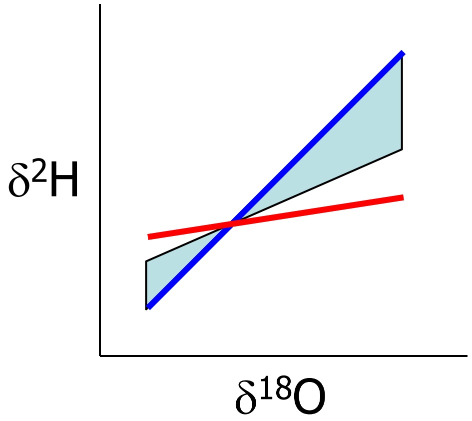


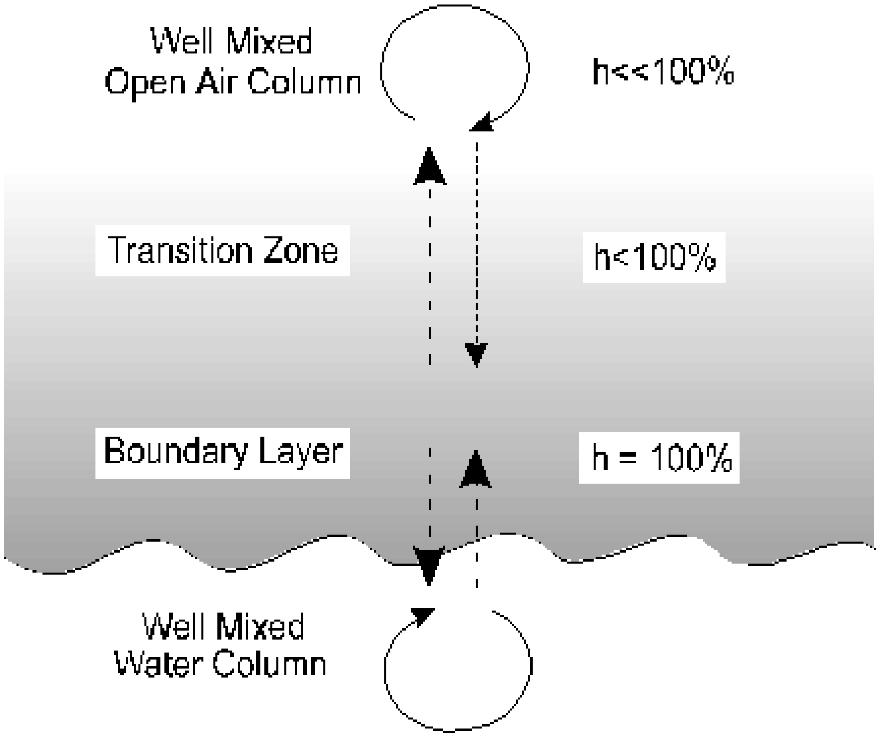


Gat, 1996

Equilibrium and kinetic enrichment factors

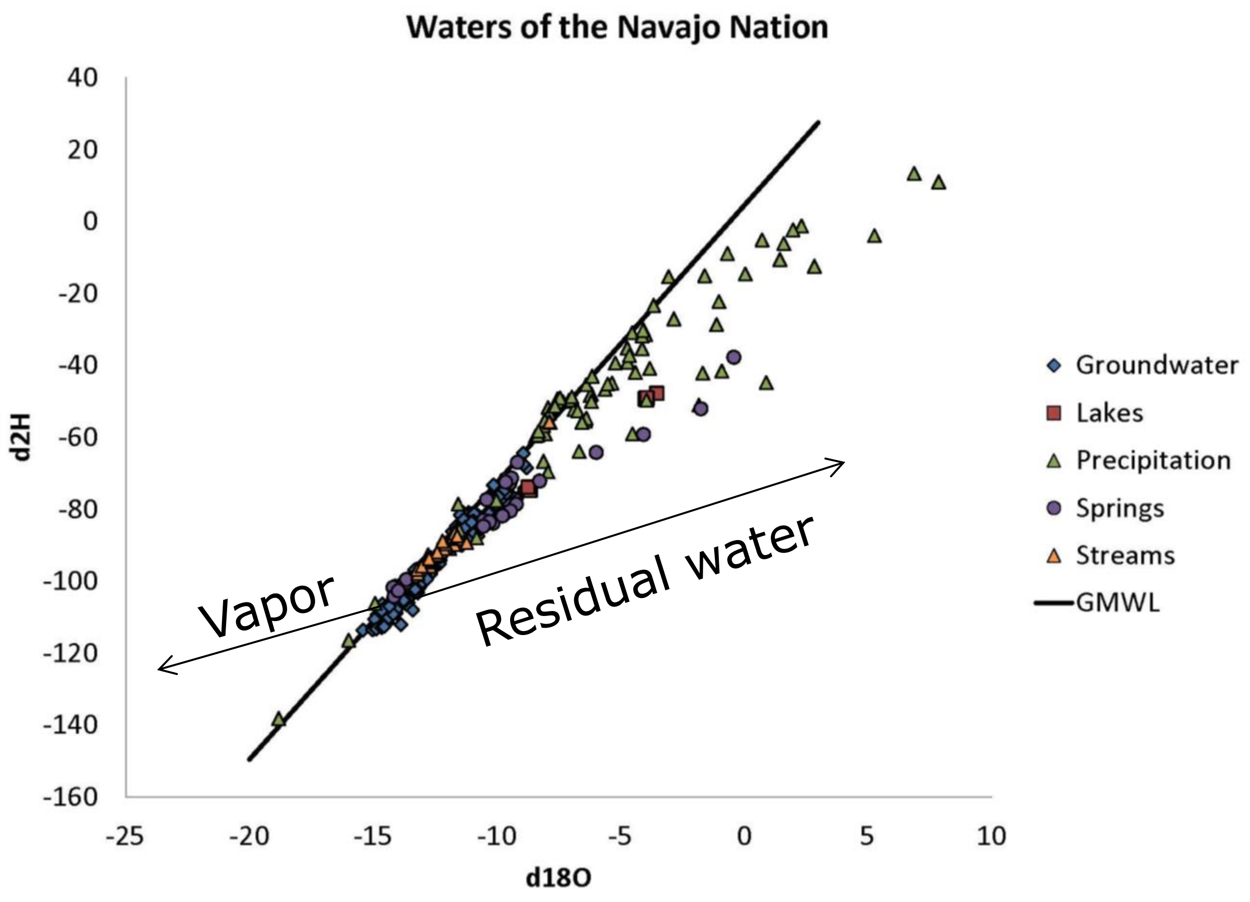
- The net ratio of ^2H and ^{18}O isotope effects is a blend of the Equilibrium and Kinetic ratios, typically between 3 and 8
- The coupled $^2H/^{18}O$ system gives us a “proxy” for kinetic fractionation… **deuterium excess**





Gat, 1996

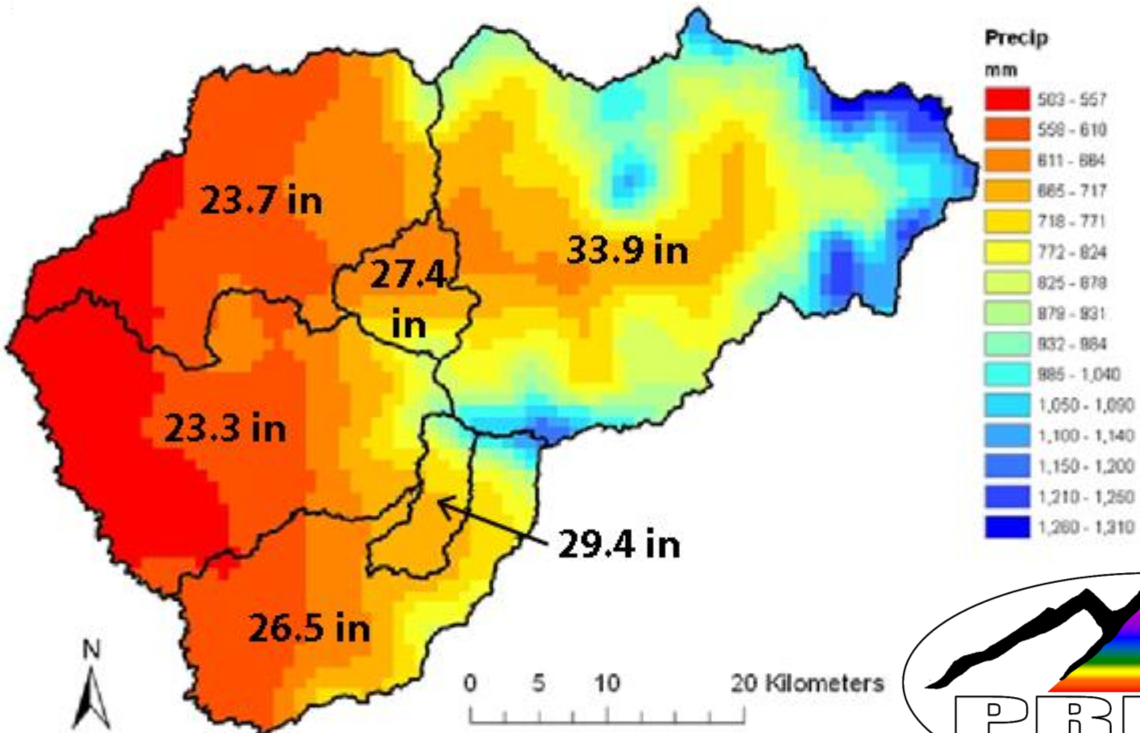
Deuterium excess



Crystal Tulley-Cordova, unpub.

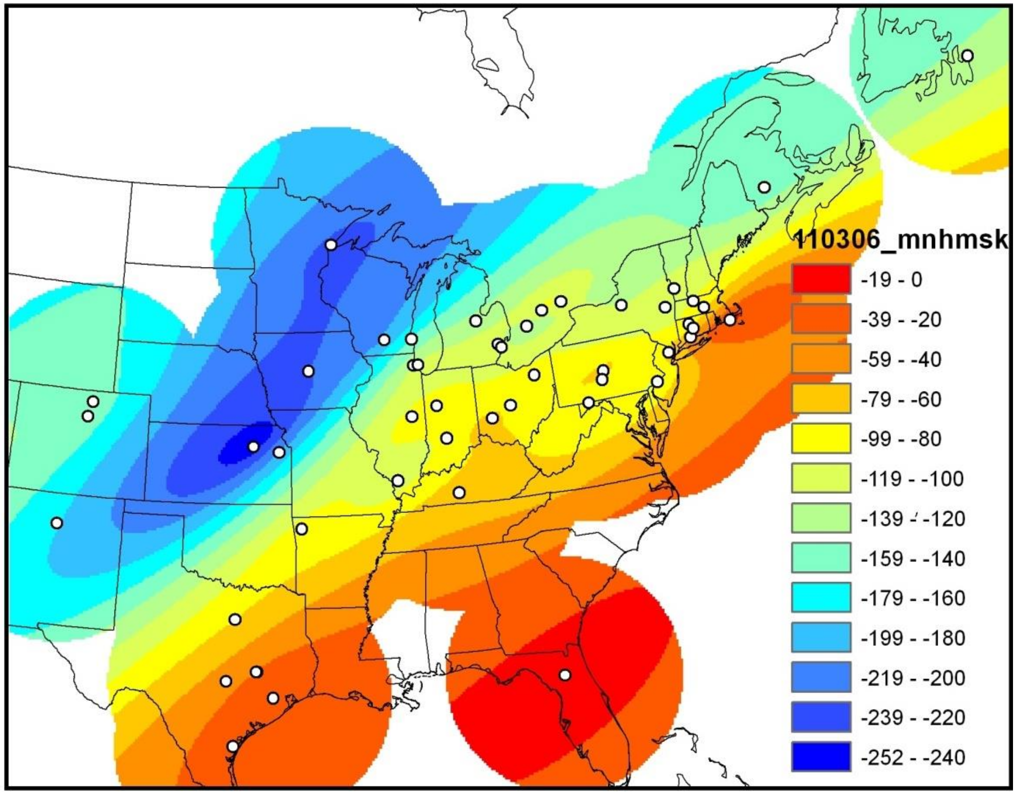
Precipitation isoscapes

- Precipitation is an incompletely observed, spatially distributed flux
- Interpolating (extrapolating) from point measurements requires robust algorithms, consideration of process



Precipitation isoscapes

- What about precipitation isotope ratios?
  - + Ratio of fluxes
  - - Relatively poorly observed



Spatial interpolation

- Given spatially distributed data $Z(x_i)$, estimate the unknown value $z(x_0)$ as a weighted average of $Z(x_i)$

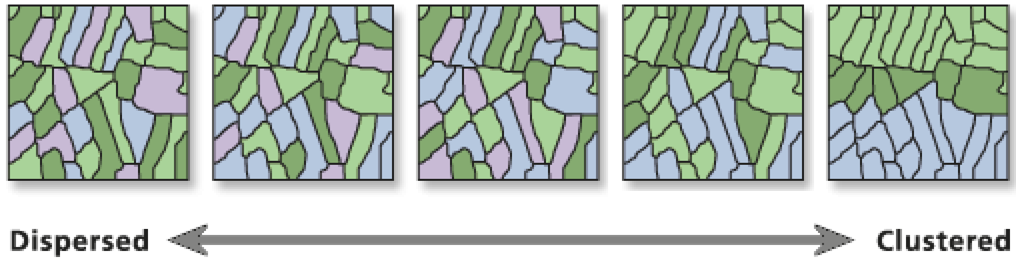
$$z(x_0) = \sum_{i=0}^{n} w_i(x_0) \times Z(x_i)$$

- Challenge is in the determination of a model for $w_i(x_0)$

- General concepts/assumptions
  - Spatial autocorrelation – closely spaced points are closely related
  - Stationarity – 1°: expected mean and/or variance of the population of true values invariant over domain; 2°: spatial correlation structure invariant over domain

Testing spatial autocorrelation

- Are closely spaced values *more similar* than distantly spaced ones?
  - *More dissimilar*?
  - *Neither?*



- Moran's I statistic (global):

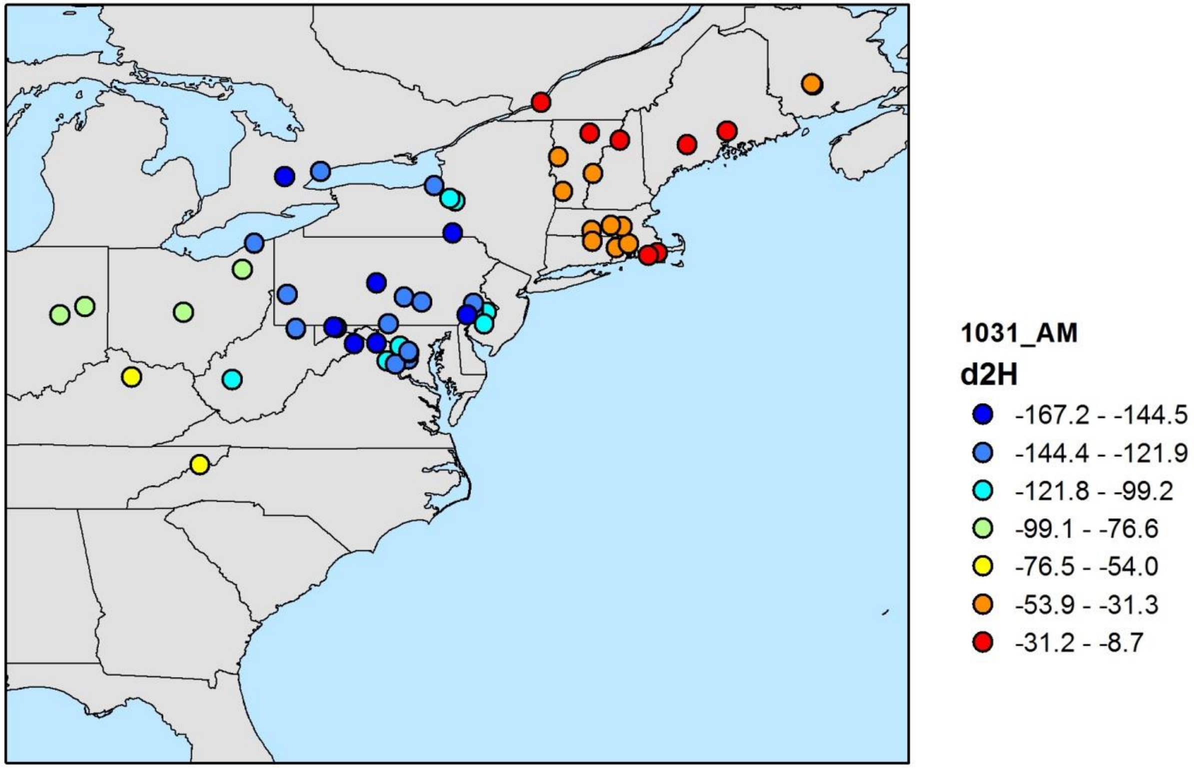
$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} \Delta z_i \Delta z_j}{\sum_{i=1}^{n} \Delta z_i^2}$$

S_0 = aggregate weight

$\Delta z_i = z_i - \mu_z$

- I = -1 values spatially dispersed
- I = +1 values spatially correlated

Superstorm Sandy example



Moran's I = 0.90 (ID^2)

Z = 13.8

$p << 0.001$

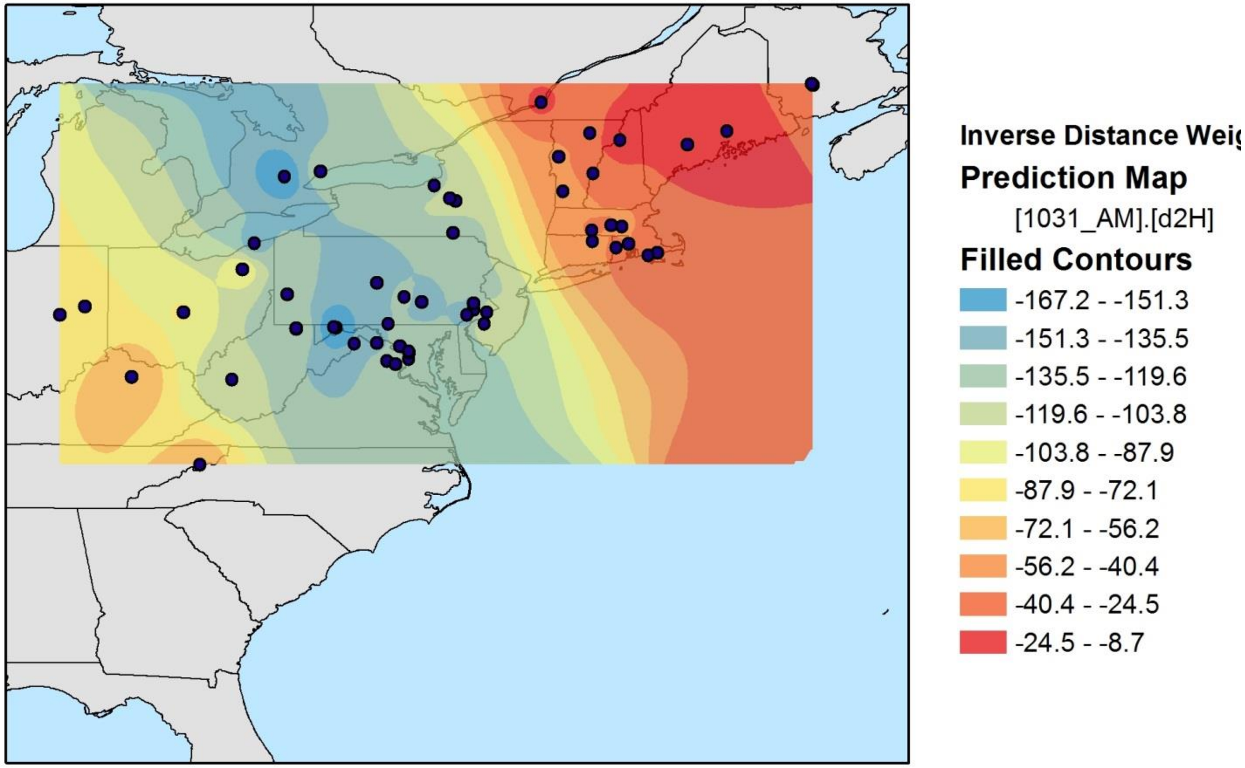
Deterministic methods

- Assume functional form of spatial correlation structure to calculate weights
- Inverse distance

$$w_{i,j} = \left(\frac{1}{d}\right)^p$$

- *p* determines decay of weights with distance, can be assumed or optimized
- Quick, easy, predictable
- Arbitrary, prone to ‘bulls eye’ effects

Inverse Distance



- Optimized $p = 2.8$

Geostatistics - Kriging

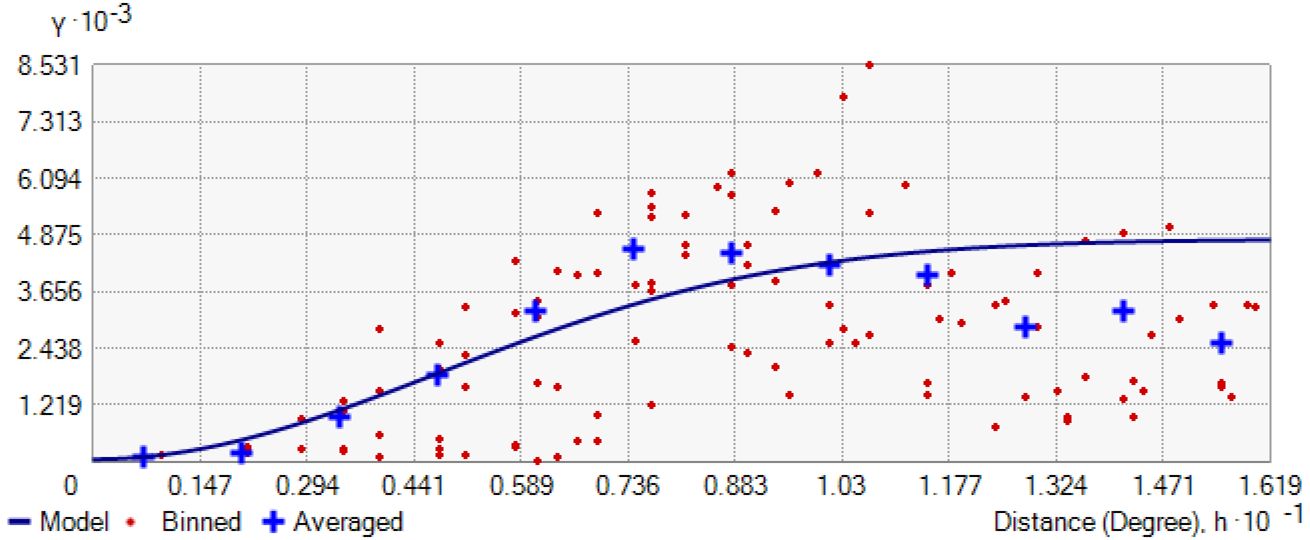
- Use statistical properties of dataset to infer spatial correlation structure

$$y(x_i) = \mu + \varepsilon_i$$

- Assume that y is the result of a random process with a mean μ and spatially autocorrelated error ε_i
  - Data are n realizations
- Assume 2nd order stationarity -> fit semivariogram model to observation
- Various assumptions about μ
  - 1st order stationarity + known (simple) or unknown (ordinary kriging)
  - Non-stationary, deterministic (universal kriging)

Sample and model semivariogram

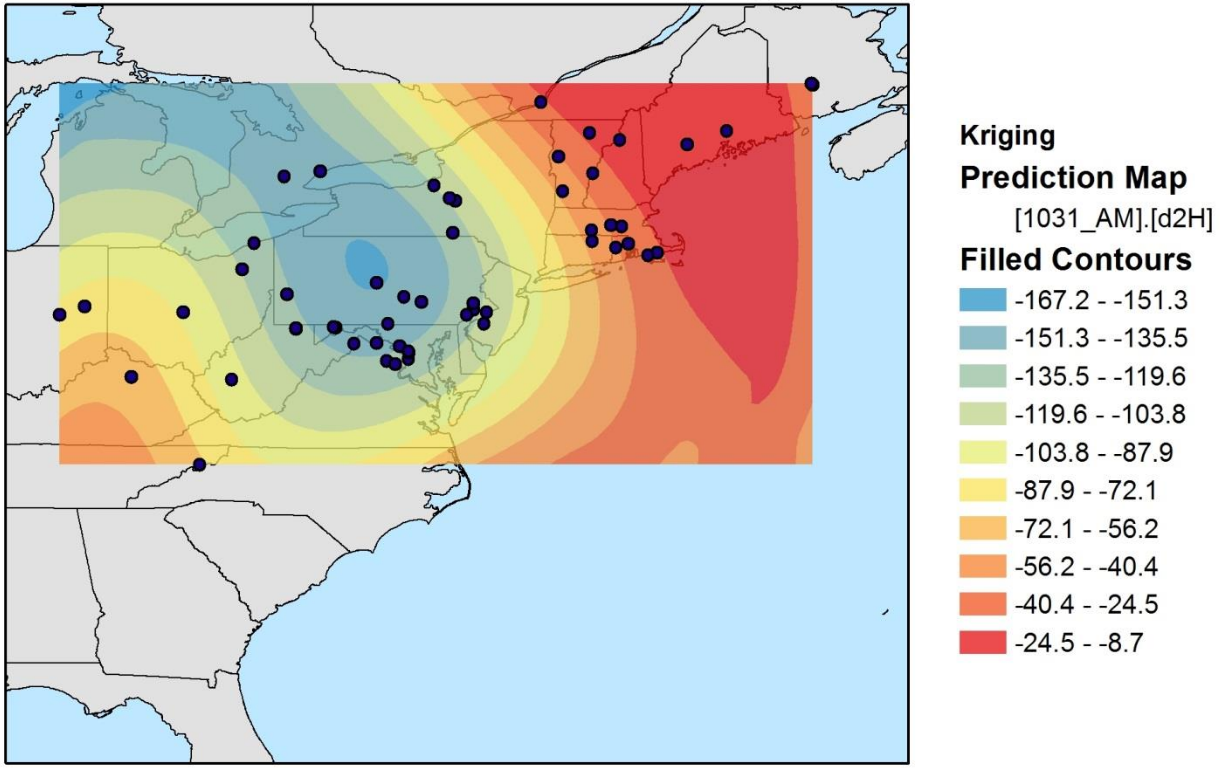
- Sample semivariogram: observed dissimilarity of values as a function of distance
- Semivariogram model: parametric function describing semivariance as function of distance
- The "art" of Kriging…although data can be used to optimize the semivariogram model you must choose the functional form



Semivariogram models

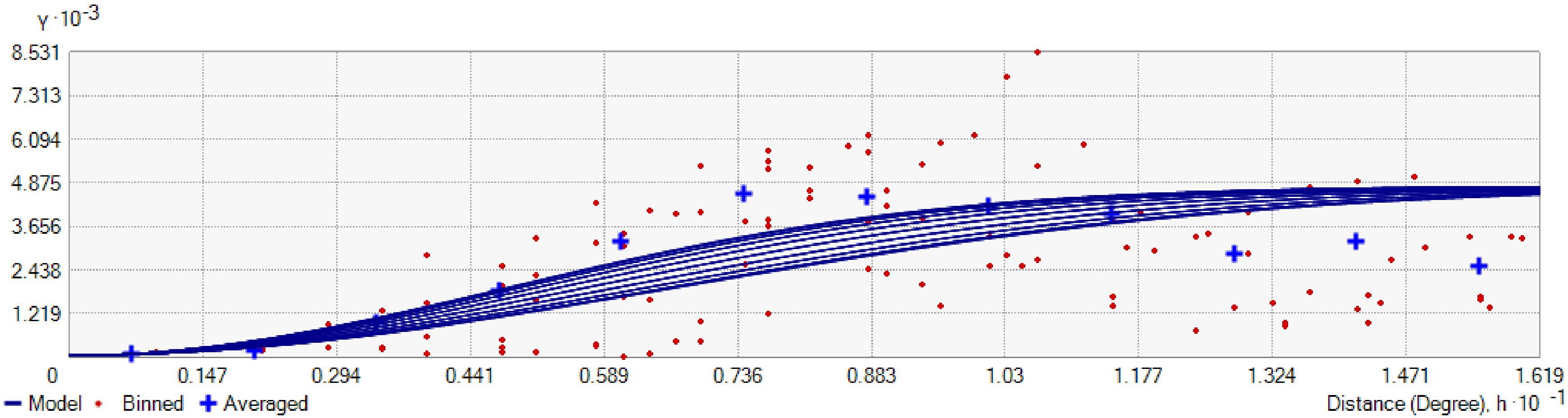
- Common forms
  - Matern
  - Spherical
  - Gaussian
- Parameters (varies with form)
  - Range: Decay with distance
  - Sill: Maximum semivariance for values at distant points
  - Nugget: Semivariance at semivariogram intercept (measurement error or heterogeneity)
  - Shape: Rate of weight decay with distance

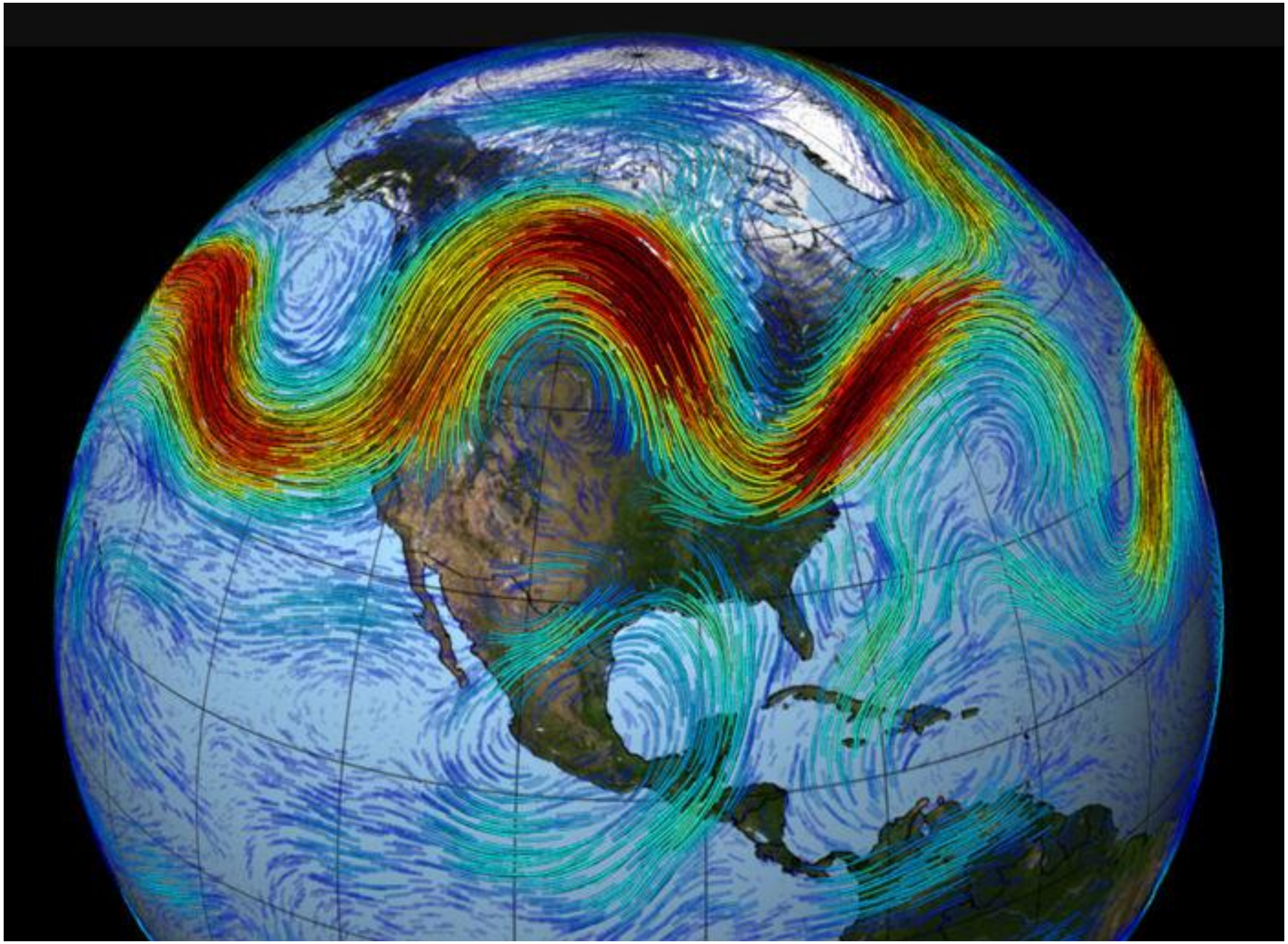
Ordinary Kriging

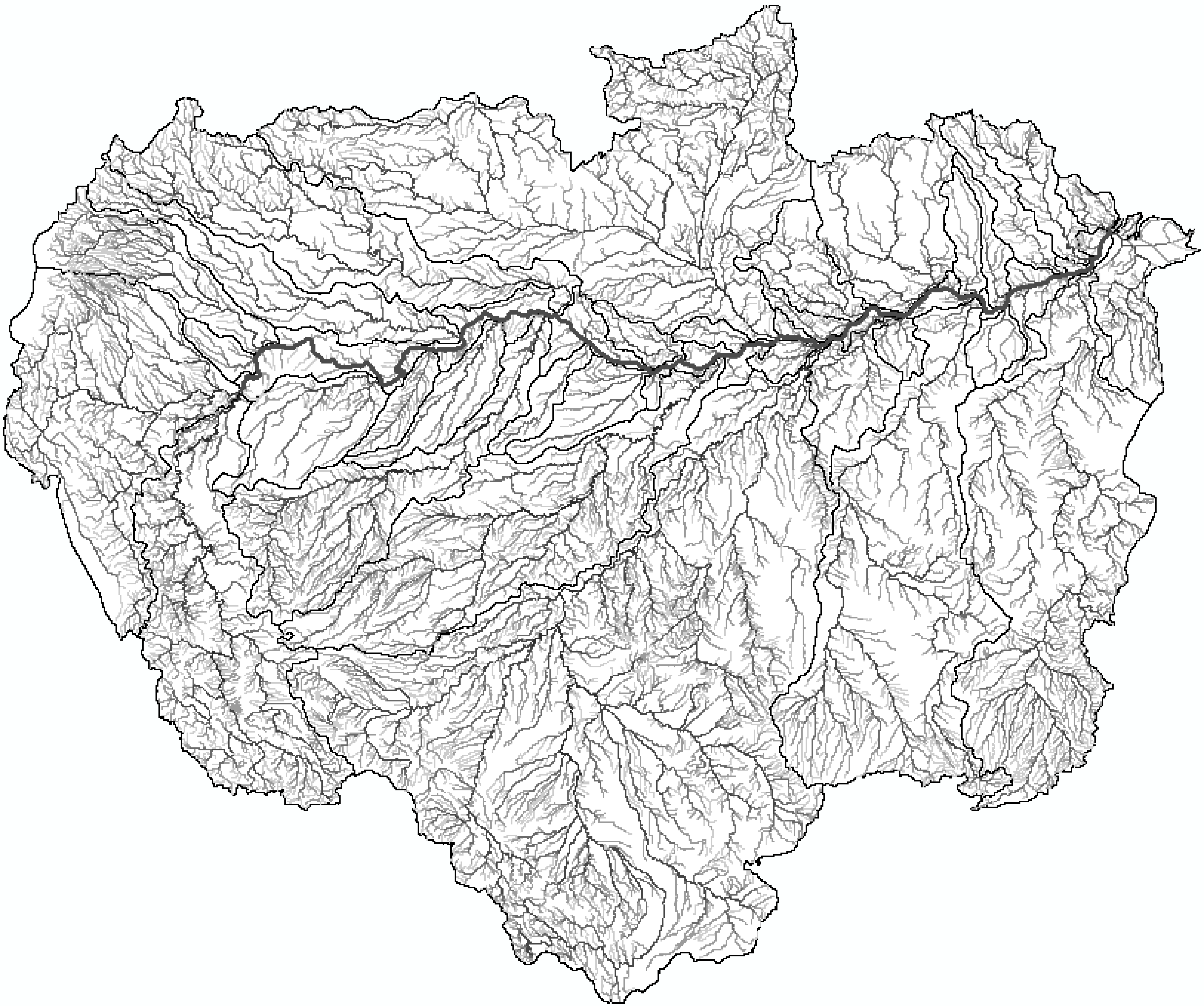


Anisotropy

- Spatial relationships are often directional
- Including anisotropy factor allows you to ‘transform’ spatial domain to regularize system geometry
- Alternative (non-Euclidean) geometries are possible, but not supported in standard software

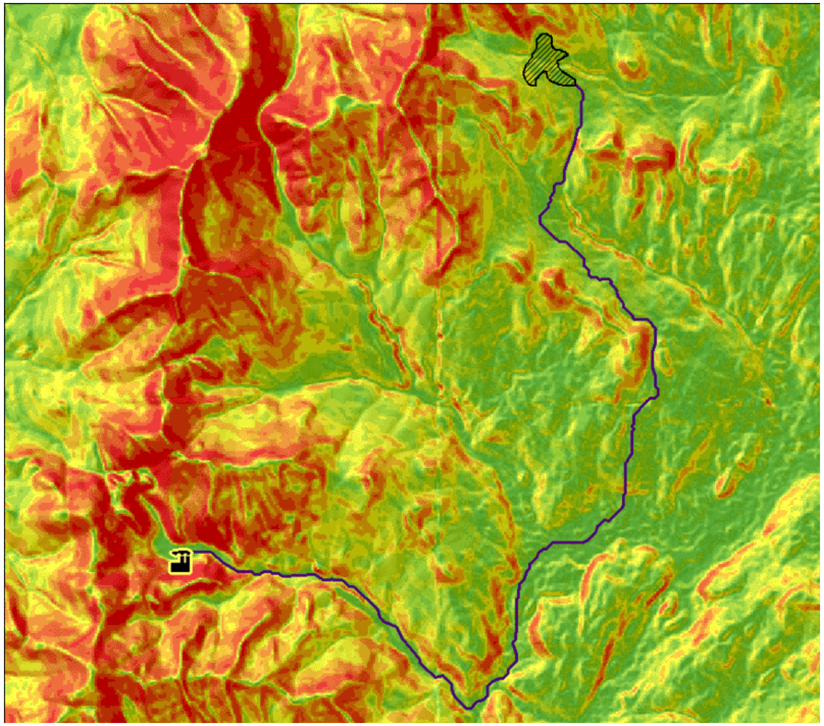


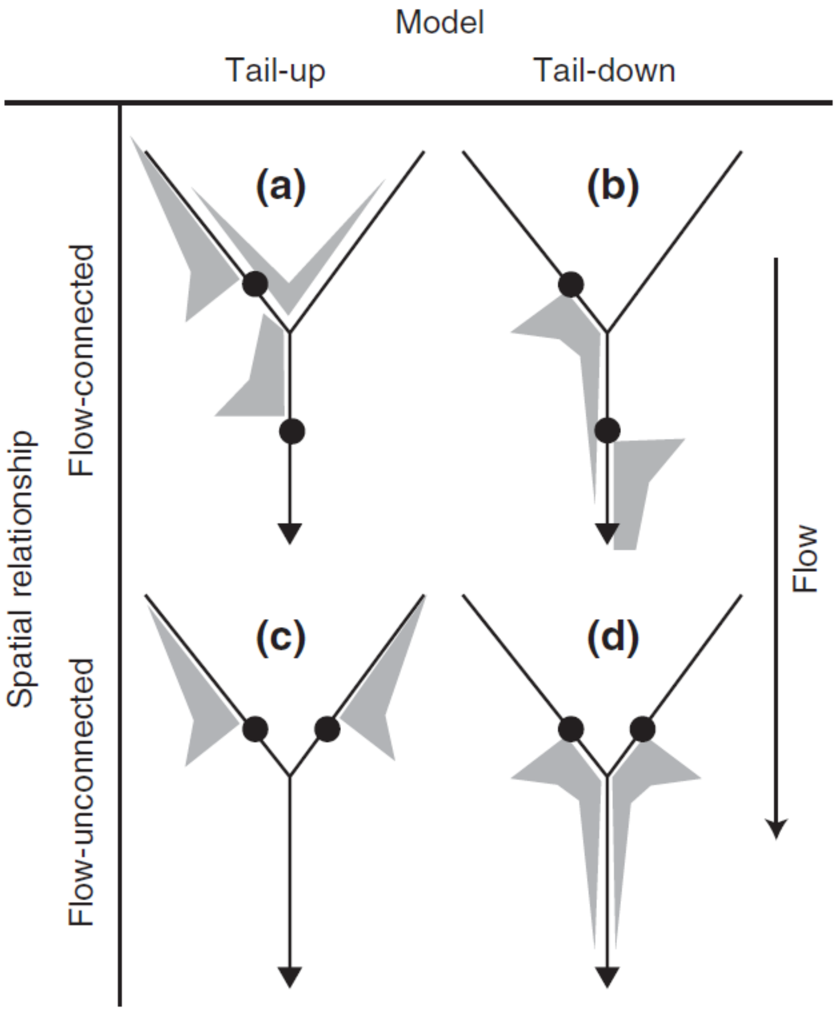




Alternative geometries

- Traditional geostatistics uses a regular Euclidean conception of distance, but this need not be so





Isaak et al., 2014, *WIRES Water*

Detrending

- Spatial correlation can be expressed over different length scales
- This leads to trade-offs between large and small scale patterns
- In addition, interpolation can often be improved by incorporation of additional (non-geographic) information

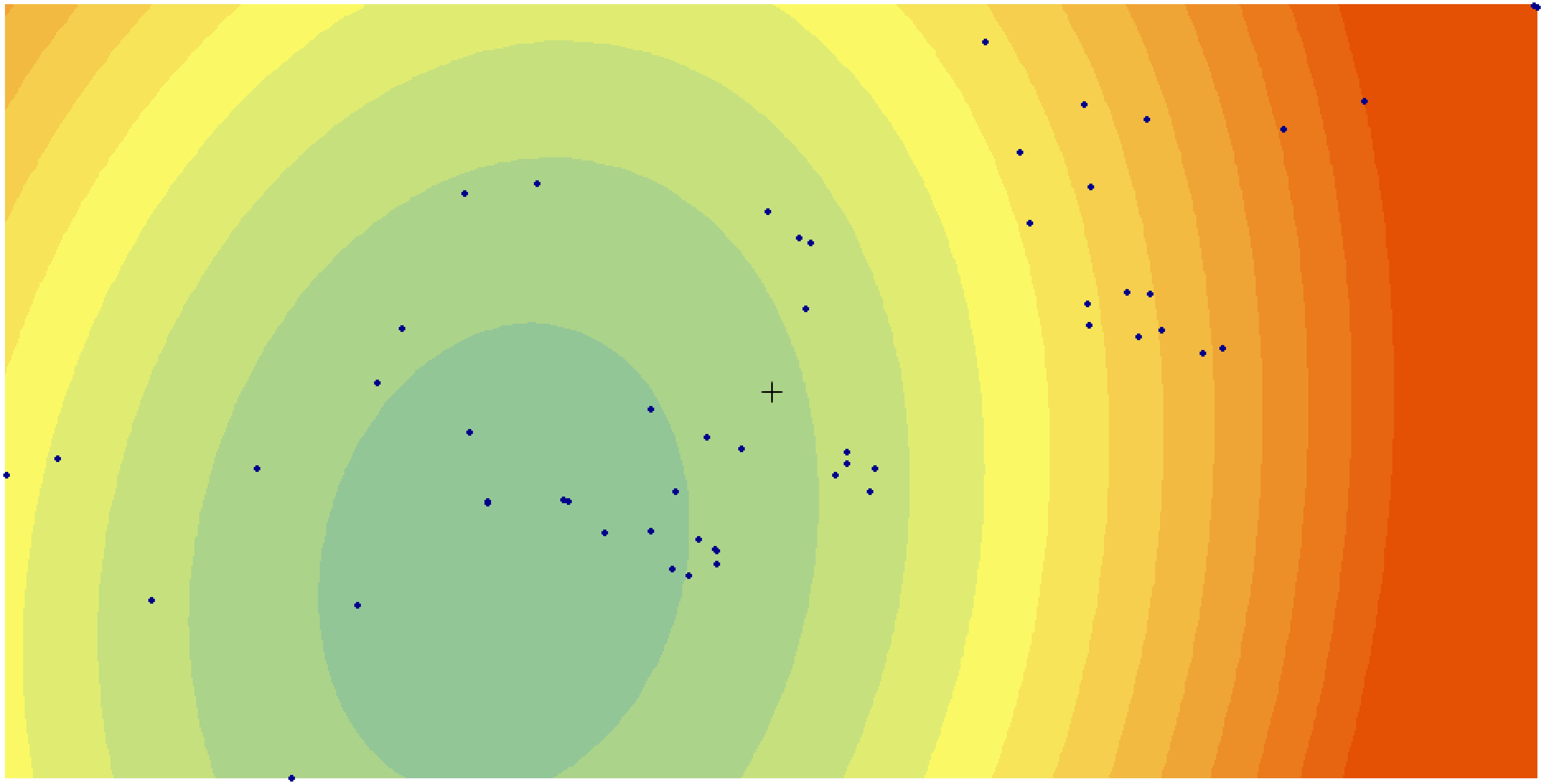
$$y(x_i) = \mu + \varepsilon_i$$

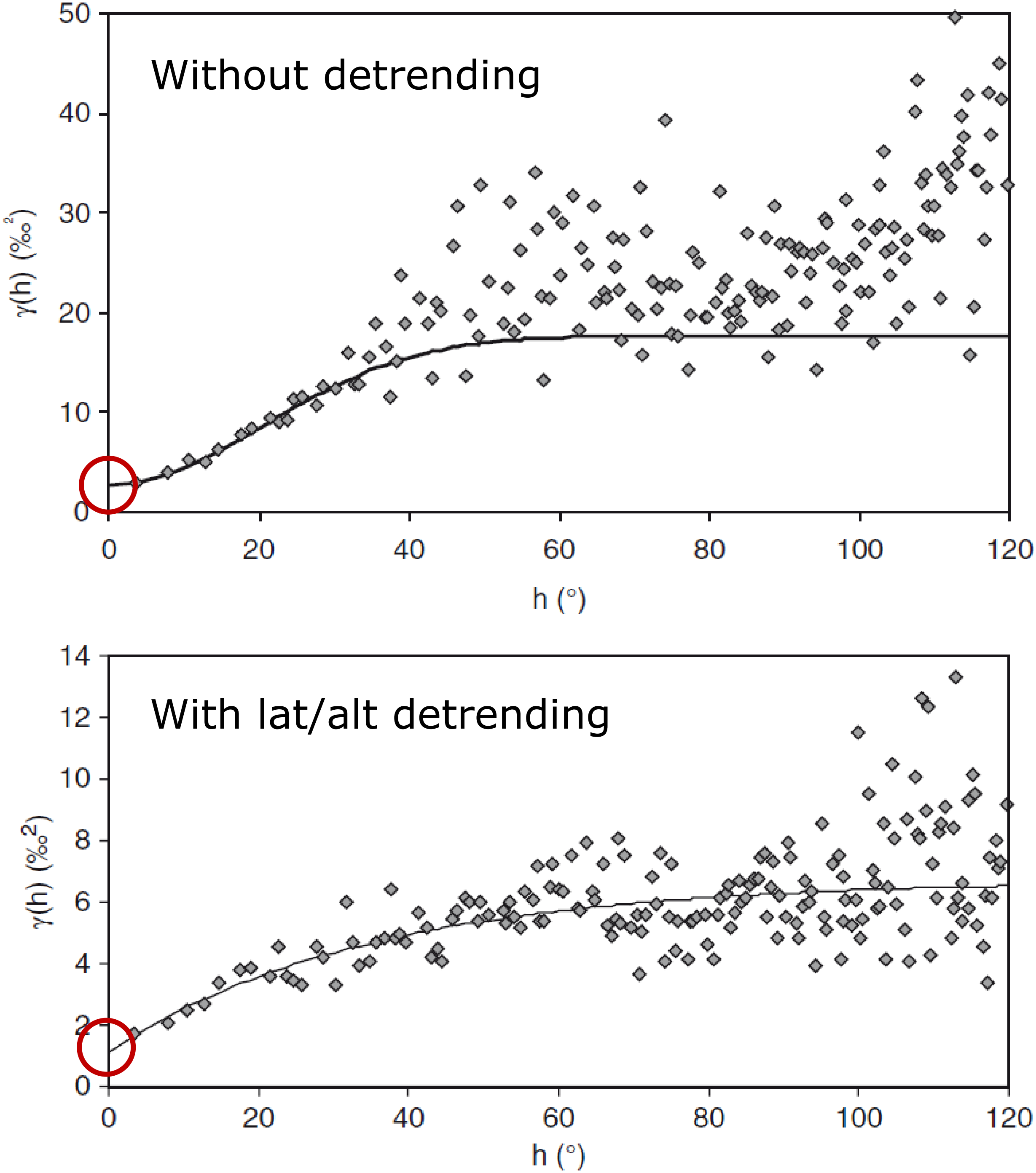
$$\Downarrow$$

$$y(x_i) = v'(x_i)\beta + \varepsilon_i$$

- Model for local mean ($v'(x_i)\beta$) can range from simple function of location to complex multivariate function incorporating ancillary variables

Universal Kriging – Trend surface



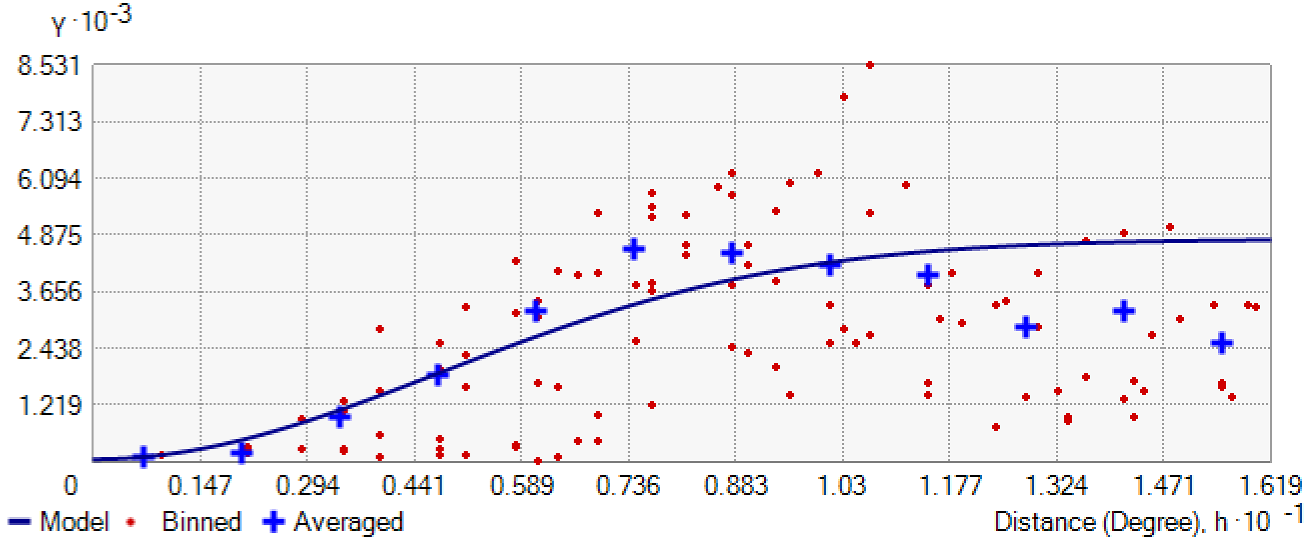


Bowen, 2010
Isoscapes

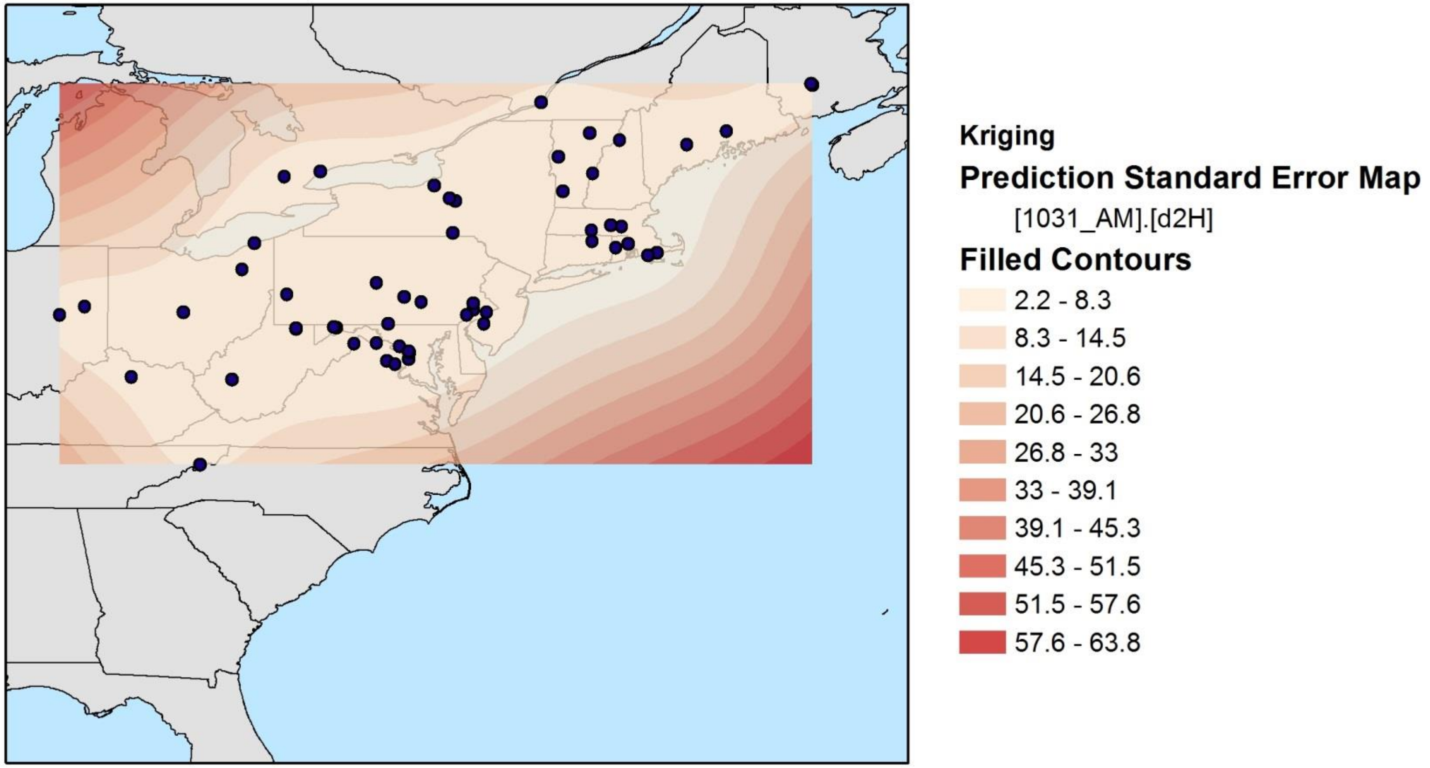
Estimating uncertainty

- Depending on method, multiple approaches are available
- Range from analytical expressions for uncertainty in model to simulation-based numerical approaches

- Kriging – variogram values basis for uncertainty of estimator



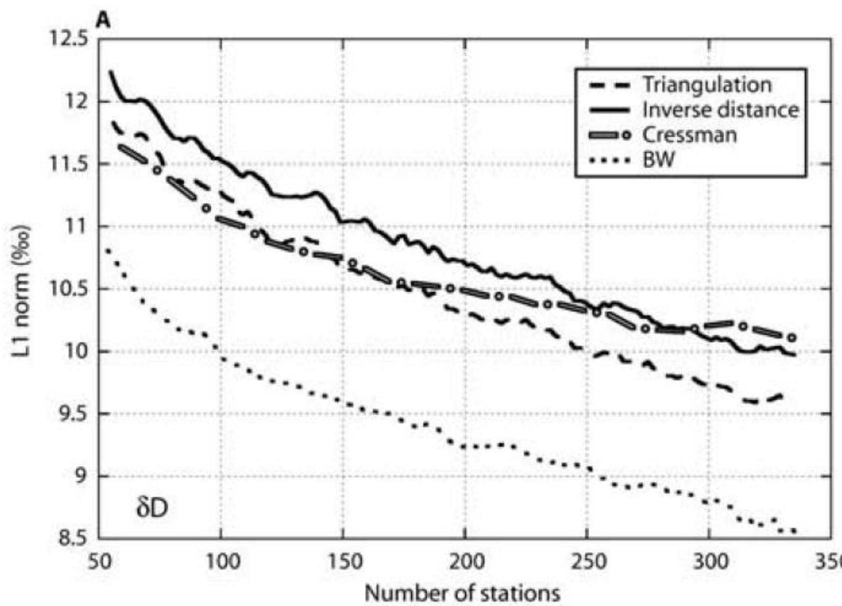
Kriging uncertainty



- Function of semivariogram model, data site distribution
- Sensitive to model assumptions!

Split-data tests

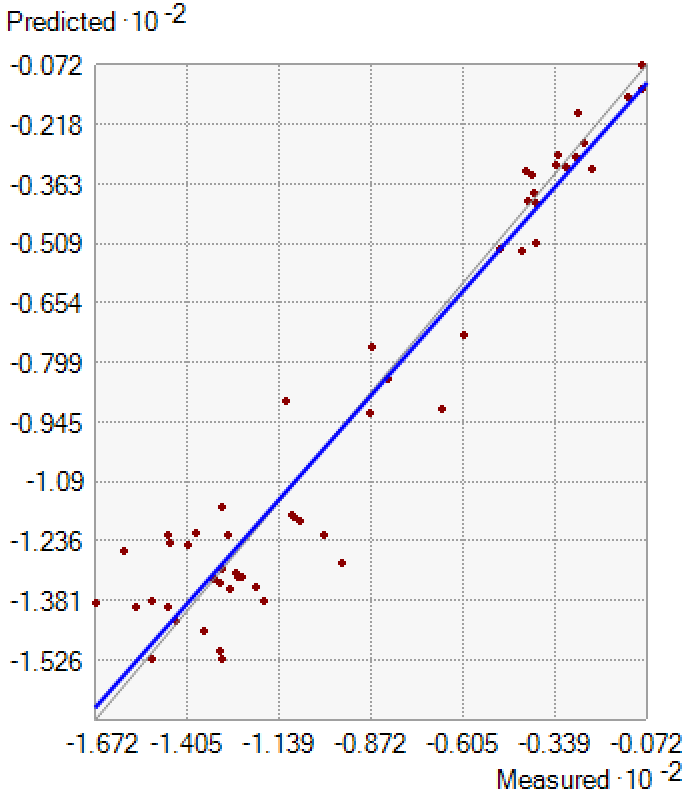
- Simple approach
  - Manually divide data into 2 subsets
  - Fit model w/ first subset
  - Validate w/ second subset
  - + Quick, easy, supported by most software
  - - Only 1 realization of model
  - How many points to include?



Bowen and Revenaugh, 2003, *WRR*

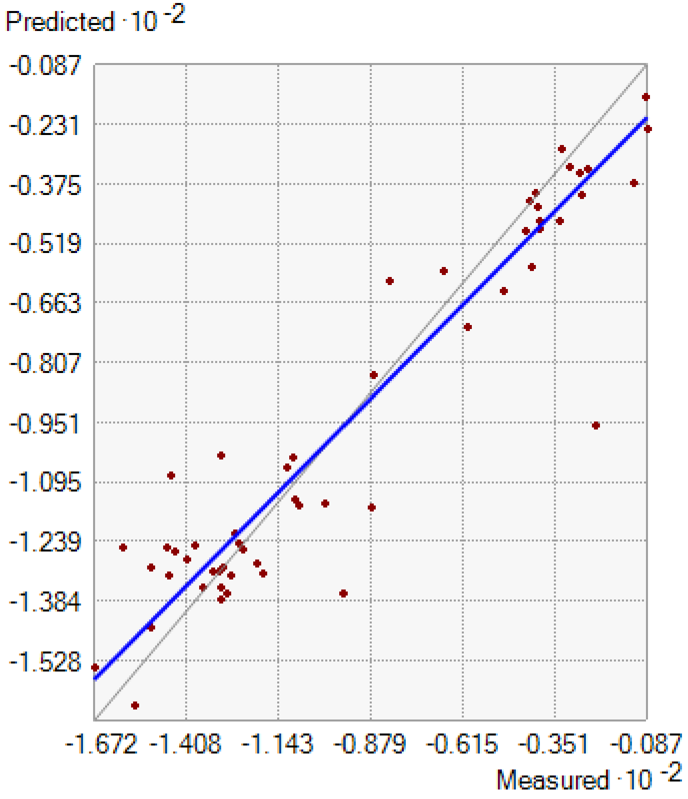
Partial cross-validation

Ordinary Kriging



RMSE = 13.4‰

Universal Kriging

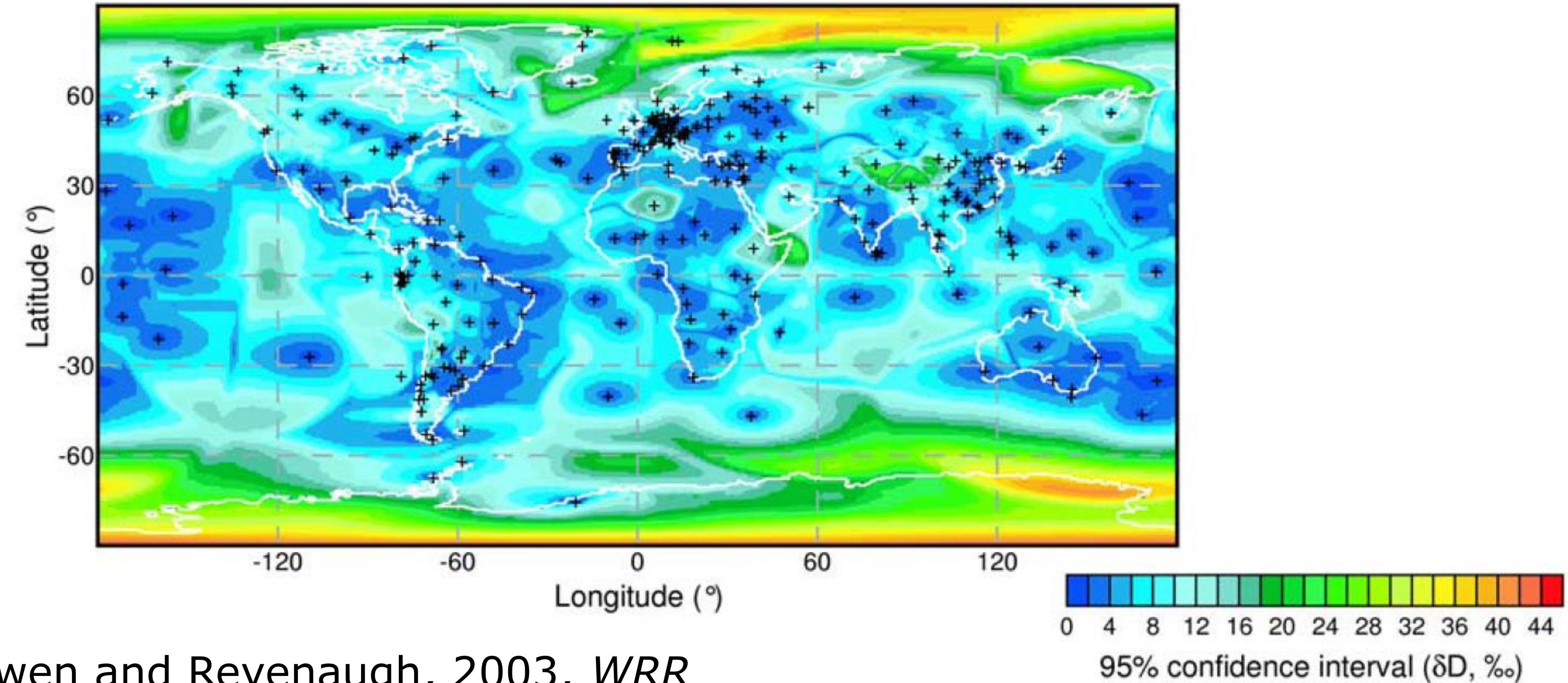


RMSE = 17.4‰

- *Note* model not iteratively re-fit

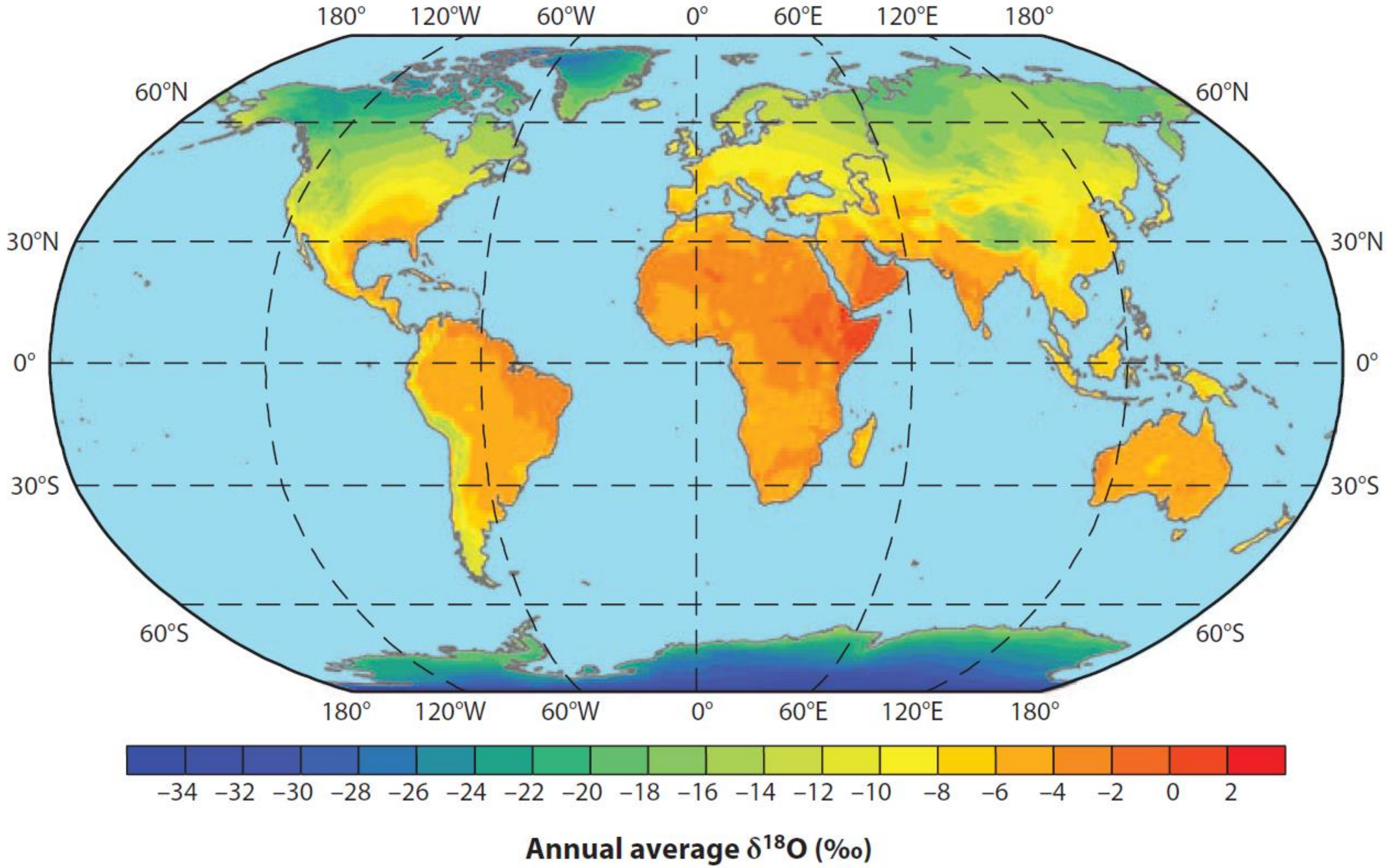
Simulation

- Develop PDFs for model parameters
- Iteratively calculate predictions to estimate PDFs for predictions across spatial domain
- Can combine w/ resamping validation approaches



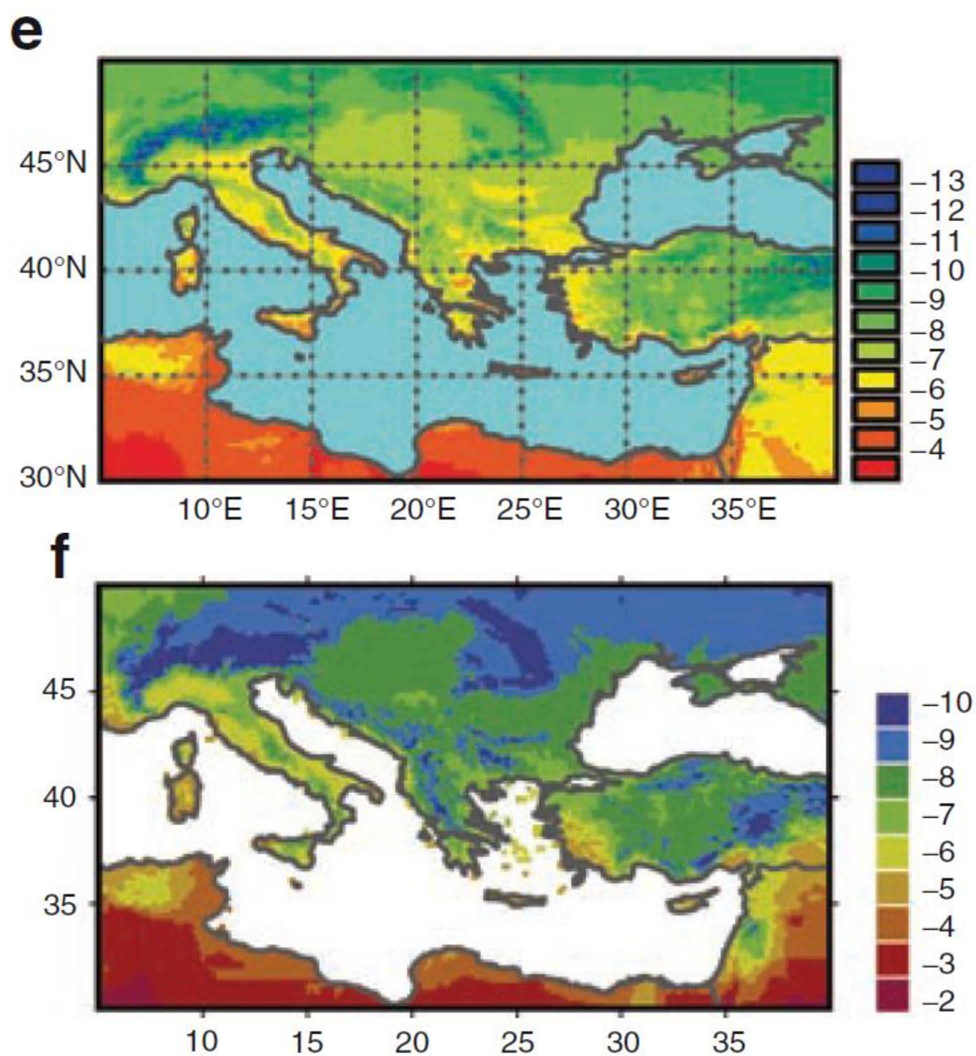
Bowen and Revenaugh, 2003, *WRR*

Precipitation isotope examples



Regional models

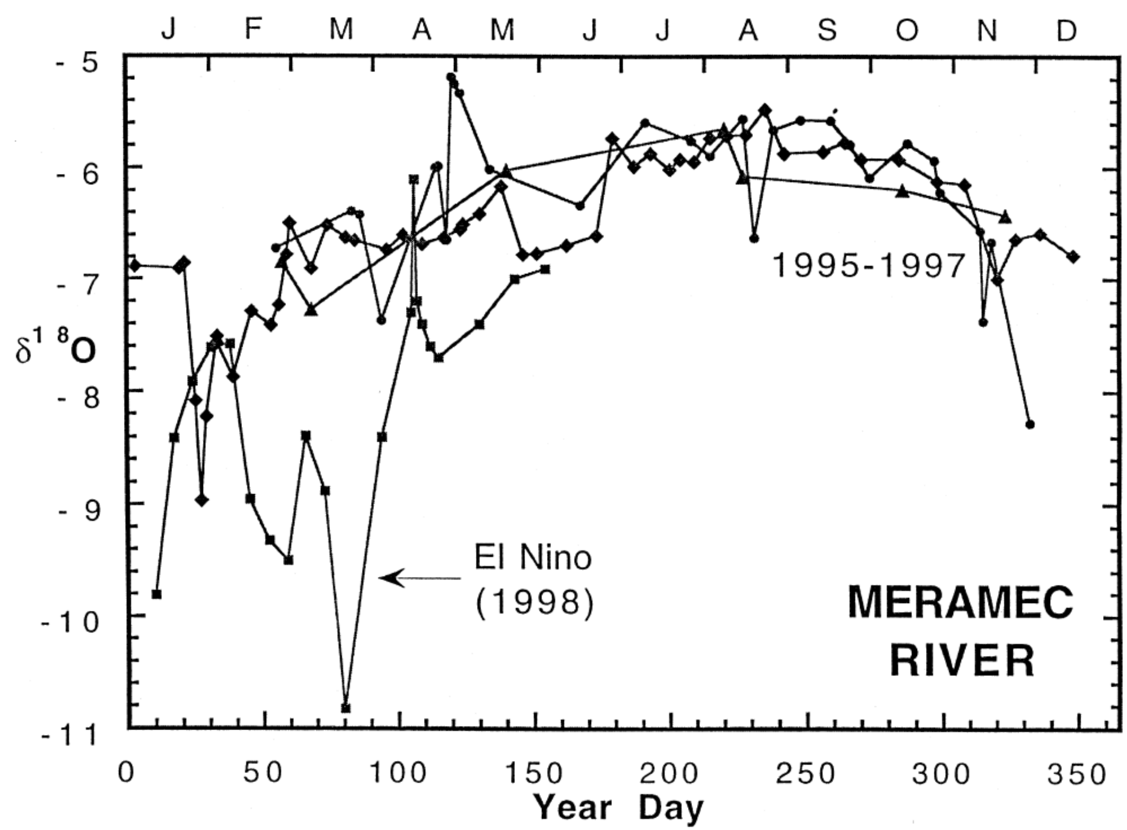
- Optimal parameterization varies with region
- Regional models can be generated over a range of spatial scales
- Recent effort pursuing global models as aggregate of local functions…



Bowen, 2010, *Isoscapes*
after Lykoudis and Argiriou, 2007, *JGR*

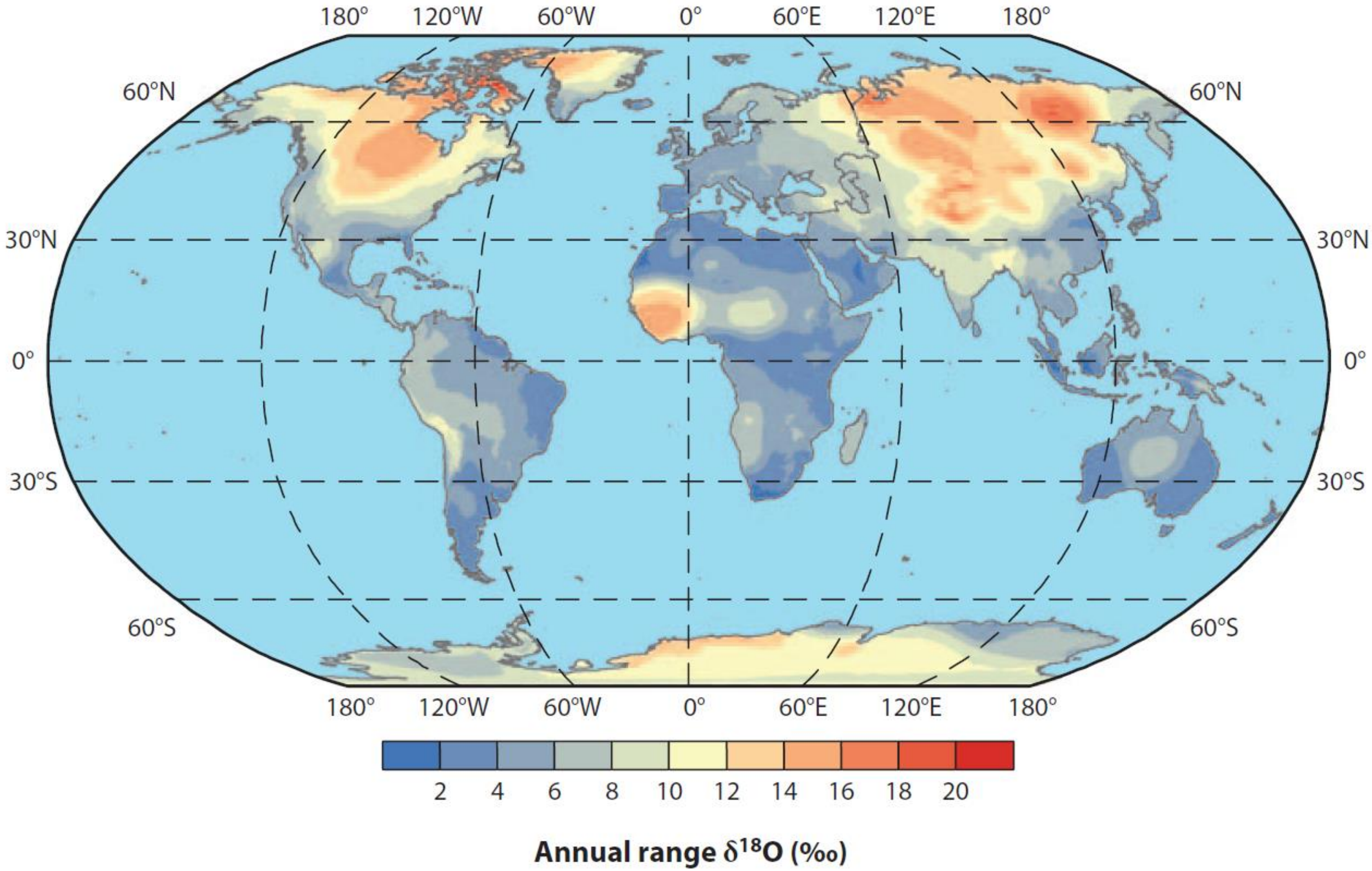
3. Interpolating in space and time

- Lots of information in water isotope time-series
- Requires understanding of precipitation isotope variation in spatial and temporal domains



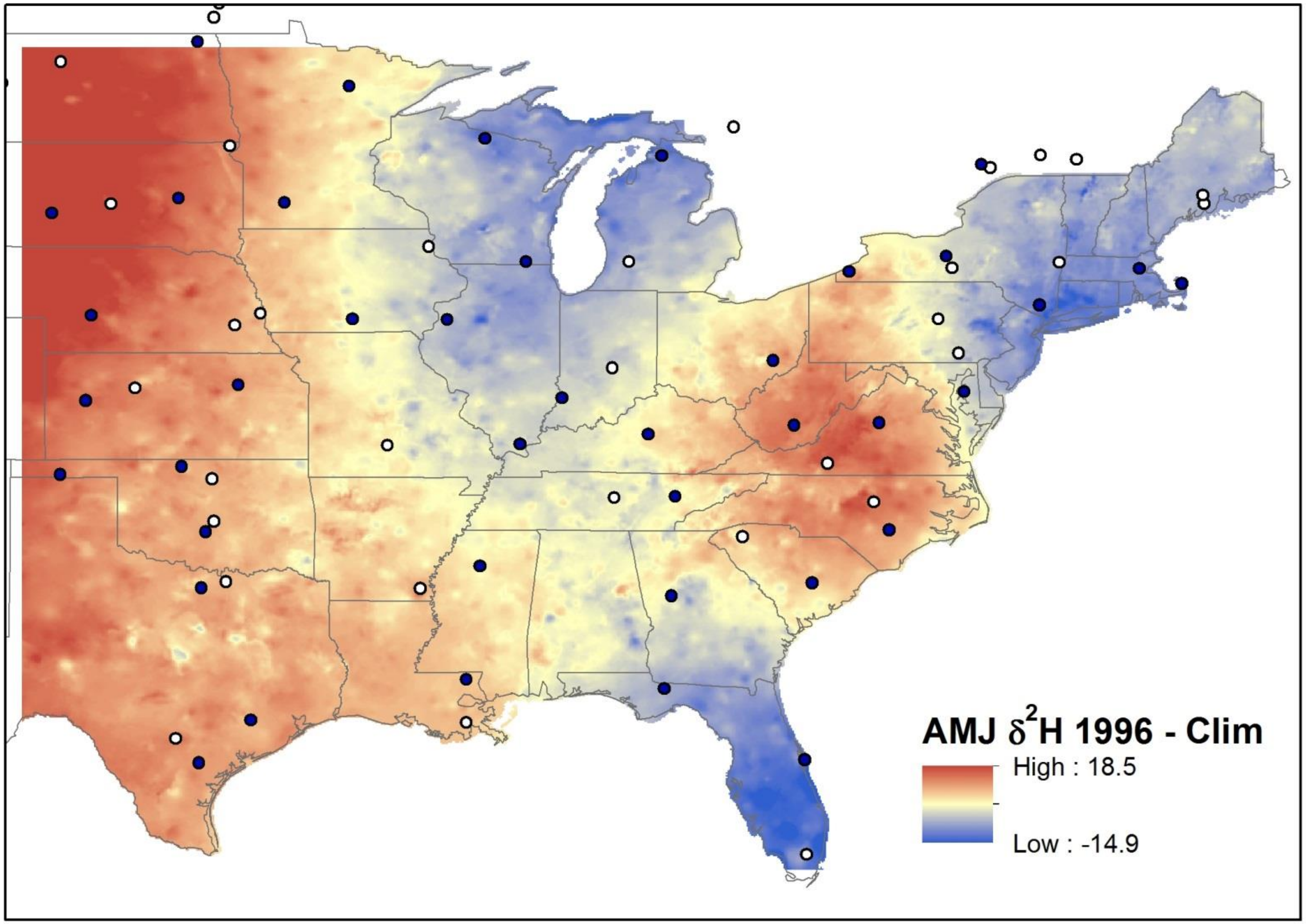
Fredrickson and Criss, 1999
Chem Geol

Temporal variation - seasonality

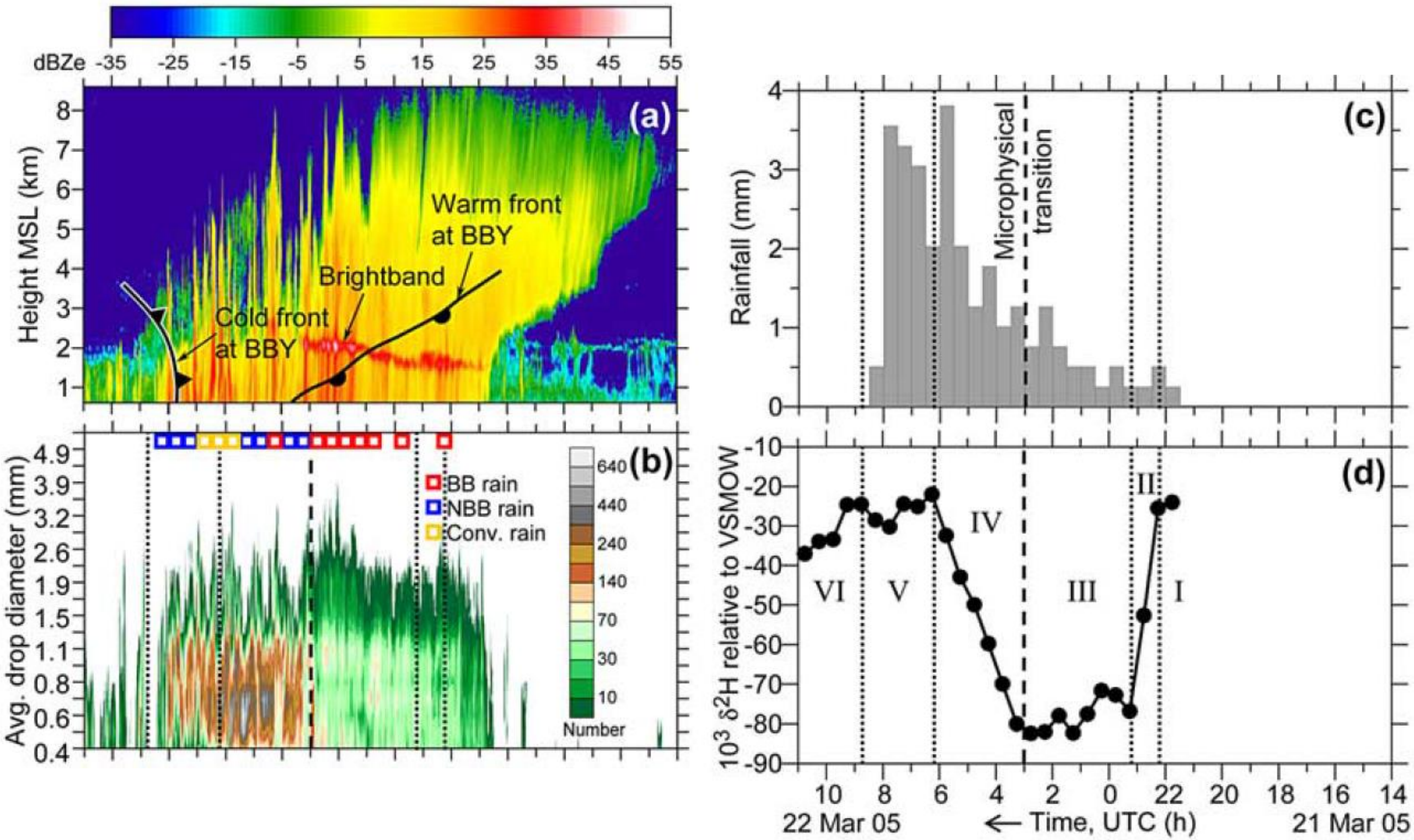


Bowen, 2008, *JGR*

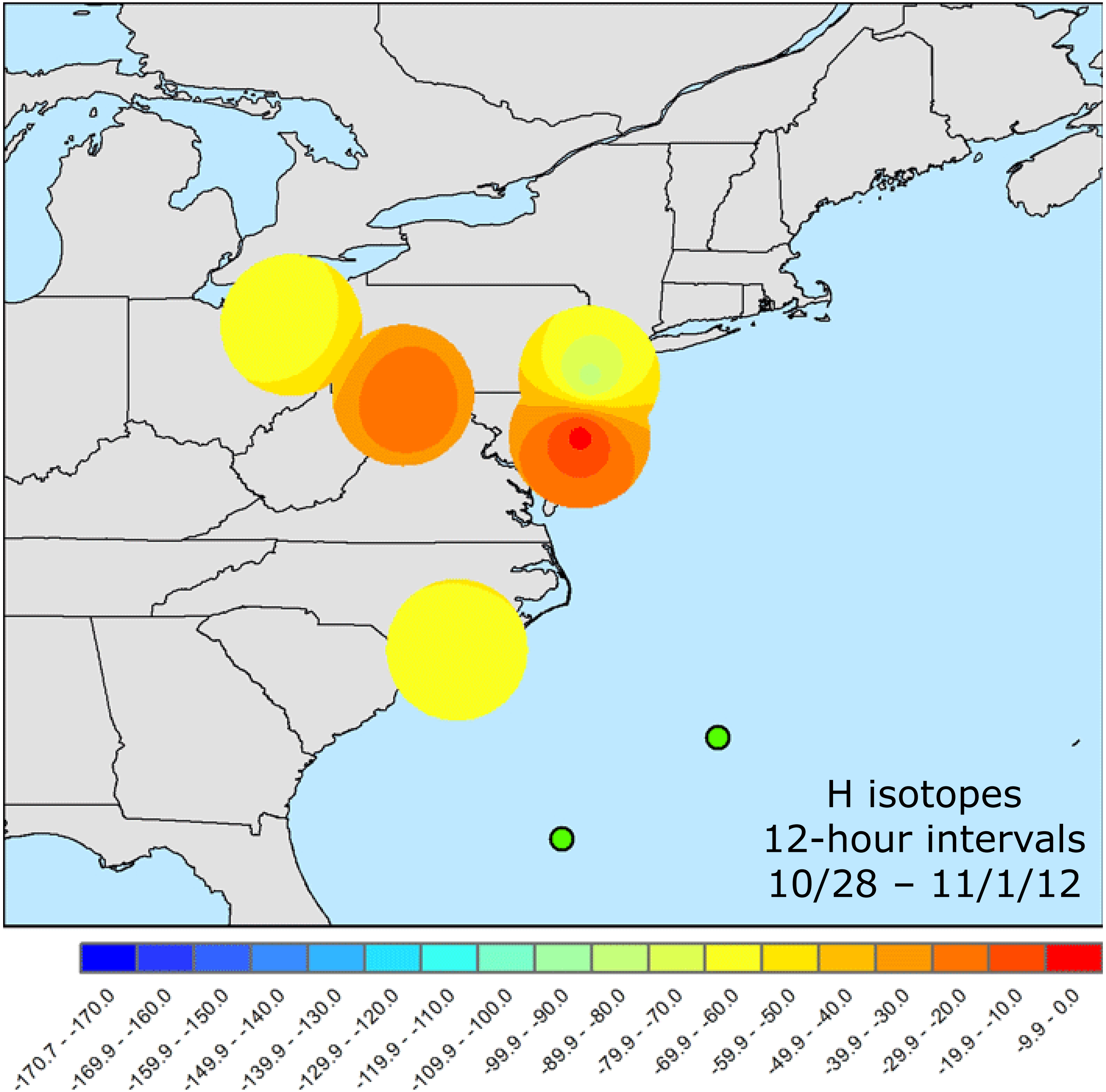
Temporal variation - interannual



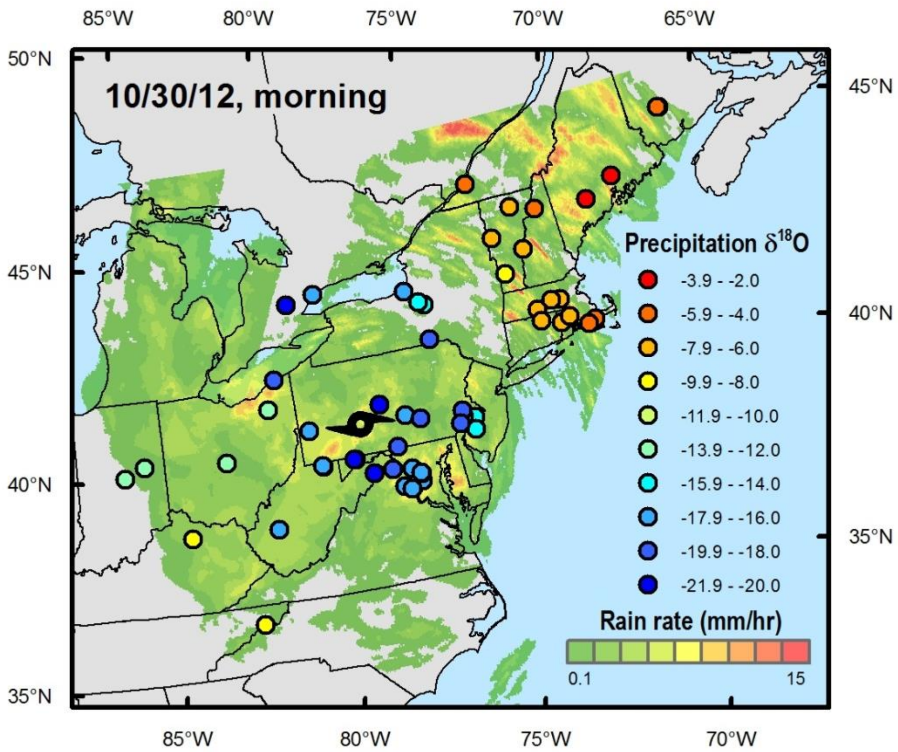
Temporal variation - meterological



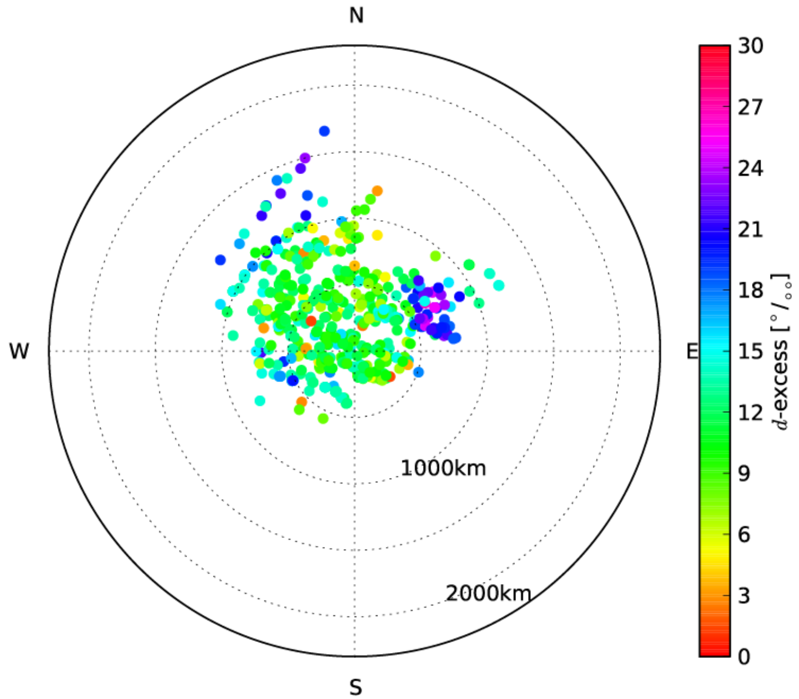
Coplen et al., 2008, *GRL*


H isotopes
12-hour intervals
10/28 – 11/1/12
-170.7 - -170.0
-169.9 - -160.0
-159.9 - -150.0
-149.9 - -140.0
-139.9 - -130.0
-129.9 - -120.0
-119.9 - -110.0
-109.9 - -100.0
-99.9 - -90.0
-89.9 - -80.0
-79.9 - -70.0
-69.9 - -60.0
-59.9 - -50.0
-49.9 - -40.0
-39.9 - -30.0
-29.9 - -20.0
-19.9 - -10.0
-9.9 - 0.0

Predictability?



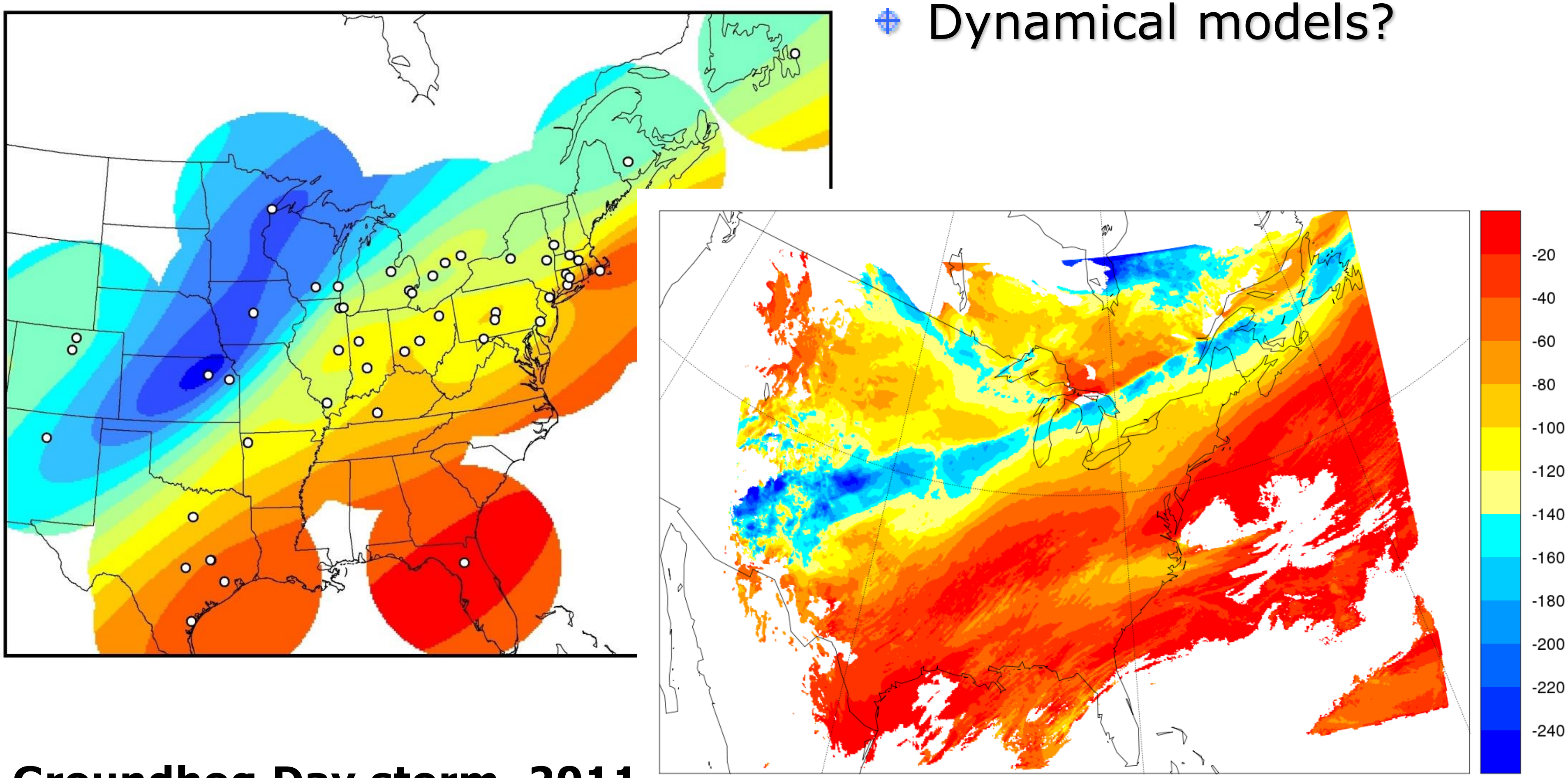
- Synoptic relationships?



Good et al., 2014, *PLoS ONE*

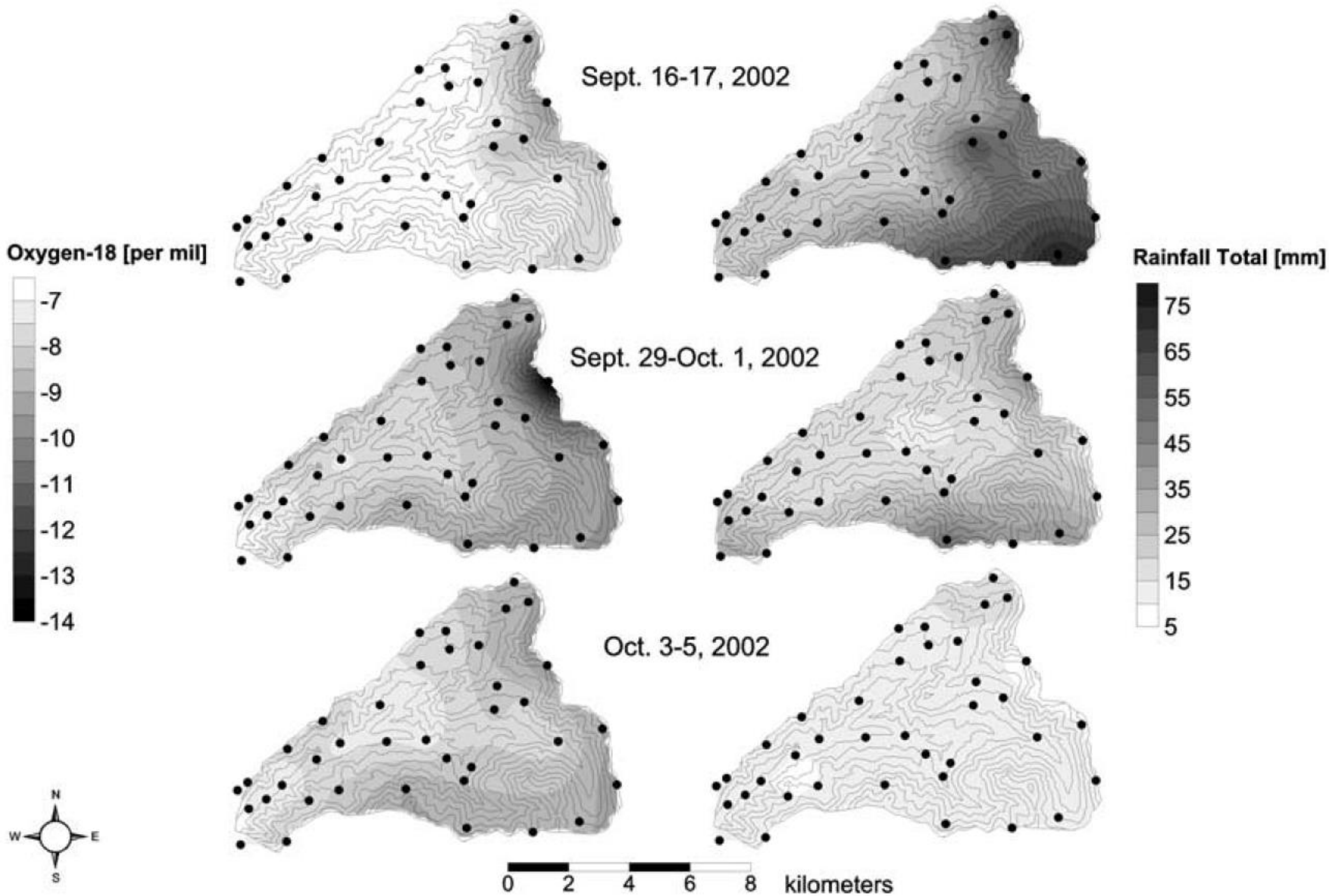
Predictability?

- Dynamical models?



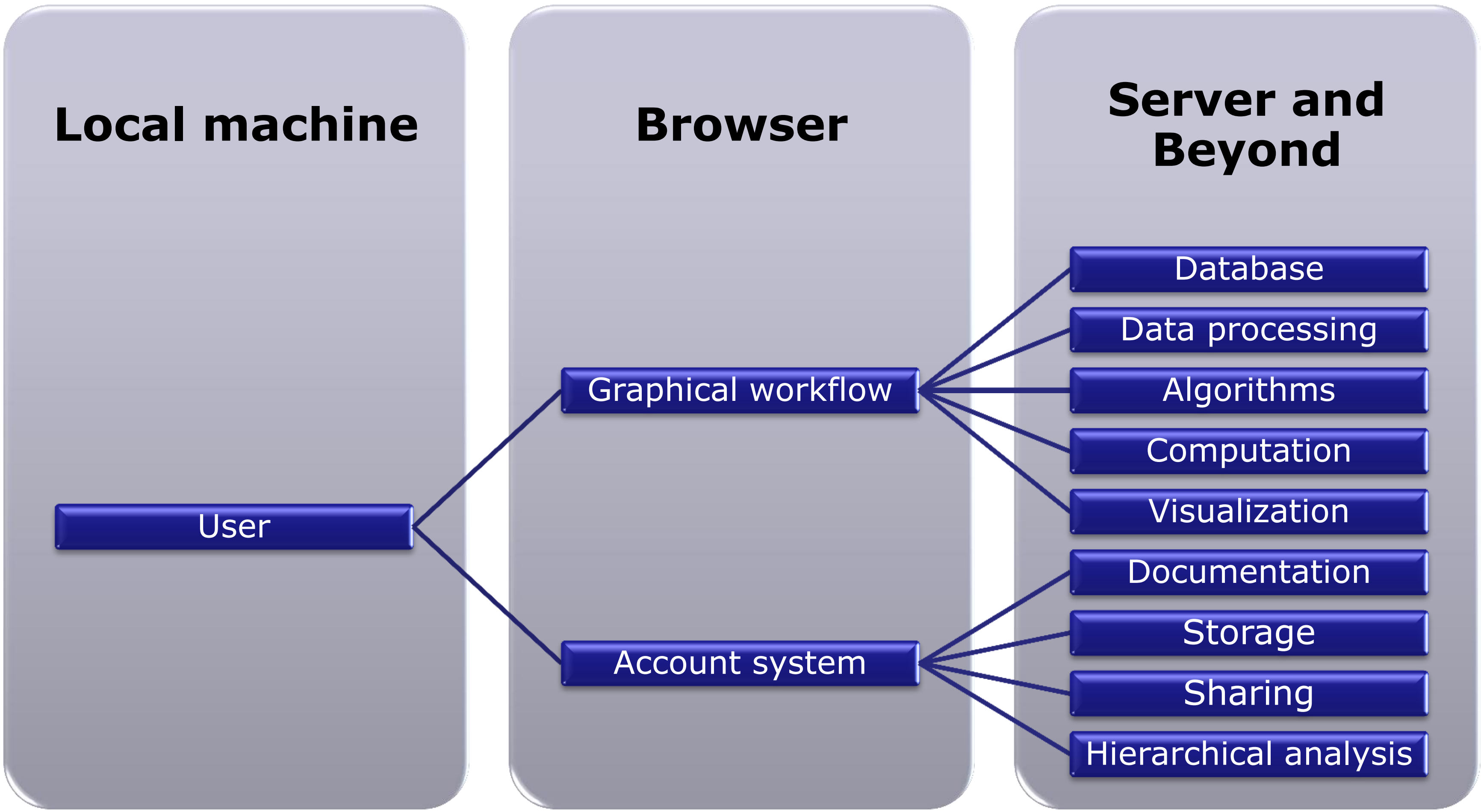
Groundhog Day storm, 2011 storm average δ²H

Emperical approach

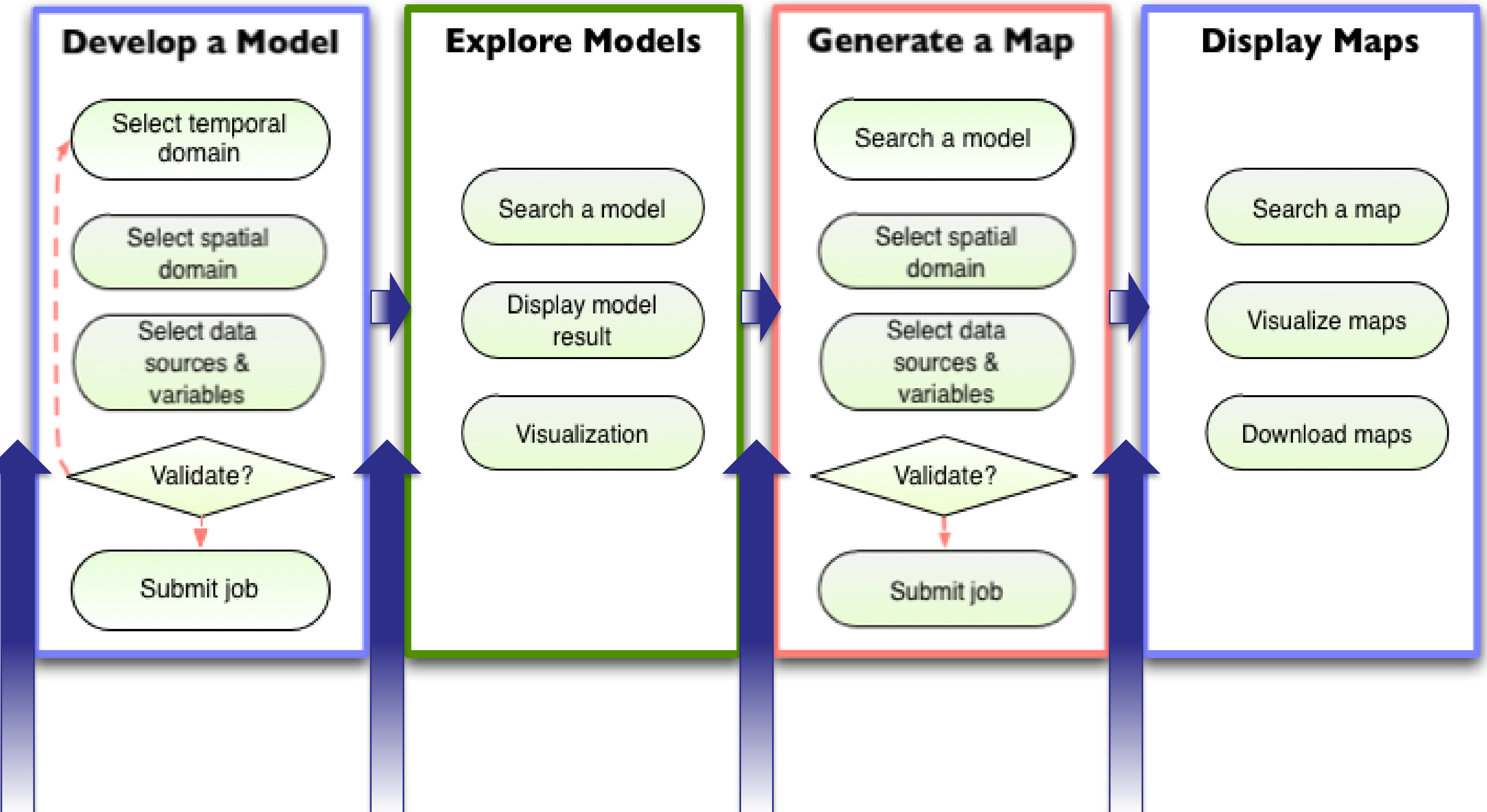


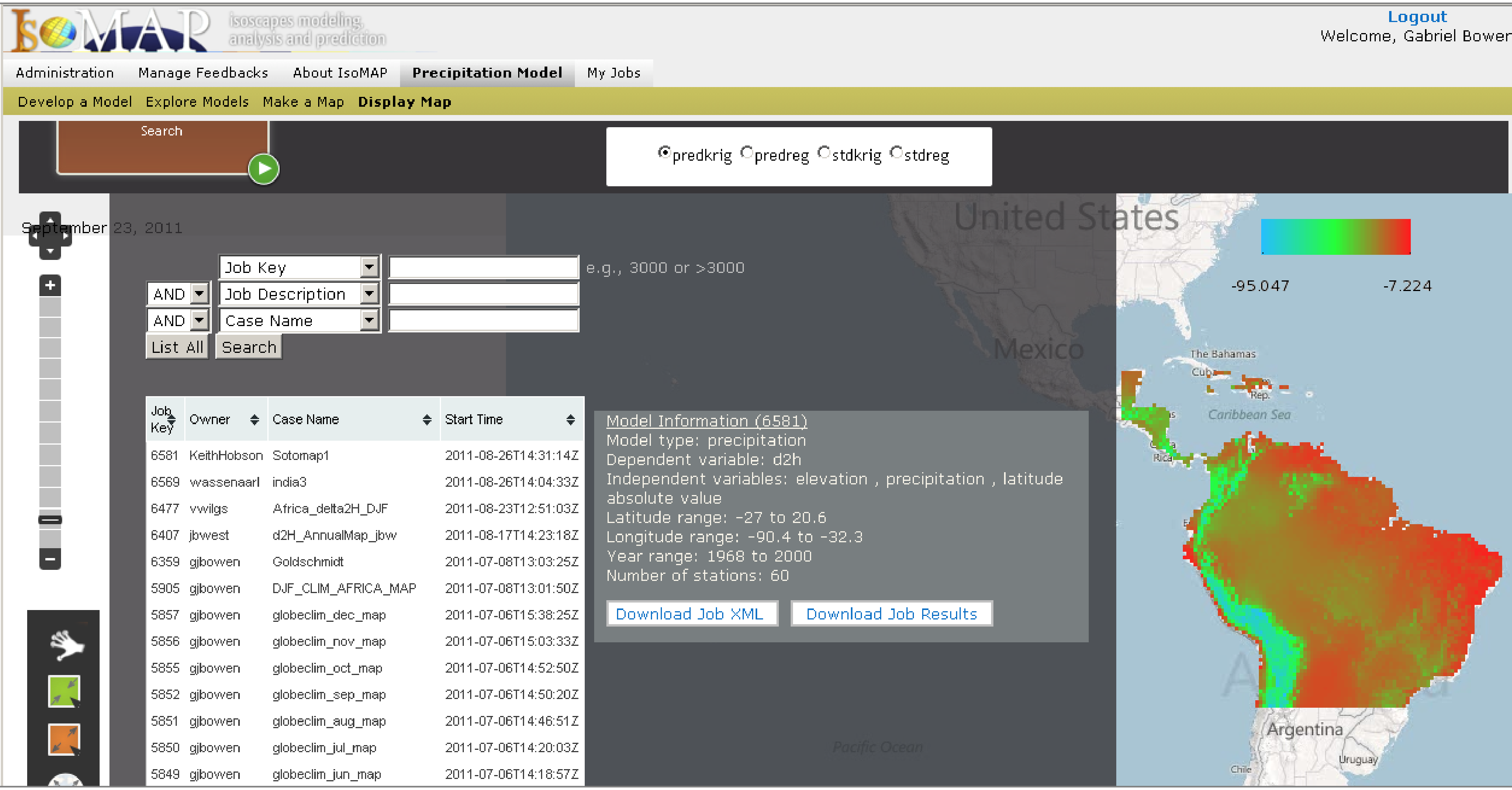
McGuire et al., 2005, *WRR*

IsoMAP (http://isomap.org)



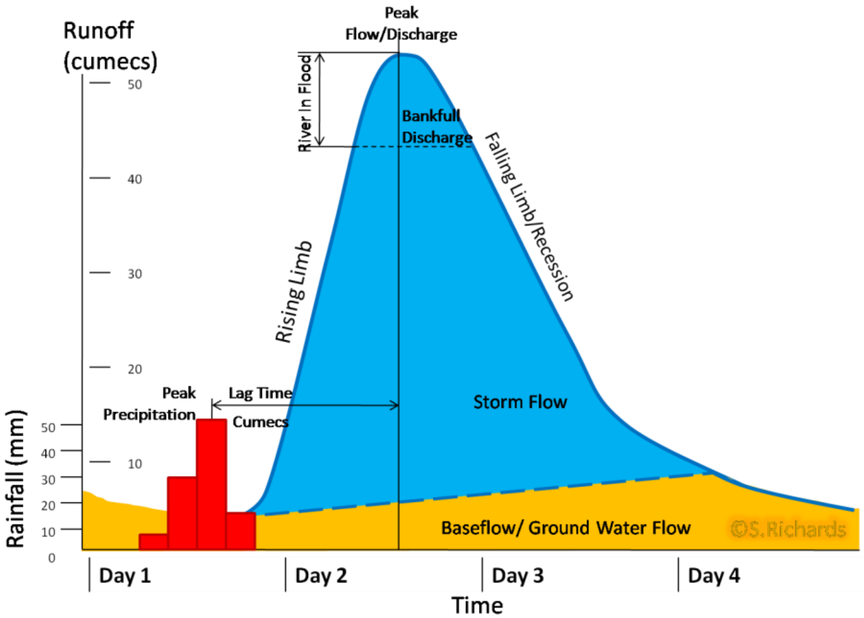
Precipitation Modeling Workflow




isoscapes modeling, analysis and prediction
Logout
Welcome, Gabriel Bowen
Administration
Manage Feedbacks
About IsoMAP
Precipitation Model
My Jobs
Develop a Model
Explore Models
Make a Map
Display Map
Search
predkrig predreg stdkrig stdreg
September 23, 2011
Job Key
AND Job Description
AND Case Name
e.g., 3000 or >3000
List All
Search
Job Key | Owner | Case Name | Start Time
6581 KeithHobson Sotomap1 2011-08-26T14:31:14Z
6569 wassenaarl india3 2011-08-26T14:04:33Z
6477 vwilgs Africa_delta2H_DJF 2011-08-23T12:51:03Z
6407 jbwest d2H_AnnualMap_jbw 2011-08-17T14:23:18Z
6359 gjbowen Goldschmidt 2011-07-08T13:03:25Z
5905 gjbowen DJF_CLIM_AFRICA_MAP 2011-07-08T13:01:50Z
5857 gjbowen globeclim_dec_map 2011-07-06T15:38:25Z
5856 gjbowen globeclim_nov_map 2011-07-06T15:03:33Z
5855 gjbowen globeclim_oct_map 2011-07-06T14:52:50Z
5852 gjbowen globeclim_sep_map 2011-07-06T14:50:20Z
5851 gjbowen globeclim_aug_map 2011-07-06T14:46:51Z
5850 gjbowen globeclim_jul_map 2011-07-06T14:20:03Z
5849 gjbowen globeclim_jun_map 2011-07-06T14:18:57Z
Model Information (6581)
Model type: precipitation
Dependent variable: d2h
Independent variables: elevation , precipitation , latitude absolute value
Latitude range: -27 to 20.6
Longitude range: -90.4 to -32.3
Year range: 1968 to 2000
Number of stations: 60
Download Job XML
Download Job Results
United States
Mexico
-95.047
-7.224
The Bahamas
Caribbean Sea
Argentina
Uruguay
Chile
Pacific Ocean

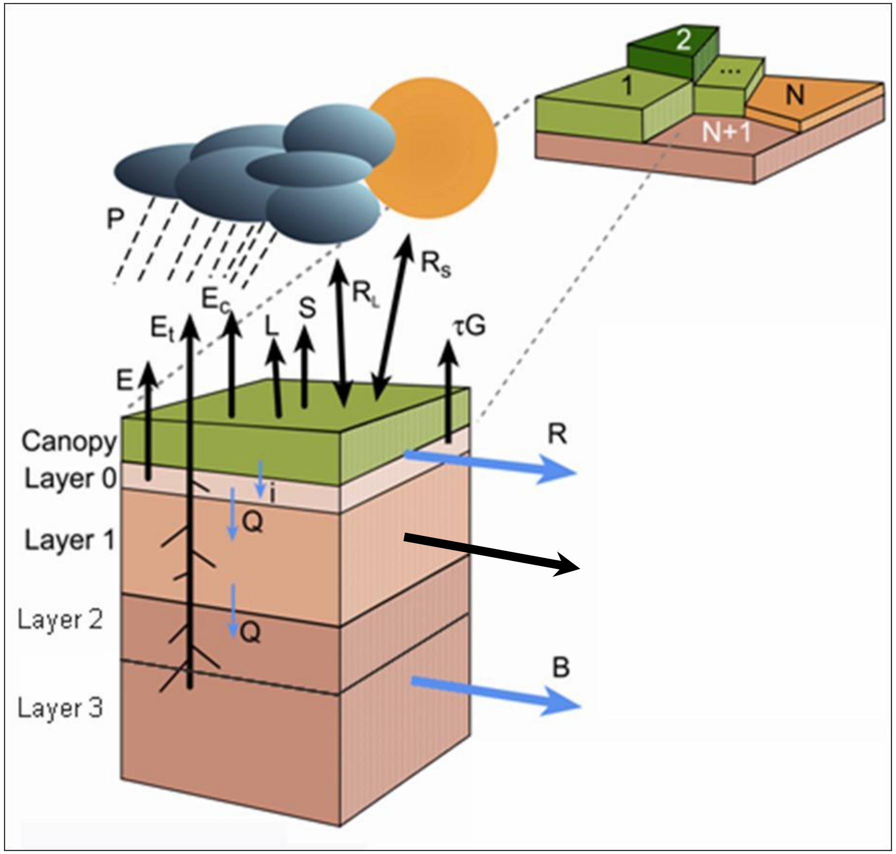
4. Most headwater catchments export old water

- Accurate rainfall-runoff models are one of the fundamental goals of catchment hydrology
  - Flood control
  - Water management
  - Water quality
- Summarized in terms of storm hydrograph



Rainfall routing

- How is storm precipitation delivered to streams?
  - Overland flow
  - Interflow
  - Groundwater recharge/baseflow
- What are the transit times associated with these flowpaths?



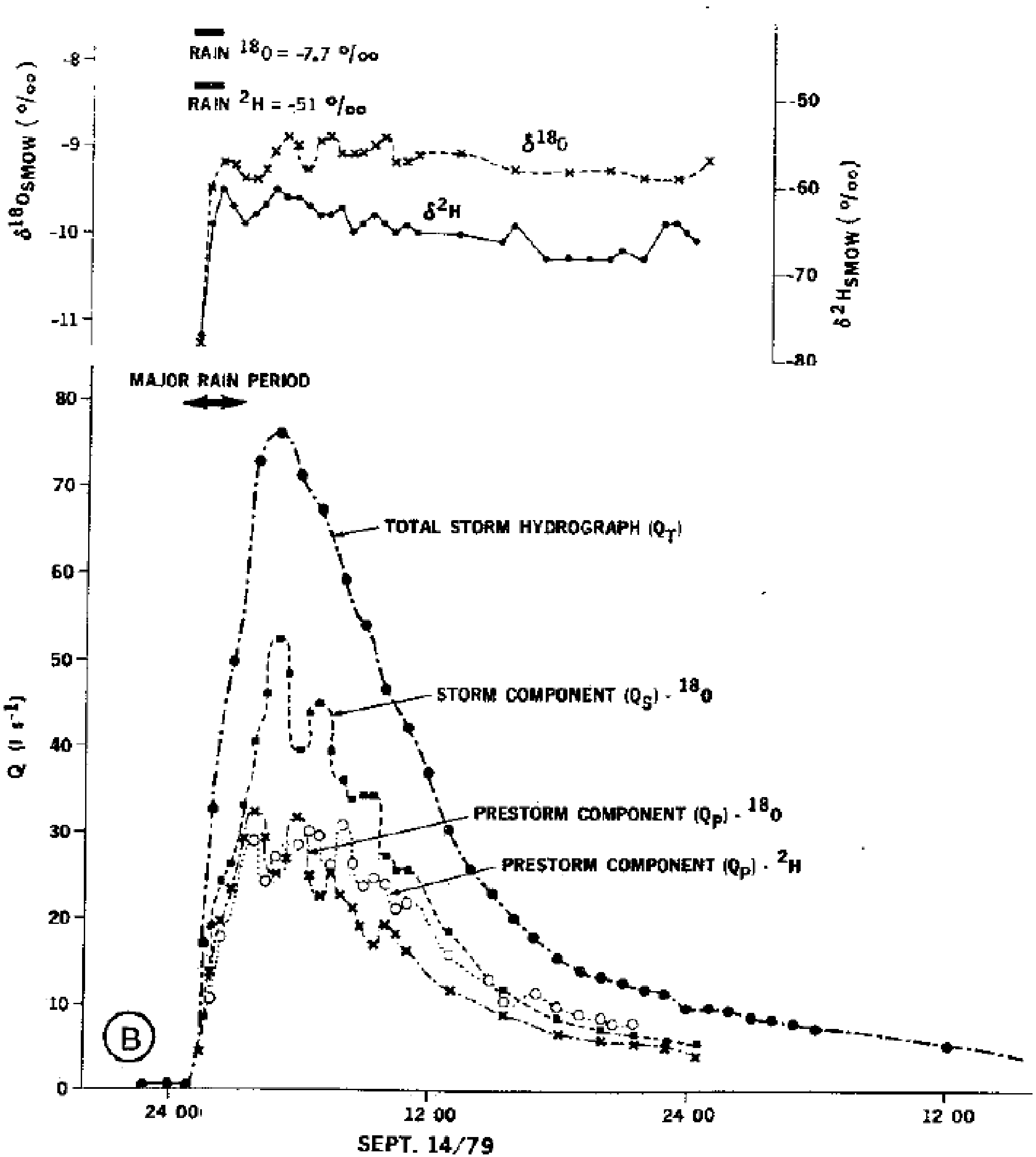
Hydrograph separation

- Given any conservative tracer that is present in different abundance in ***pre-event*** and ***event*** water, the fraction of pre-event water in storm flow at any time is

$$f_{pe} = \frac{C_s - C_e}{C_{pe} - C_e}$$

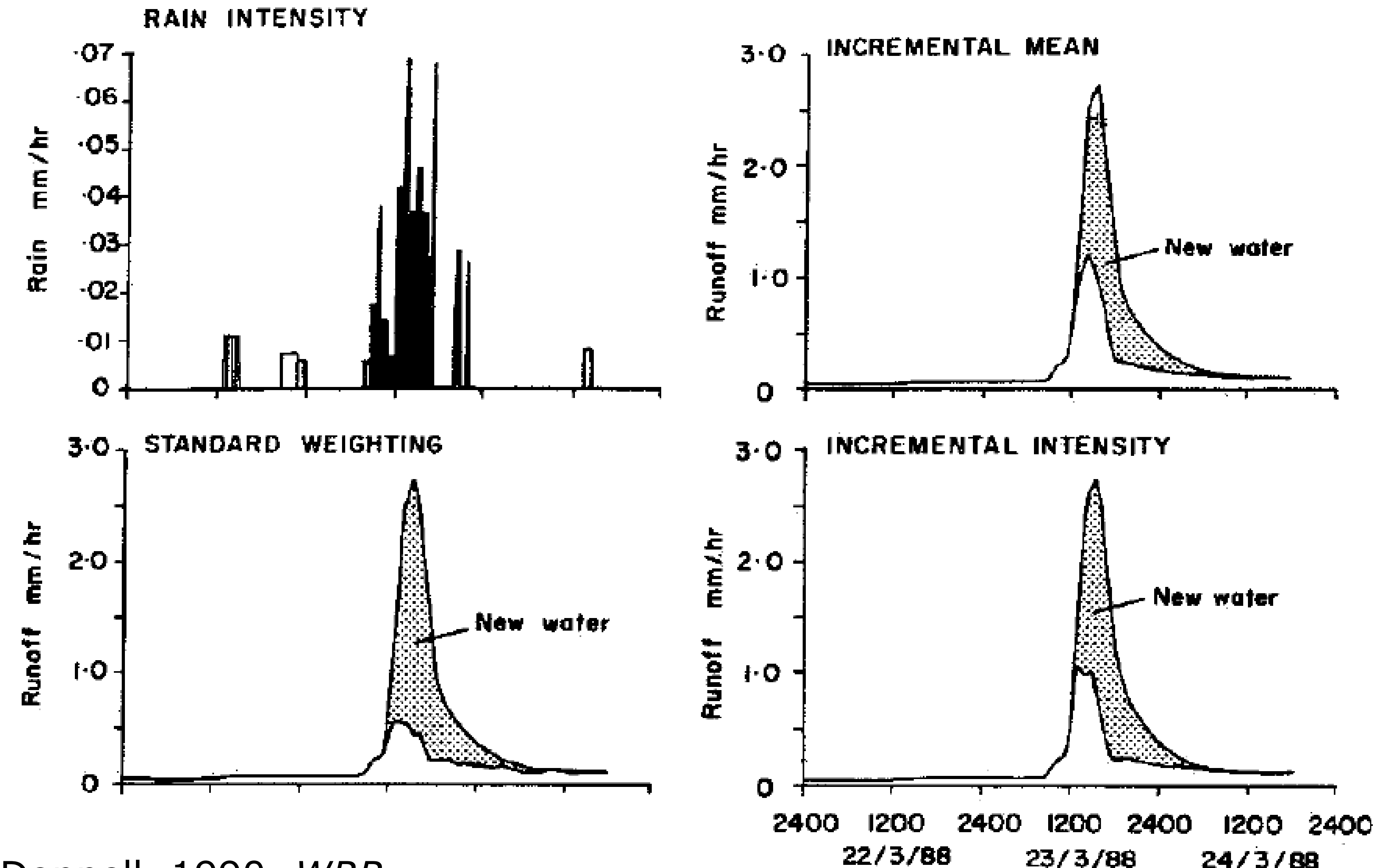
- Major assumption: C_e and C_{pe} are constant and can be accurately characterized

- Isotope hydrograph separation takes advantage of temporal variation in precipitation δ values



Bottomley et al., 1984
J Hydrol

Characterizing inputs



McDonnell, 1990, *WRR*

"Old water paradox"

Study	Location	Catchment area (ha)	Tracer	Percentage pre-event water	
				peak	volume
Jordan (1994)	Switzerland	3.6	^{18}O		45, 75
Waddington et al. (1993)	Ontario	160	^{18}O	87, 93	
McDonnell et al. (1991)	New Zealand	3.8	D	92-100	
O'Gunkoya & Jenkins (1991)*	United Kingdom	1000	D		54-90
McDonnell et al. (1990)	New Zealand	310	D		21-33
Nolan and Hill (1990)	California	1060	D		57
Bonell et al. (1990)	New Zealand	218	D		59
		310	D	38	38 to >97
Blowes and Gillham (1988)	Ontario	0.75	^{18}O	9, 45	22, 50
Turner et al. (1987)	W. Australia	82	^{18}O, D		69-95
Herrman et al. (1987)*	Germany	76	^{18}O		84
Rodhe (1987)	Sweden	3	^{18}O		81, 87
		4	^{18}O		81, 96
		17	^{18}O	87	
		50	^{18}O		85-99

....

Genereux and Hooper, 1998, *Isotope Tracers*

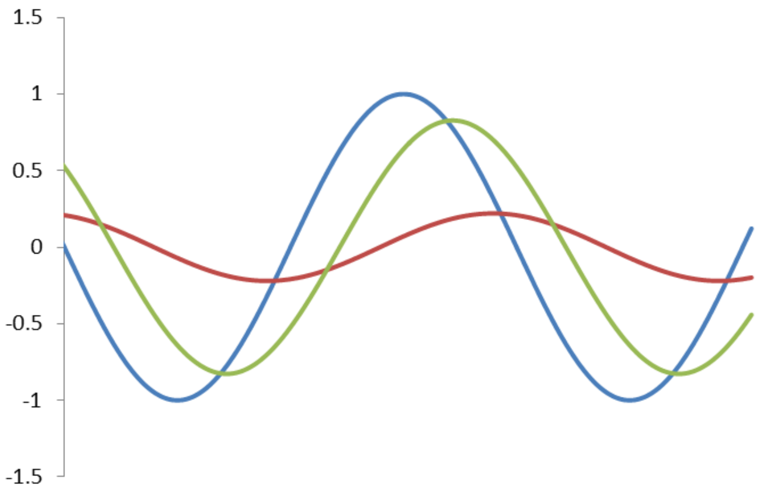
"Old water paradox"

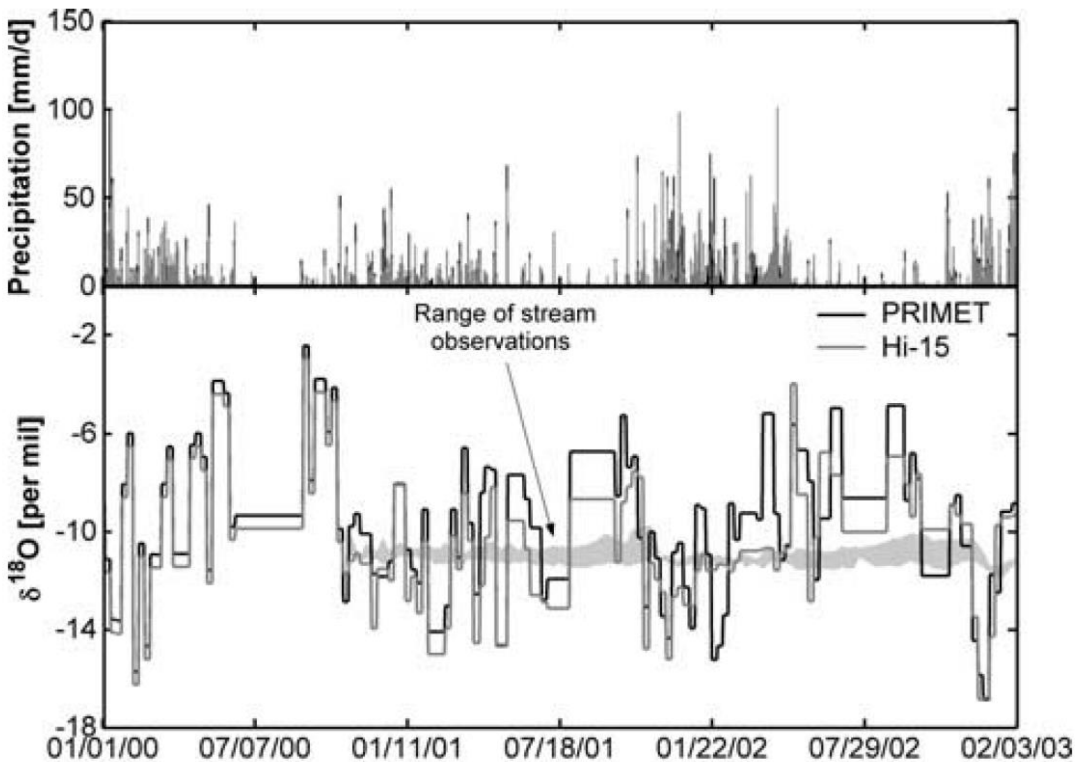
- Even in small, steep catchments, most storm flow is "old" water
- Mean residence time of water in catchments is much longer than implied by simple interpretation of storm hydrograph, rainfall-runoff models

- How does storm discharge actually work?
  - If water is not transferred directly, how does addition of precipitation rapidly force release of pre-event water?
- Hypotheses
  - Pressure waves
  - Capillary fringe
  - Macropore flow

Baseflow transit time distributions

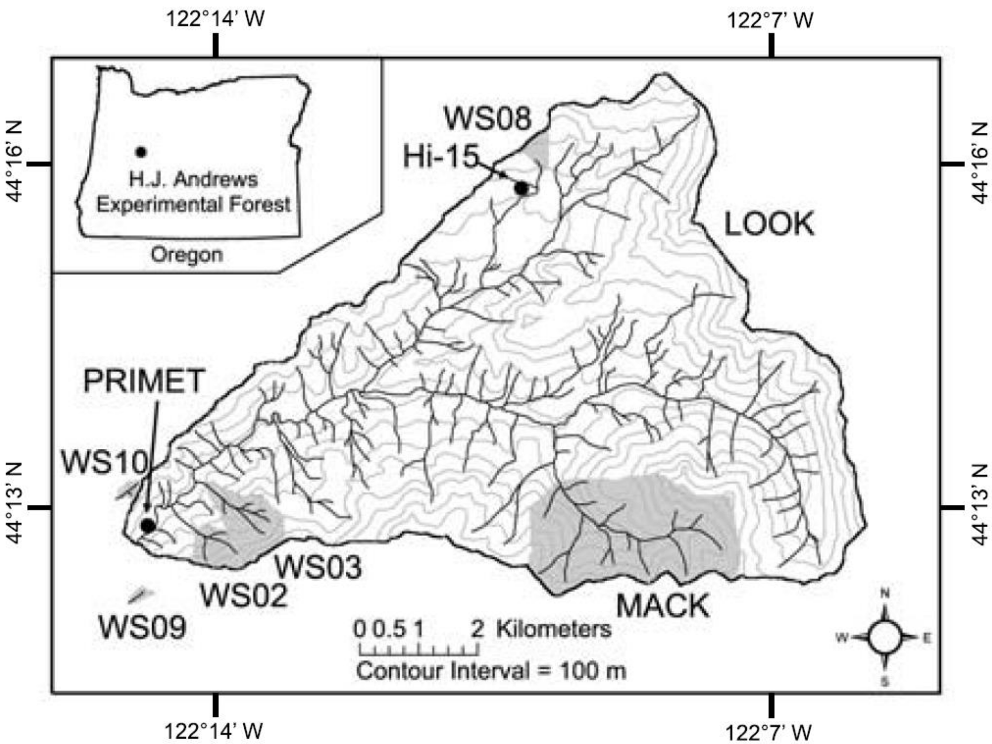
- Given measured input and output time series, optimize the function *f*(*t*) describing the distribution of transit times within a catchment



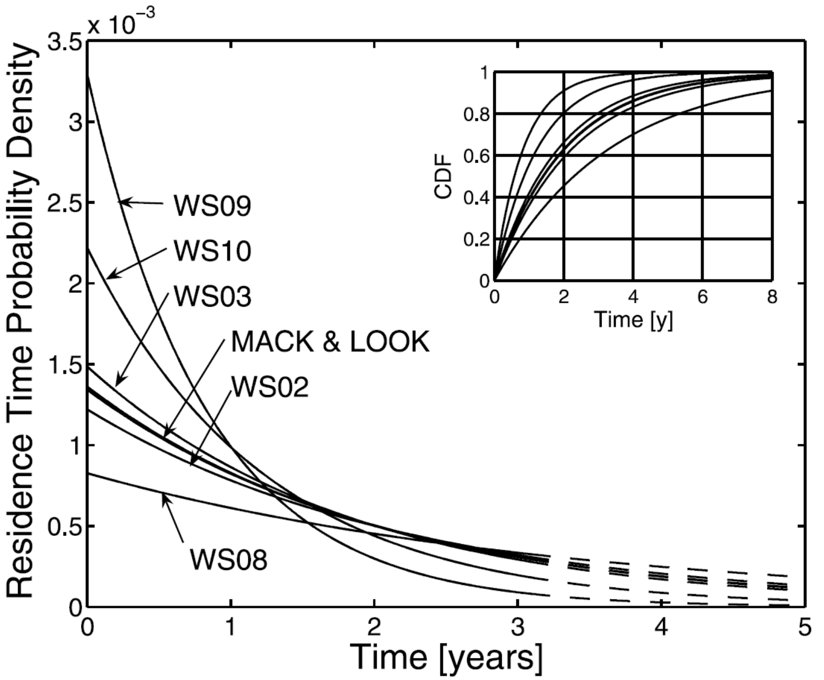


McGuire et al.
2005
WRR

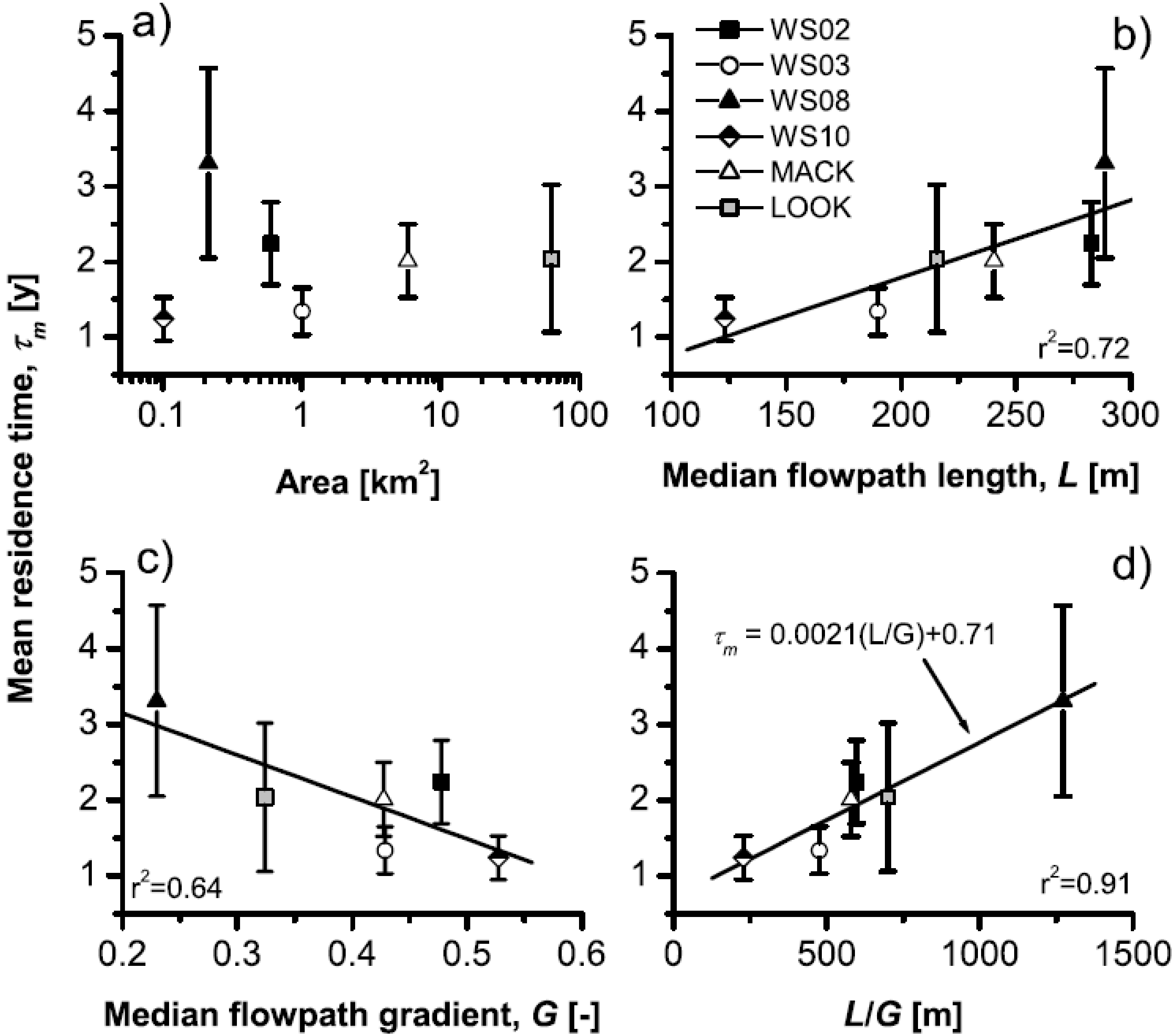
Baseflow transit time distributions



- Mean residence times are long (years)
- What catchment properties control distribution?



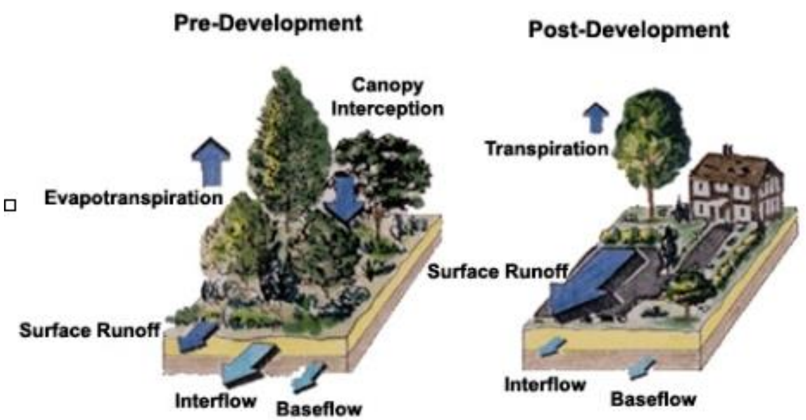
McGuire et al. 2005 *WRR*

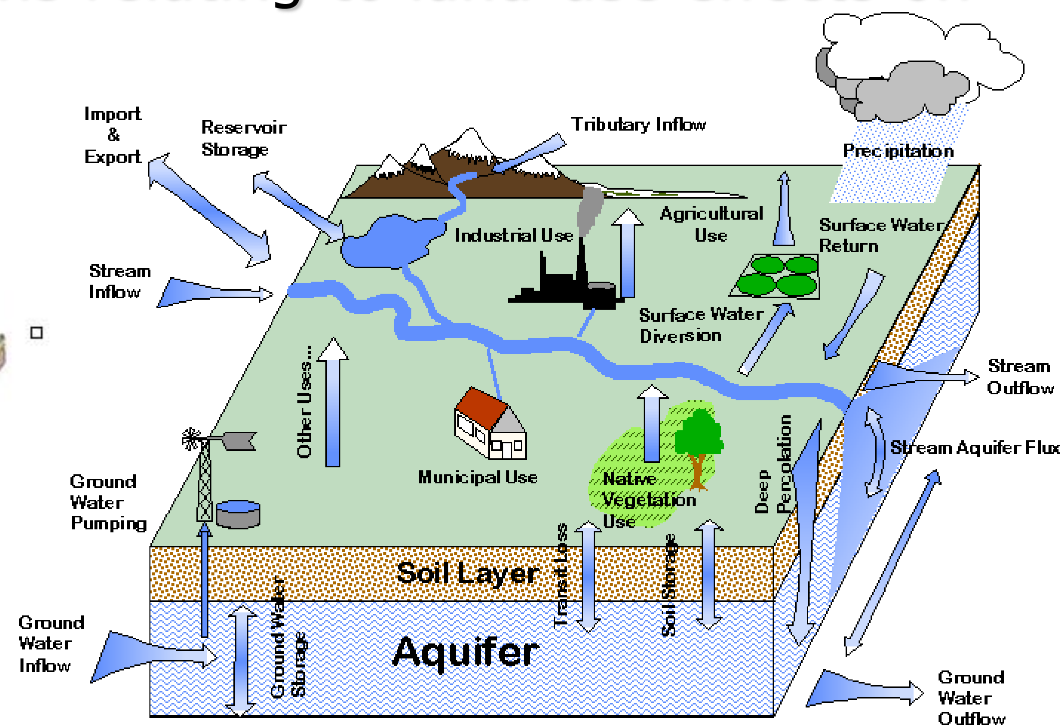


McGuire et al., 2005, *WRR*

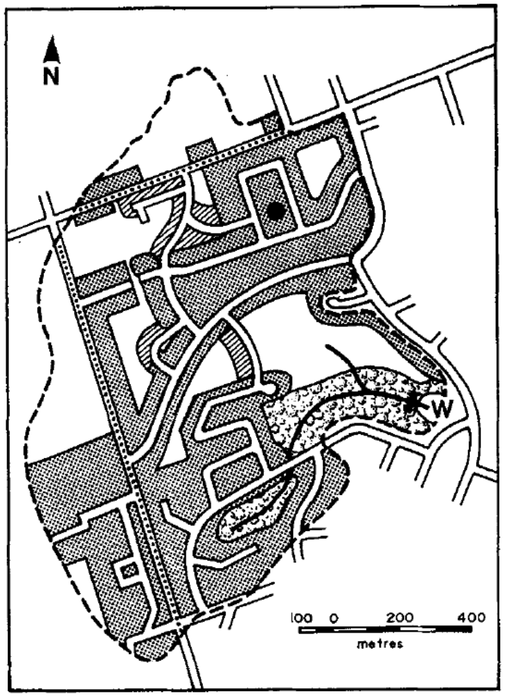
5. Urban and agricultural systems do not (always) export old water

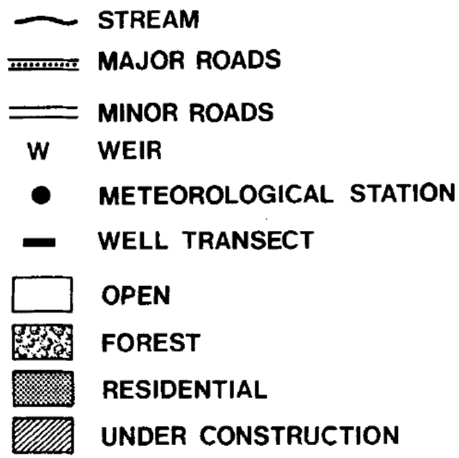
- Relatively few studies have investigated transit times and runoff routing in large catchments and human-dominated systems
- LOTS of great questions relating to land-use effects on runoff generation



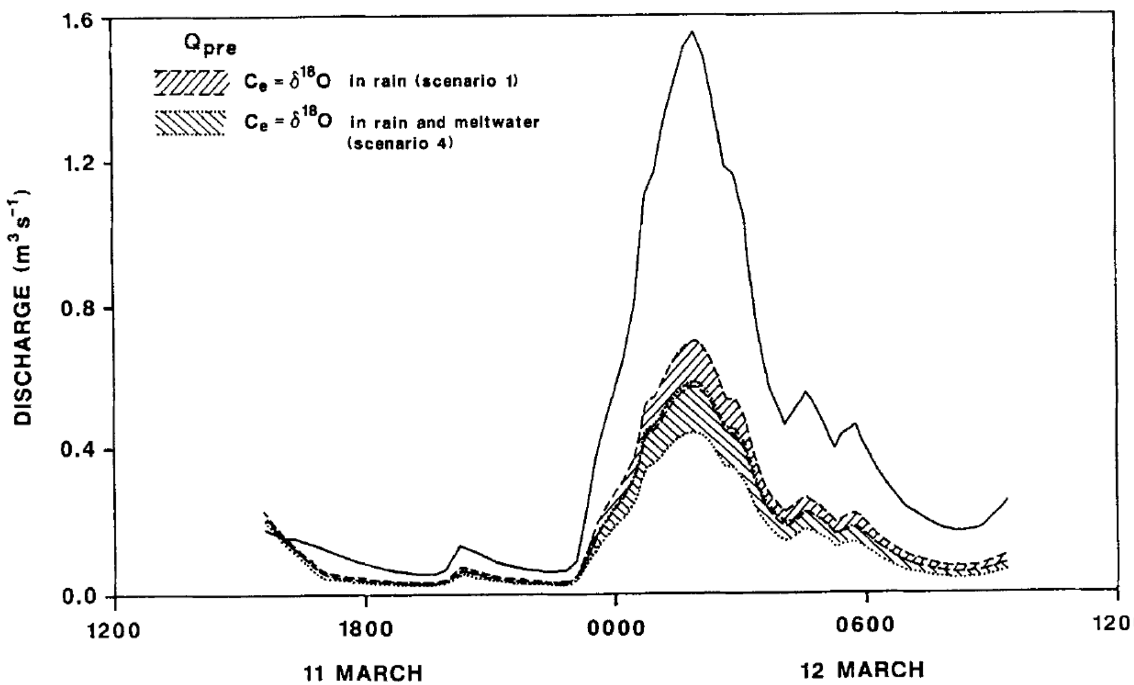


Hydrograph separation - suburban





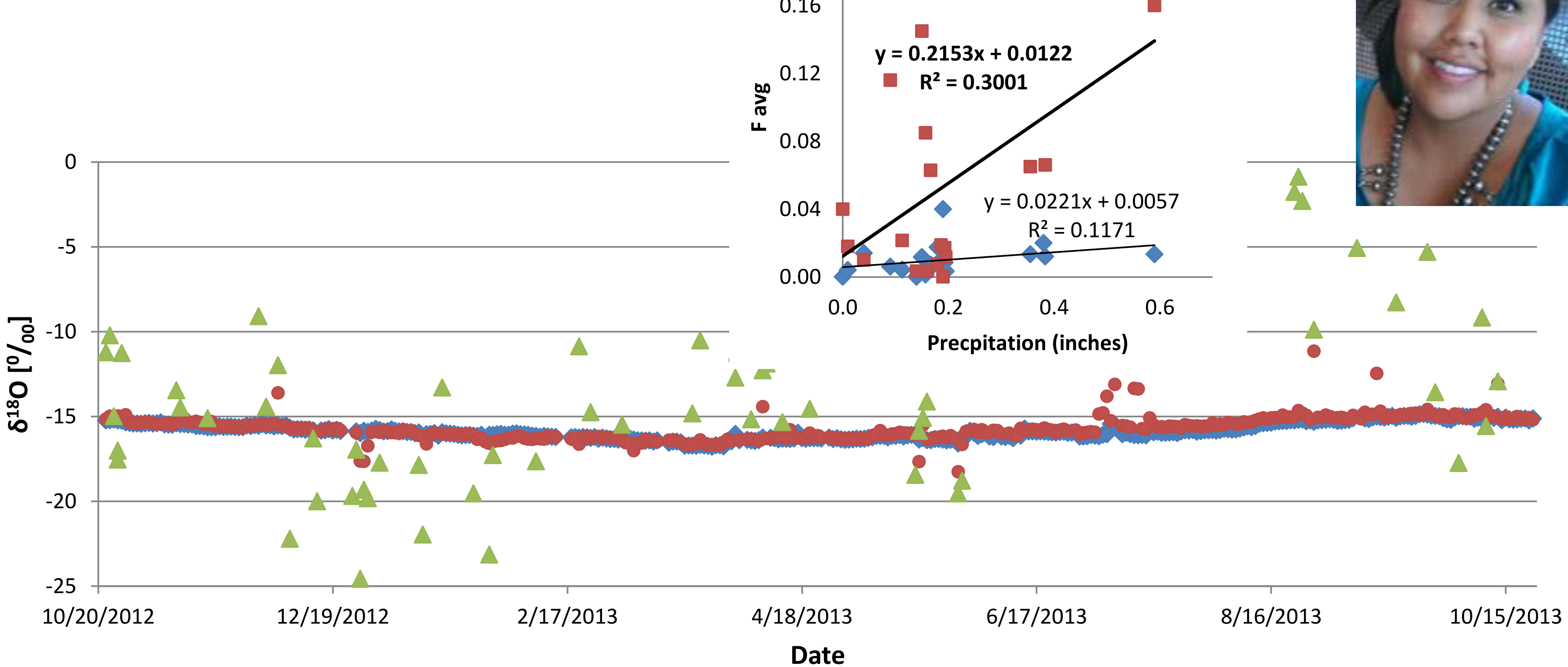
- Pre-event water <33% of storm runoff



Buttle et al., 1995

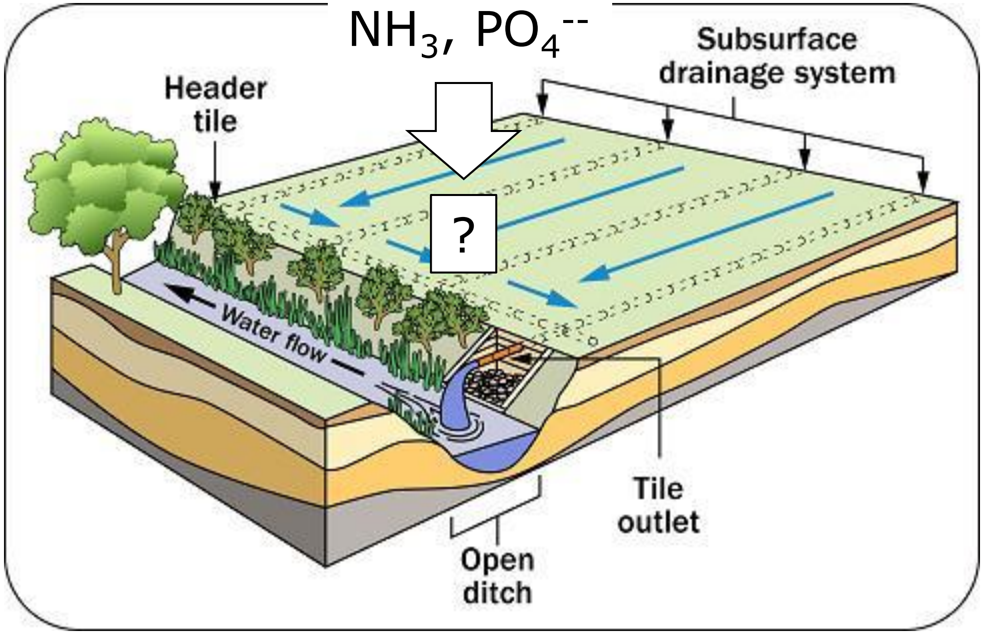
Urban system – Red Butte Creek

- Rapid and substantial addition of storm water in lower developed reach of catchment (UU campus)
- Seasonally variable



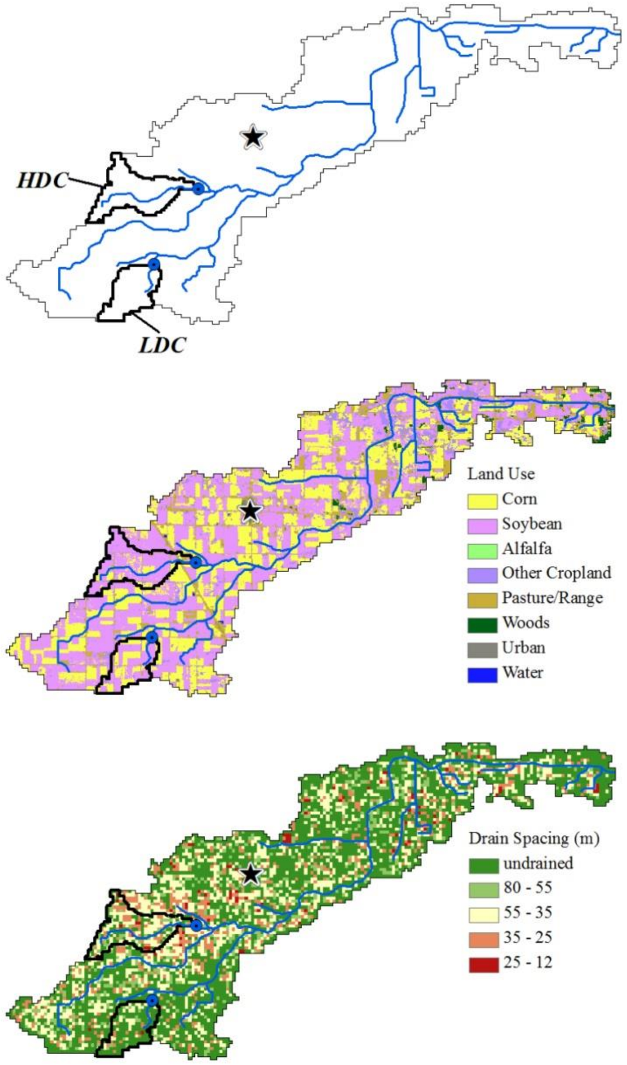
Agricultural systems – artifical drainage

- Subsurface drain network increases agricultural land quality
- Fundamentally alters hydrological flow
- What is the impact on timing, magnitude of nutrient discharge from these lands?



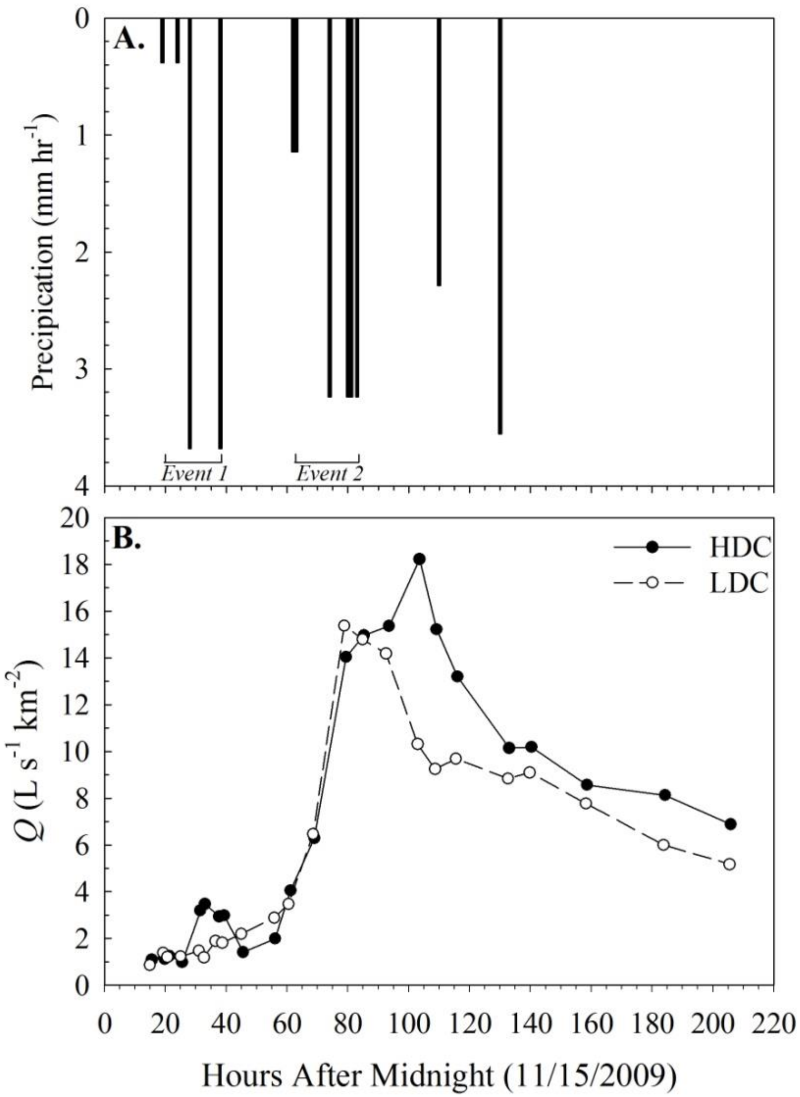
Hoagland watershed

- Paired catchment study
- High and Low drainage density catchments
- Sampling for water quality, isotopes through Nov. storm
- Student participation (EAS591 Isotope Hydrology)



Storm hydrograph

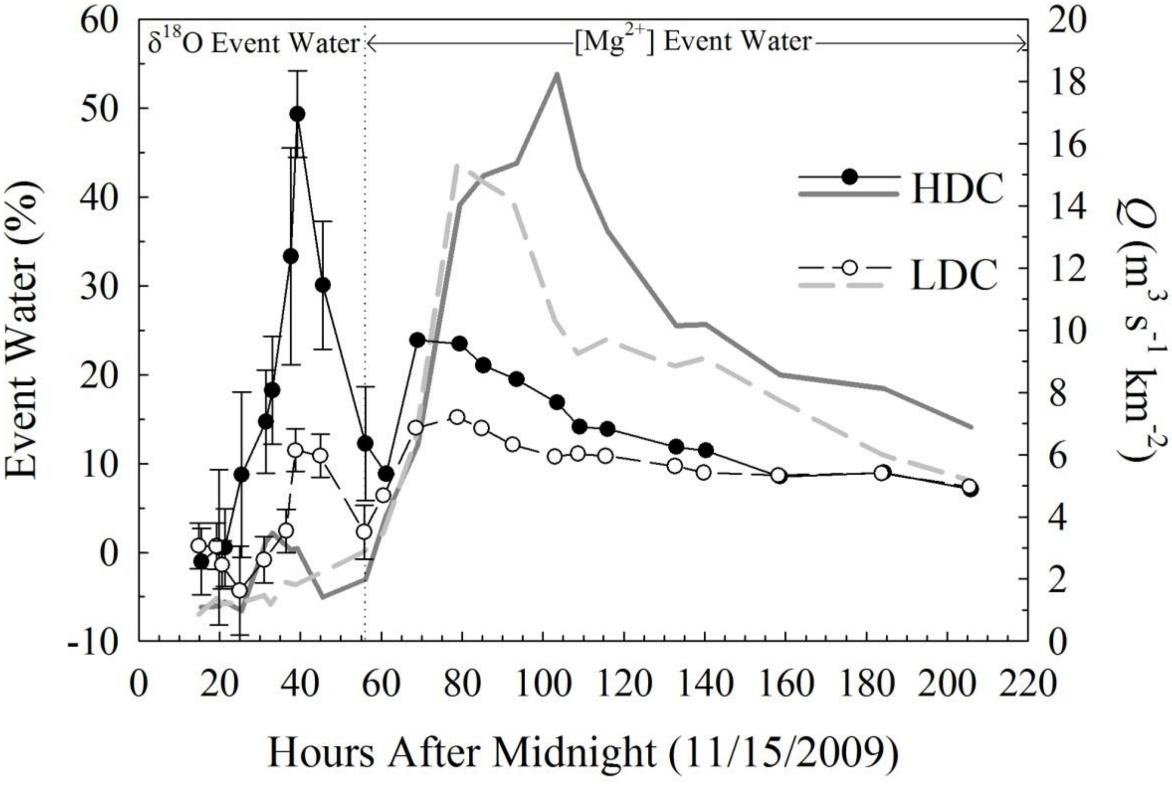
- Different timing of discharge for the high- and low-drainage catchments



Kennedy et al., 2012, *J. Hydrol.*

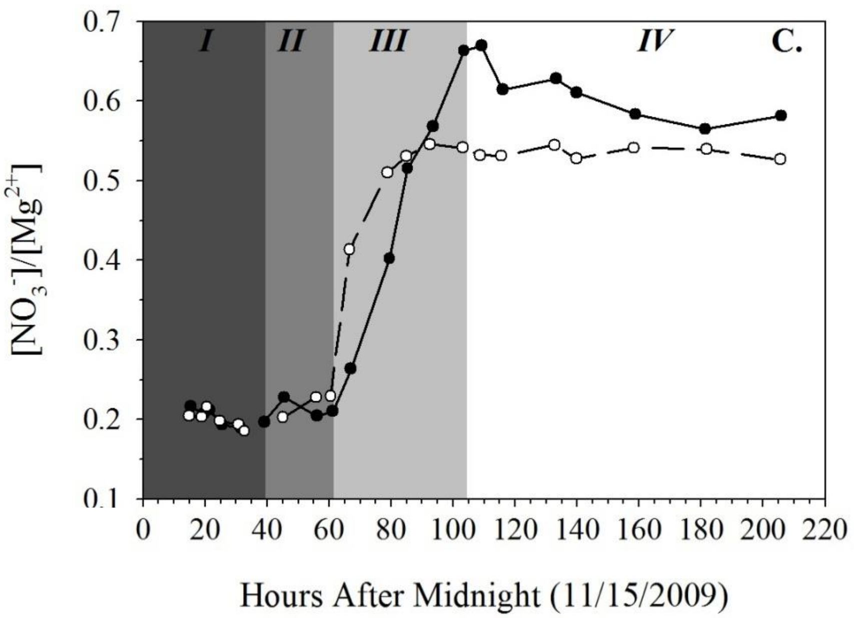
Hydrograph separation

- Partitioned storm flow into event and pre-event water components using O isotopes, Mg^{2+}
- Faster routing of storm water to stream in high-drainage catchment
- Change in storm water routing through event



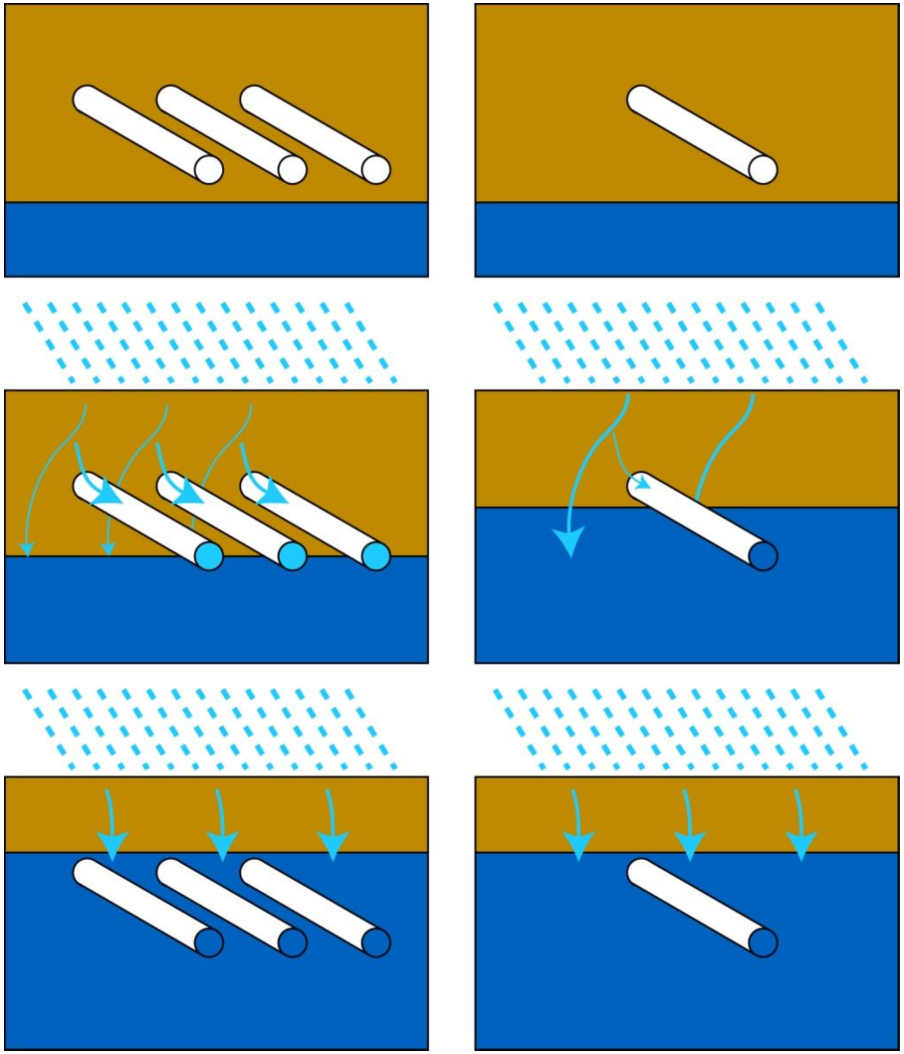
Nutrient discharge

- Timing and magnitude of peak nitrate discharge different in the two catchments



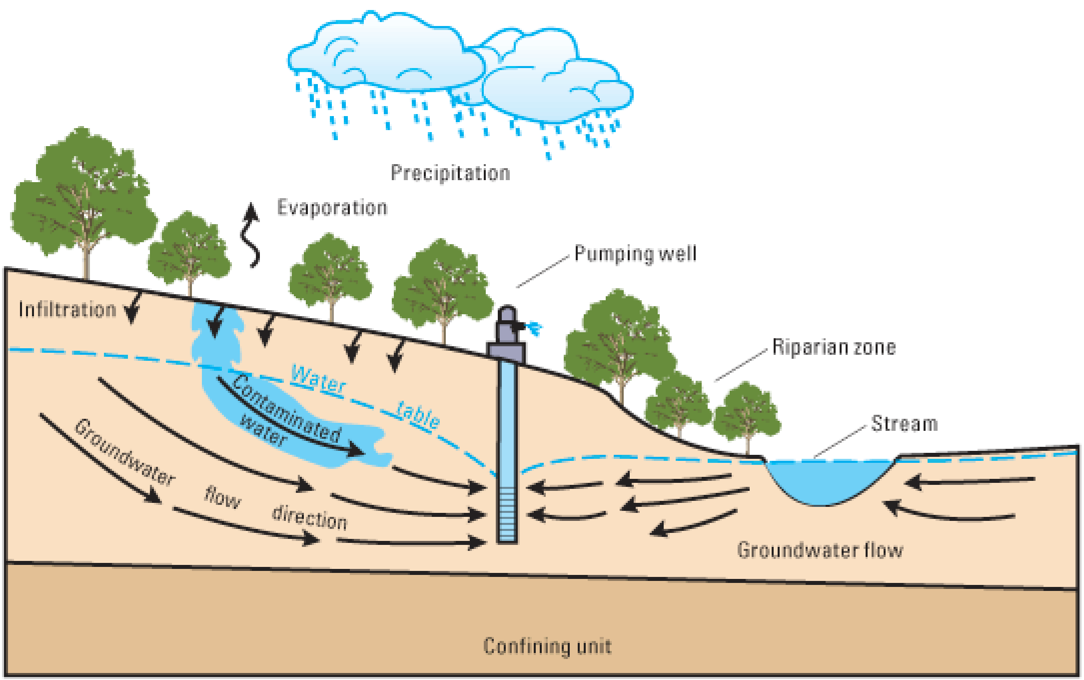
Flush/bypass model

- Late season, drains largely inactive
- Drains divert storm water, slowing water table recharge
- Drains activation and discharge of high-N groundwater lags in high-drainage catchment
- Diversion of infiltration changes ‘flashiness’ of contaminant export

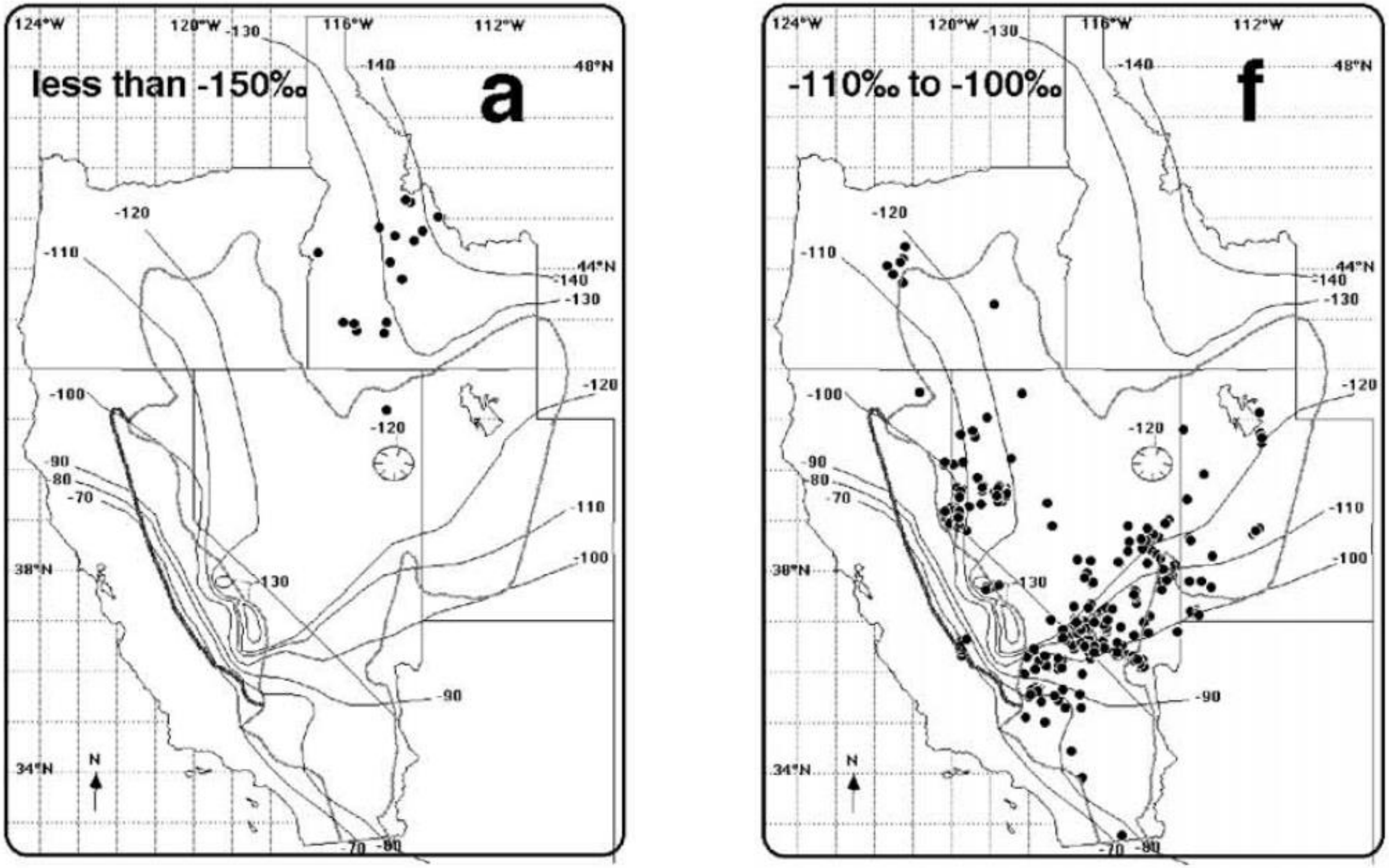


6. Groundwater looks like local precipitation, except when it isn't

- In most cases groundwater is a well mixed integrator of infiltration
- Dogma is that groundwater values usually approximate those of 'annual average precipitation'
  - Unbiased recharge



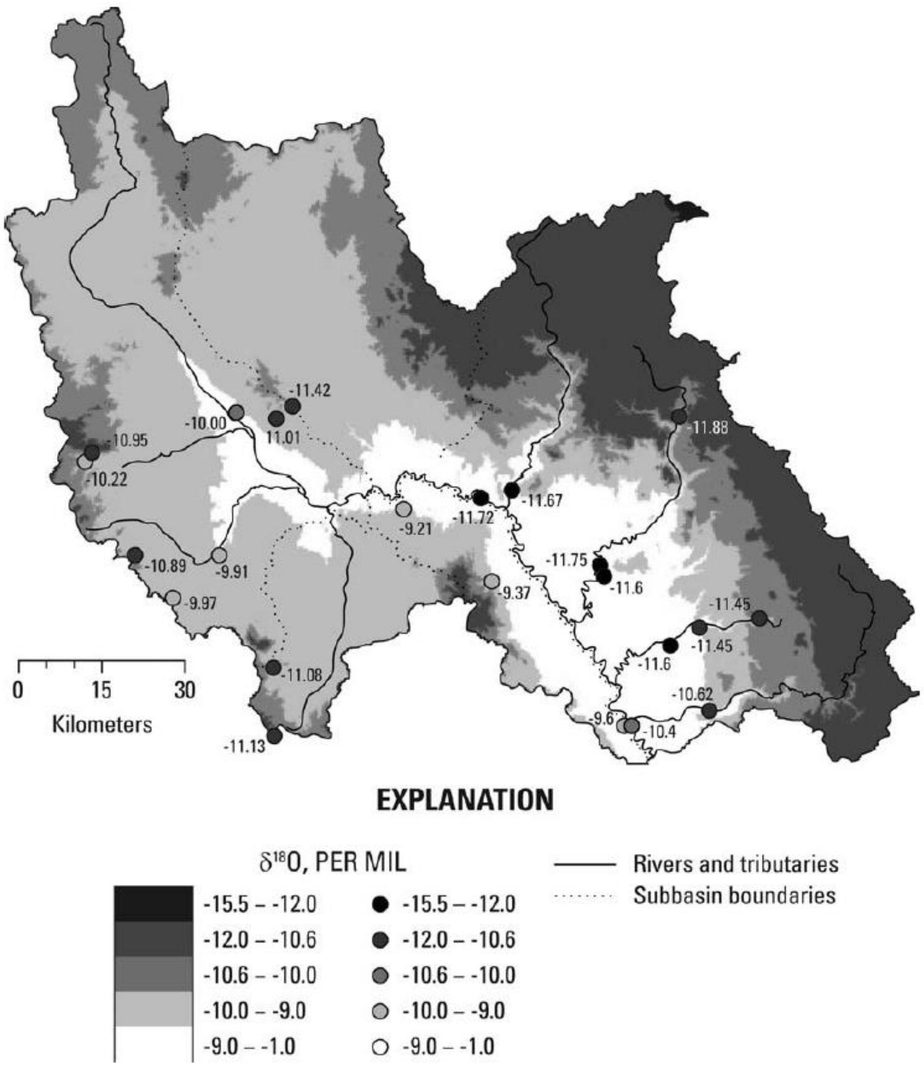
Great Basin waters



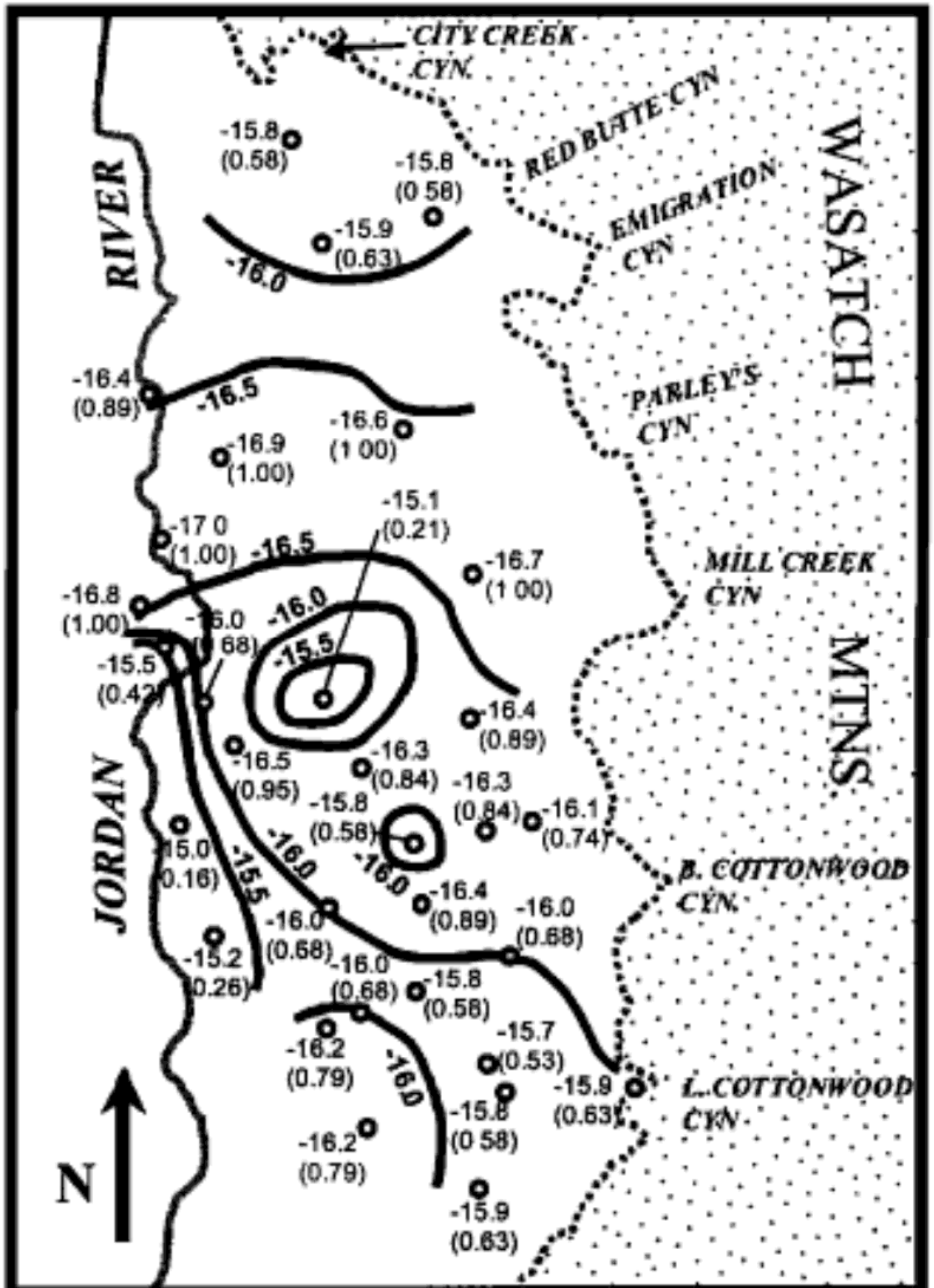
Smith et al., 2002, *JGR*

Sources of recharge

- Tracing recharge sources requires
  - Spatial or temporal structure in recharge waters
  - Conservative behavior
- In mountainous regions elevation is often a useful (and important) source of isotopic signal

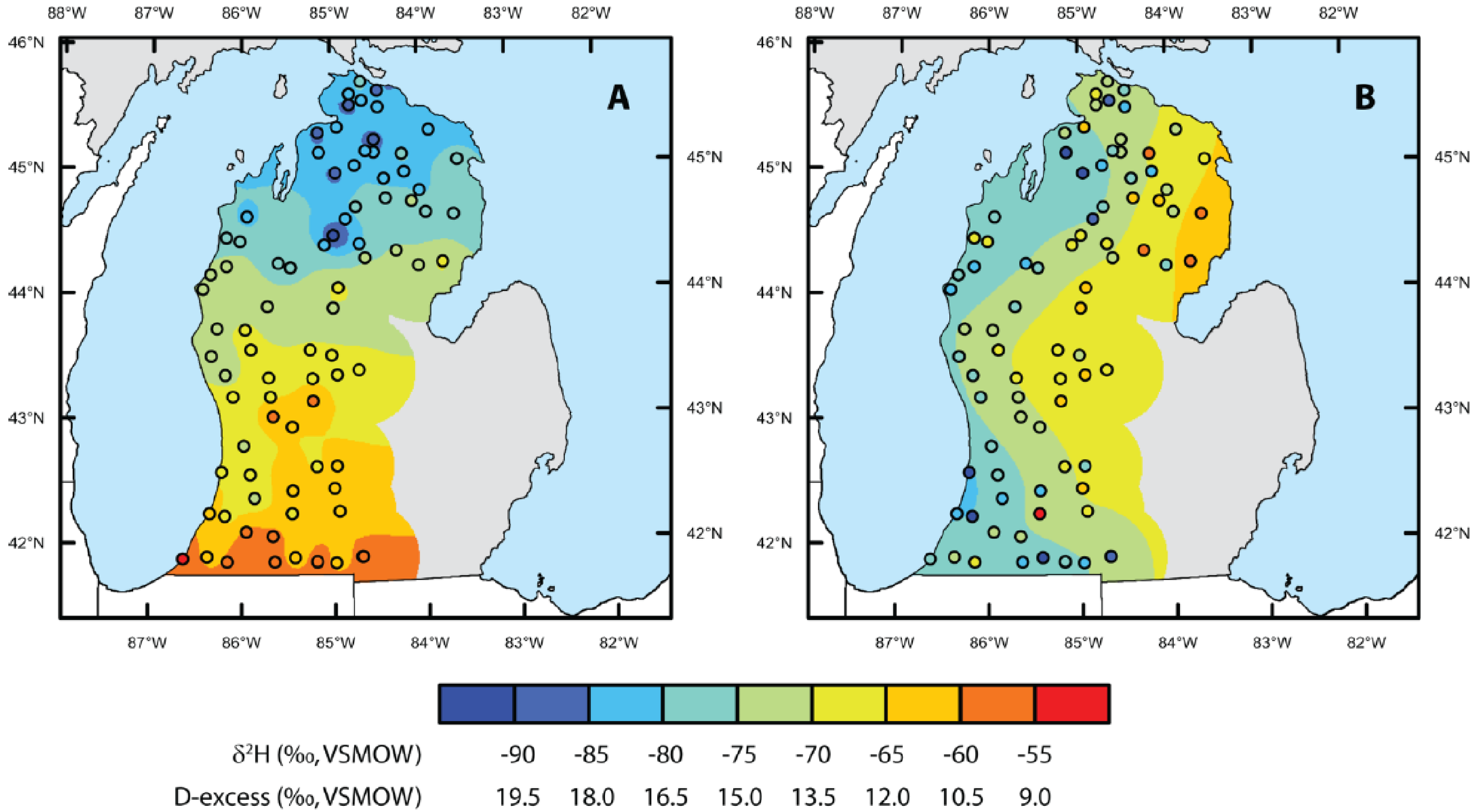


Blasch and Bryson, 2007, *Ground Water*



Manning and Solomon, 2004, *GW Recharge*

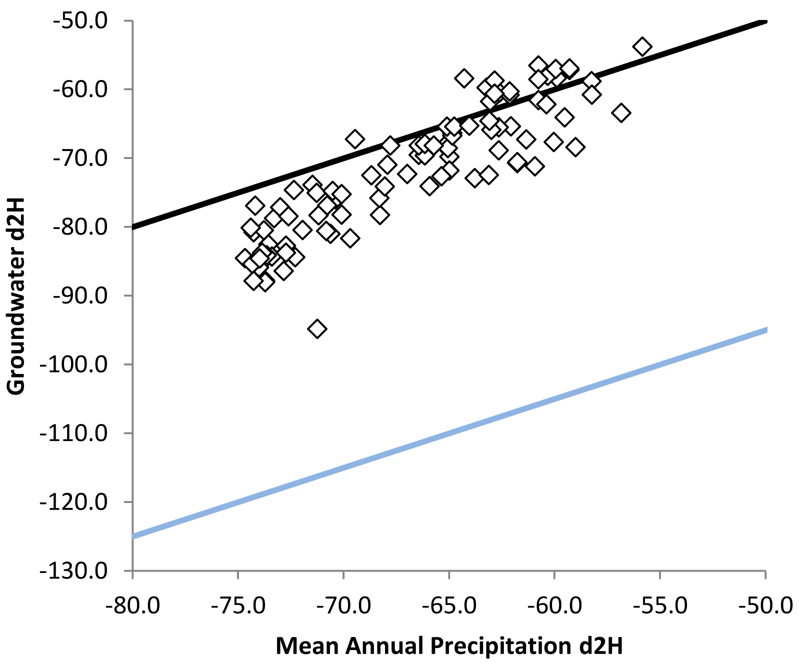
Michigan shallow groundwater



Bowen et al., 2012, *Ecosphere*

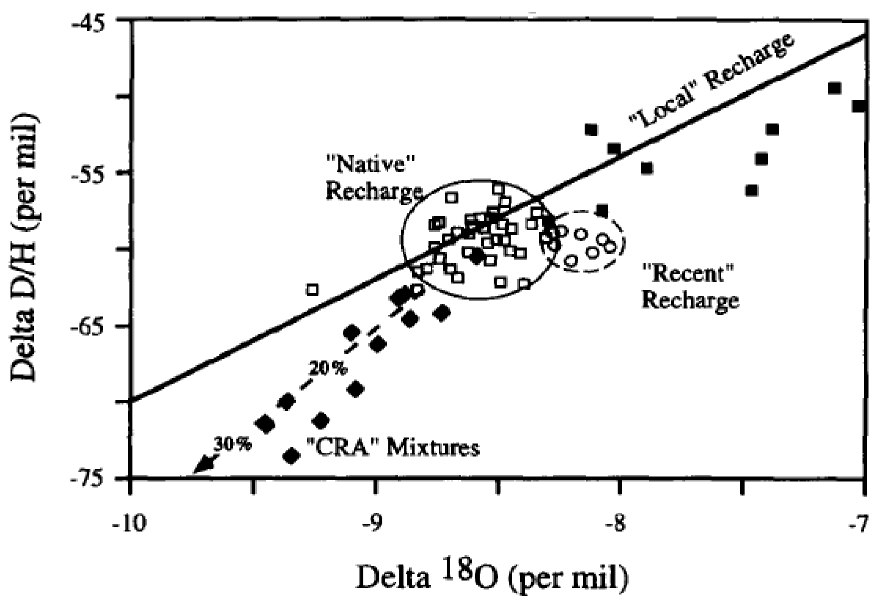
Michigan shallow groundwater

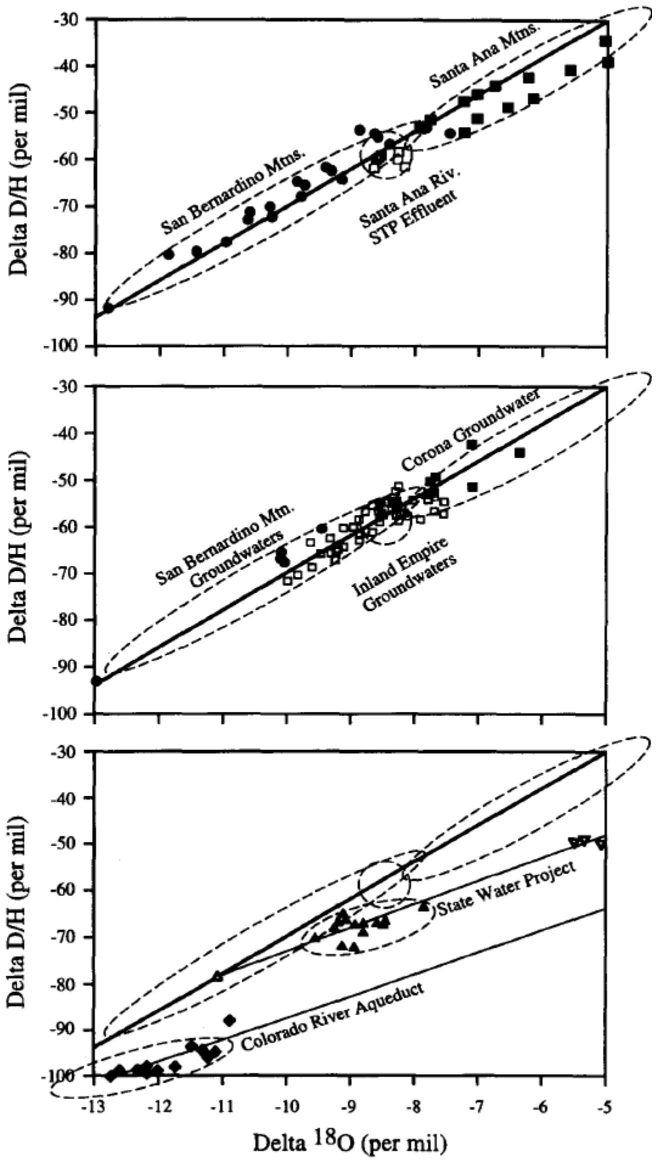
- Patterns match precipitation data, predictions to first order
- Systematic offset (ground water lighter than mean annual precipitation)
  - Increases with latitude
- Seasonally biased GW recharge



Humans – another dimension

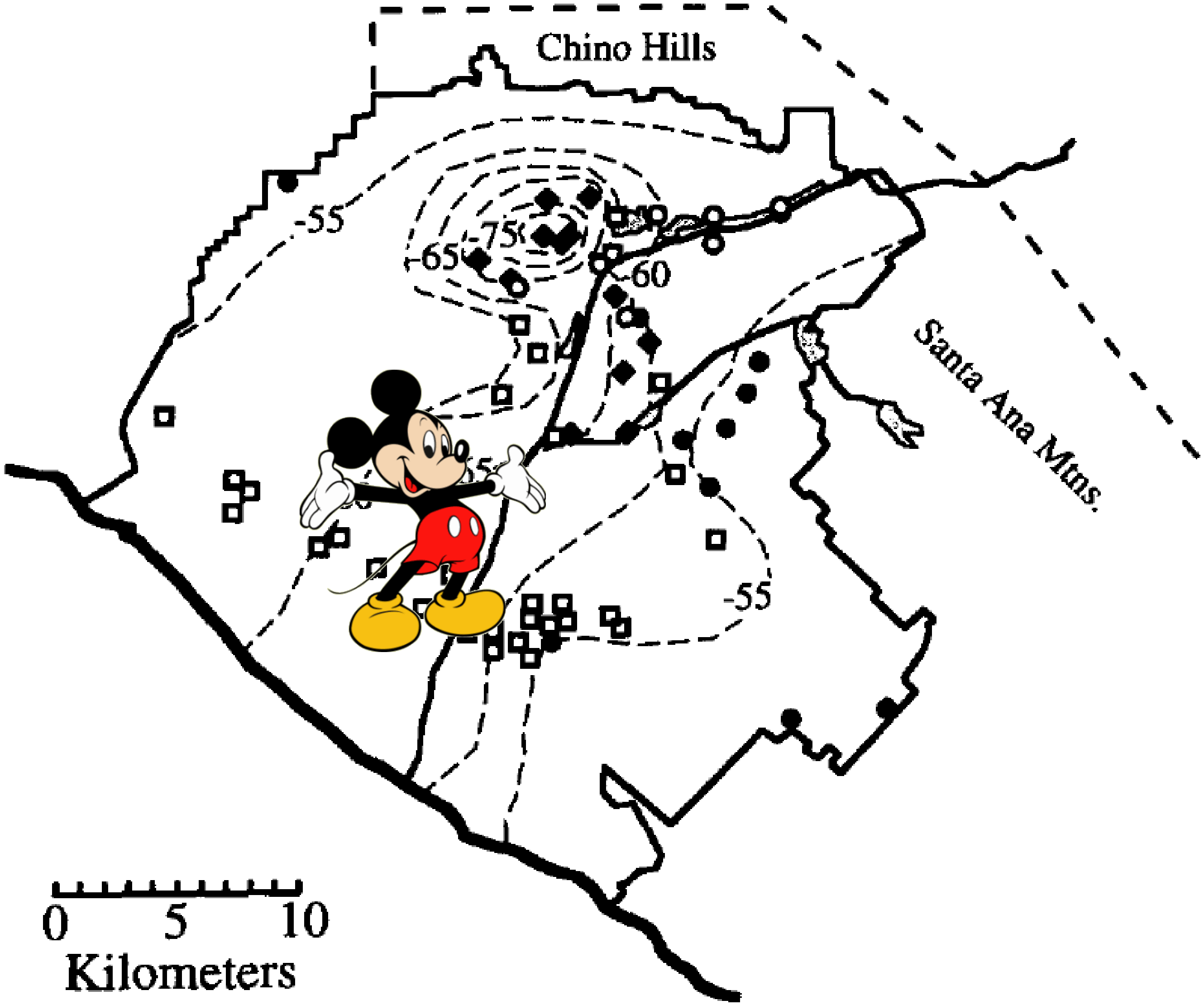
- Not all recharge is 'natural'
  - Purposeful (storage)
  - Inadvertent (leakage)
- Transported water signatures

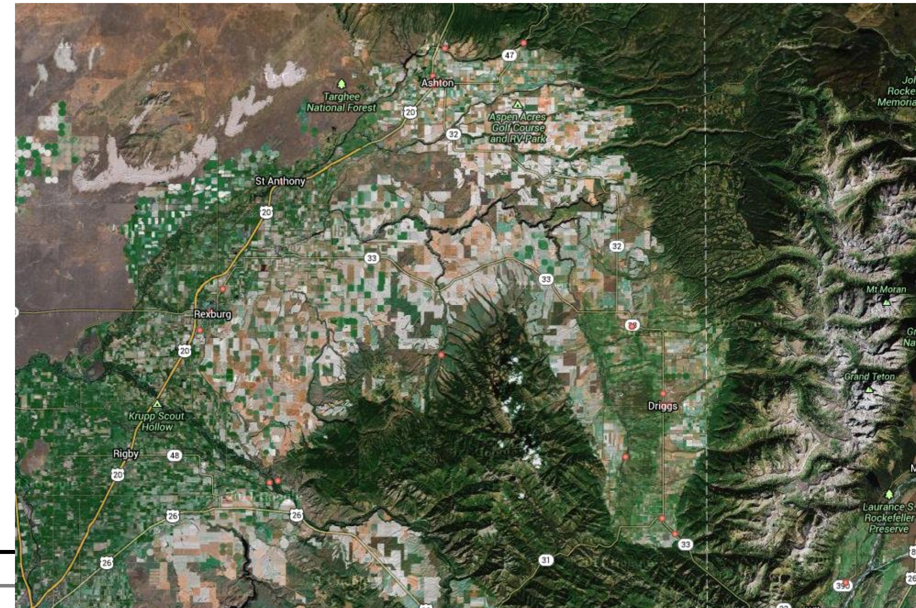


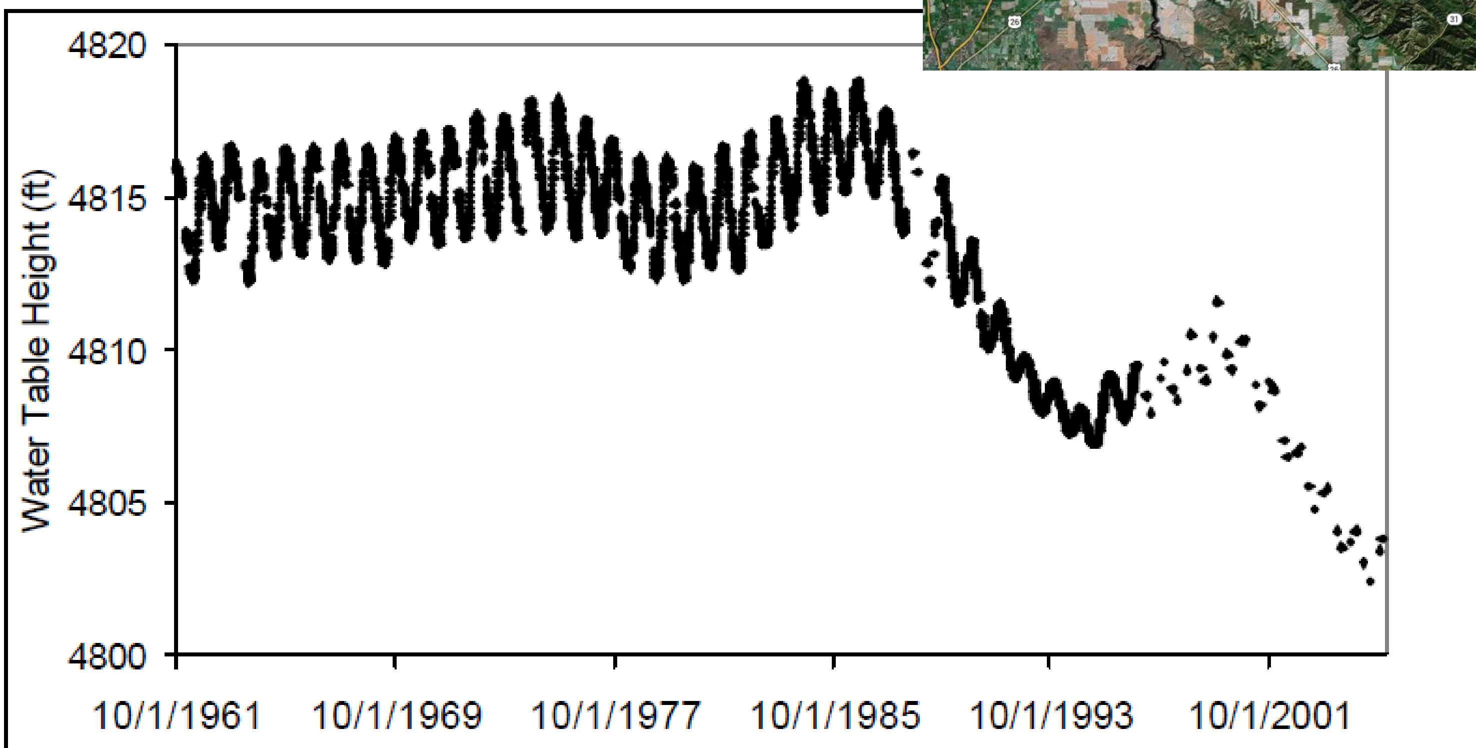


Williams, 1997, *J. Hydrol.*

Artificial recharge



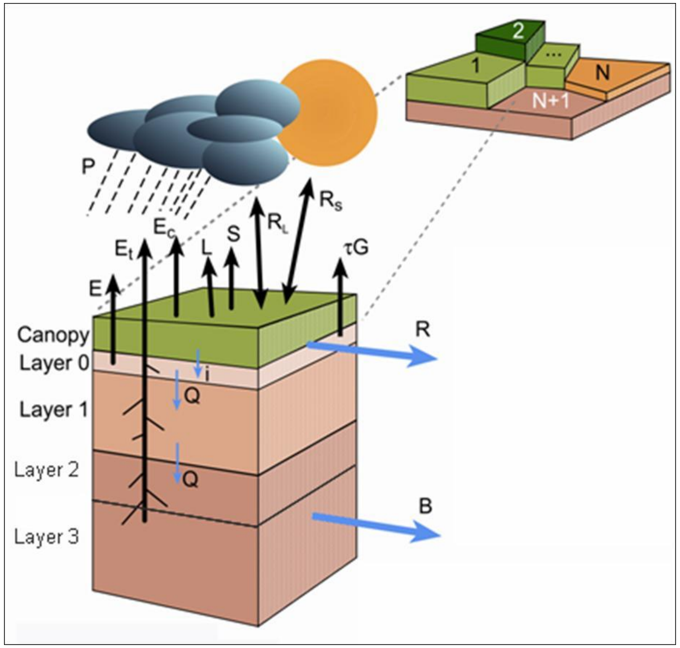




Van Kirk et al., 2010

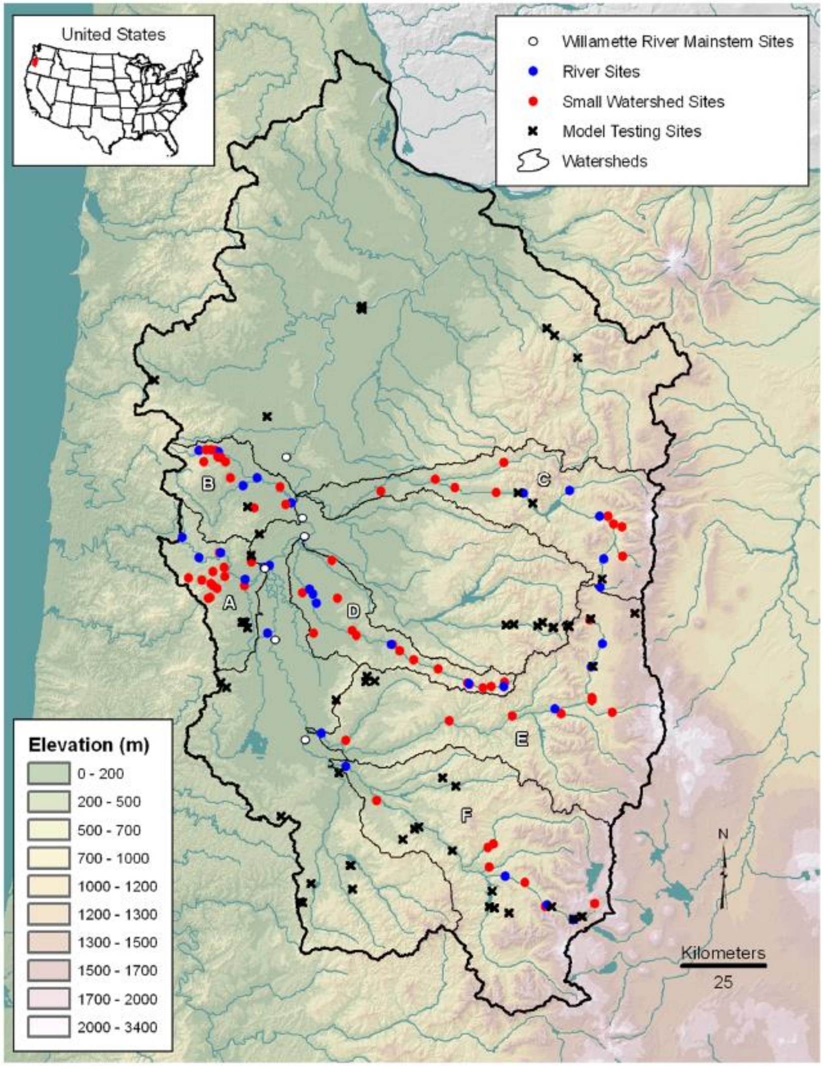
7. Regional water balance trends are easy to extract from rivers

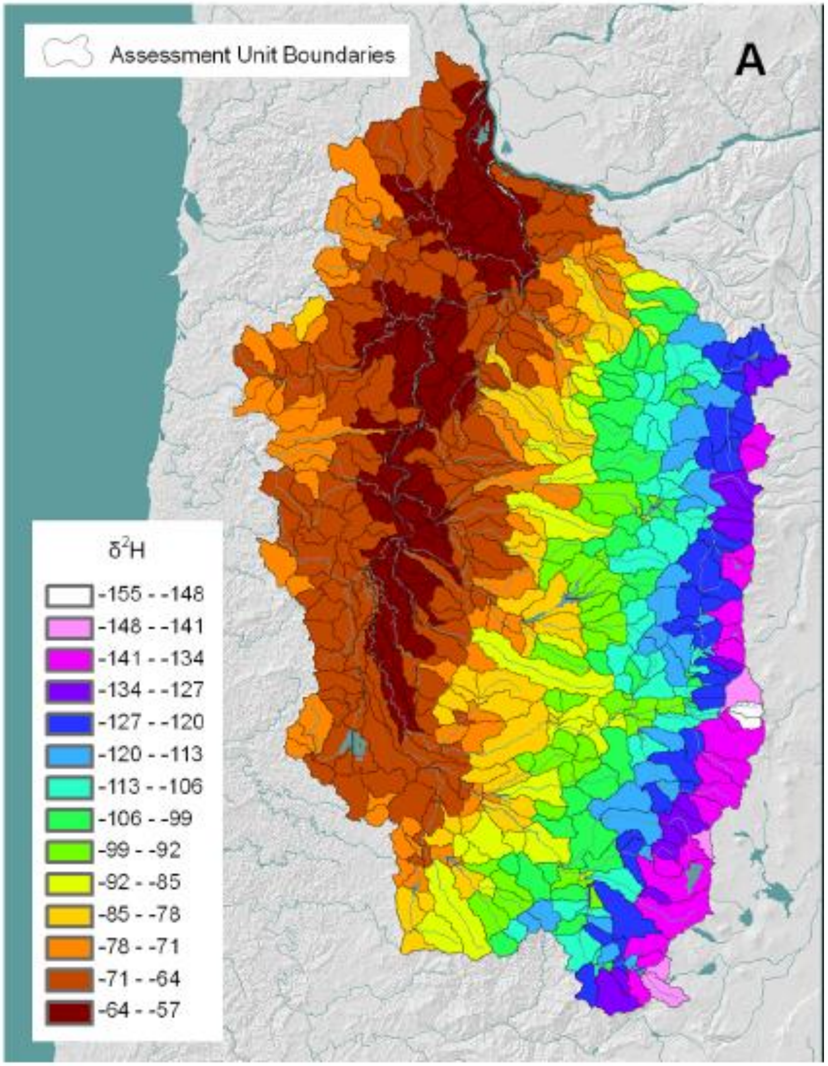
- Many (not all) properties of catchments exhibit regional consistency
  - Climatic
  - Topographic
  - Geological
  - Biological
- Can isotopes be used to identify key properties and characterize catchments?



www.hydro.washington.edu

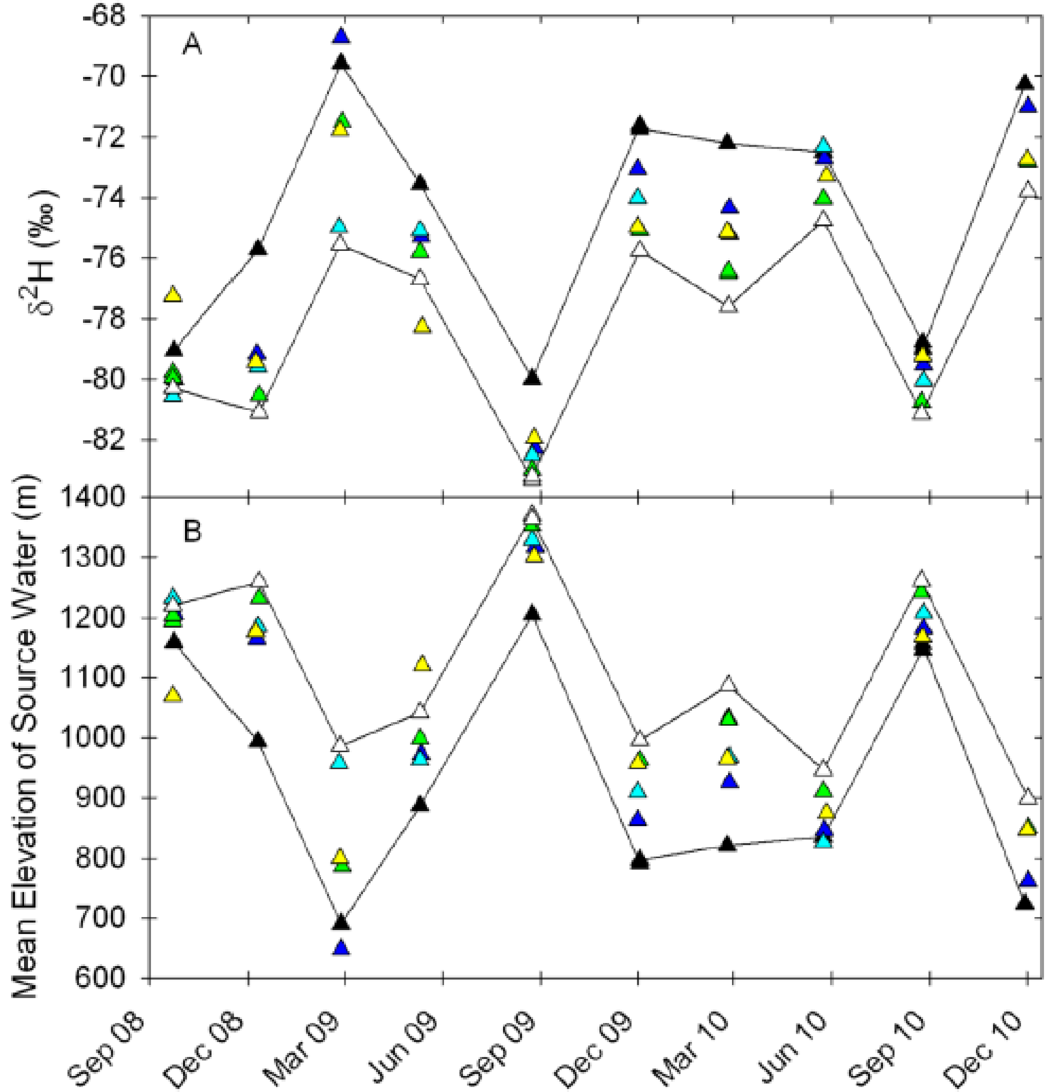
Oregon rivers



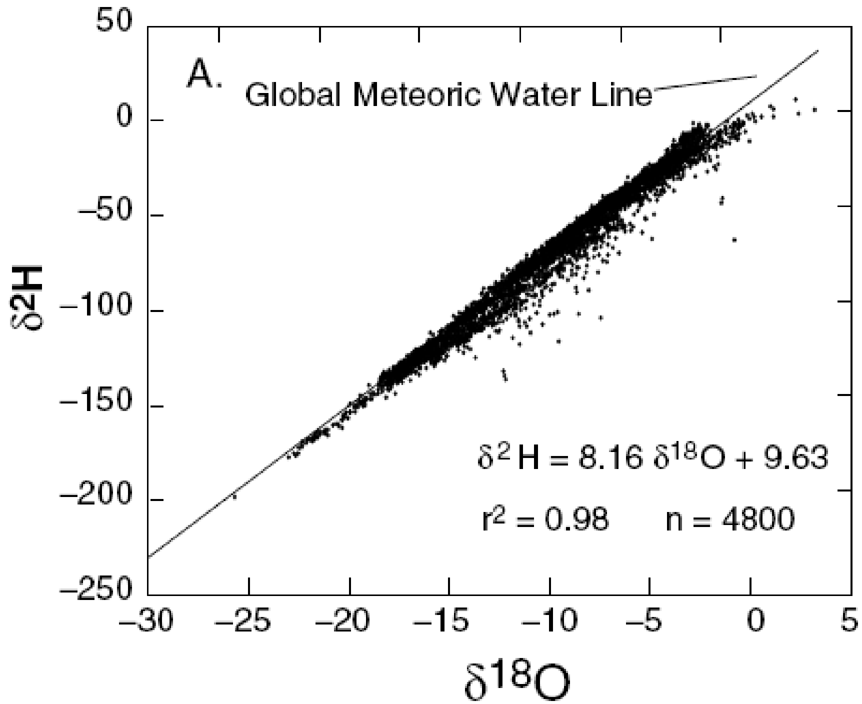


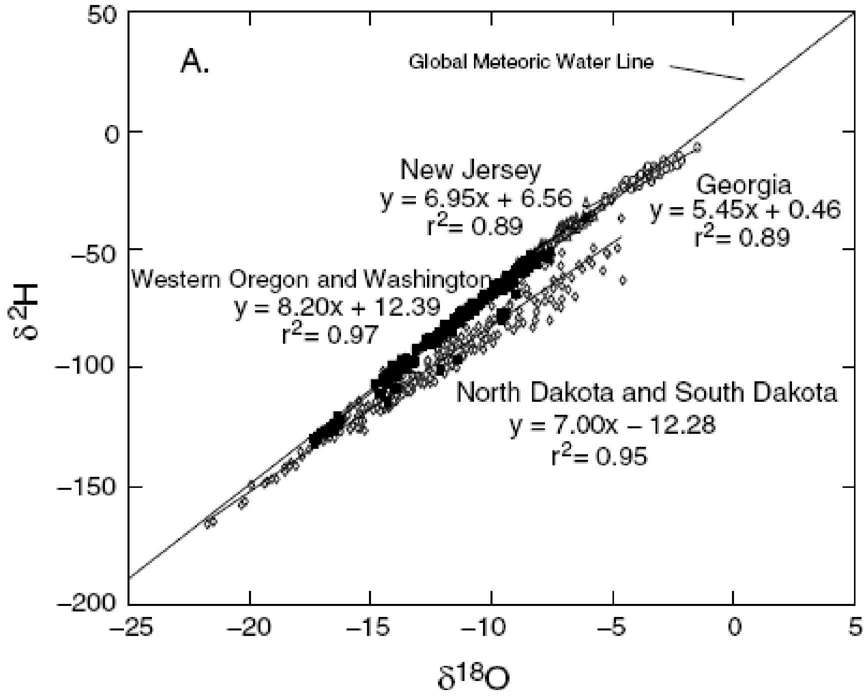
Brooks et al., 2012, *Ecosphere*

Willamette River



River water isotopes – continental scale



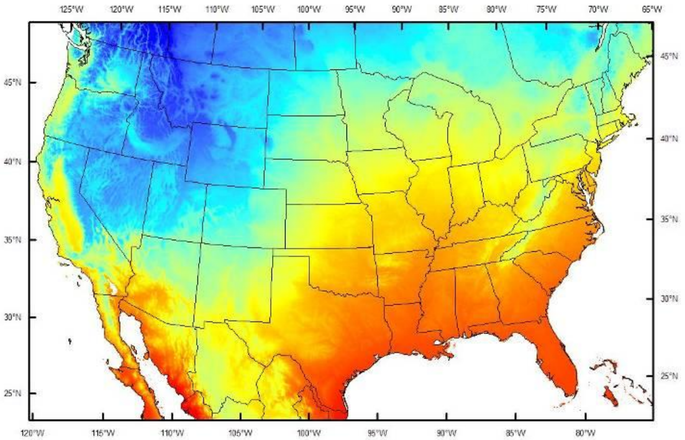


Kendall & Coplen, 2001

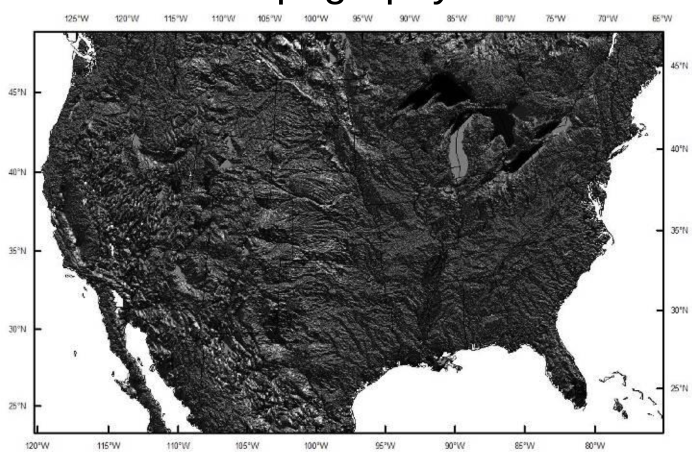
River water isotopes: rainfall-runoff model

- Can we reproduce isotope differences between surface water and precipitation using process models?

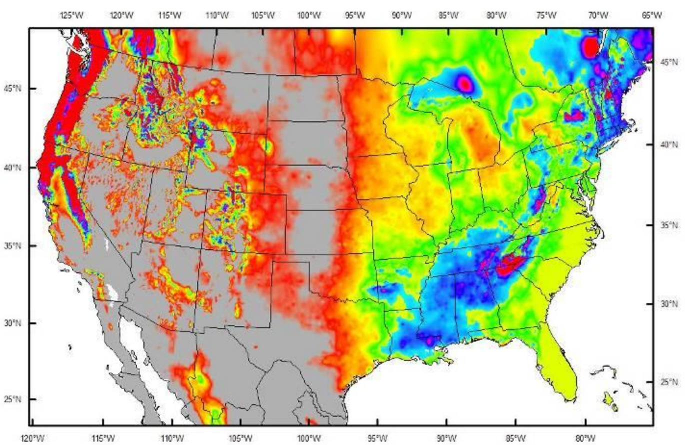
Precipitation isotopes



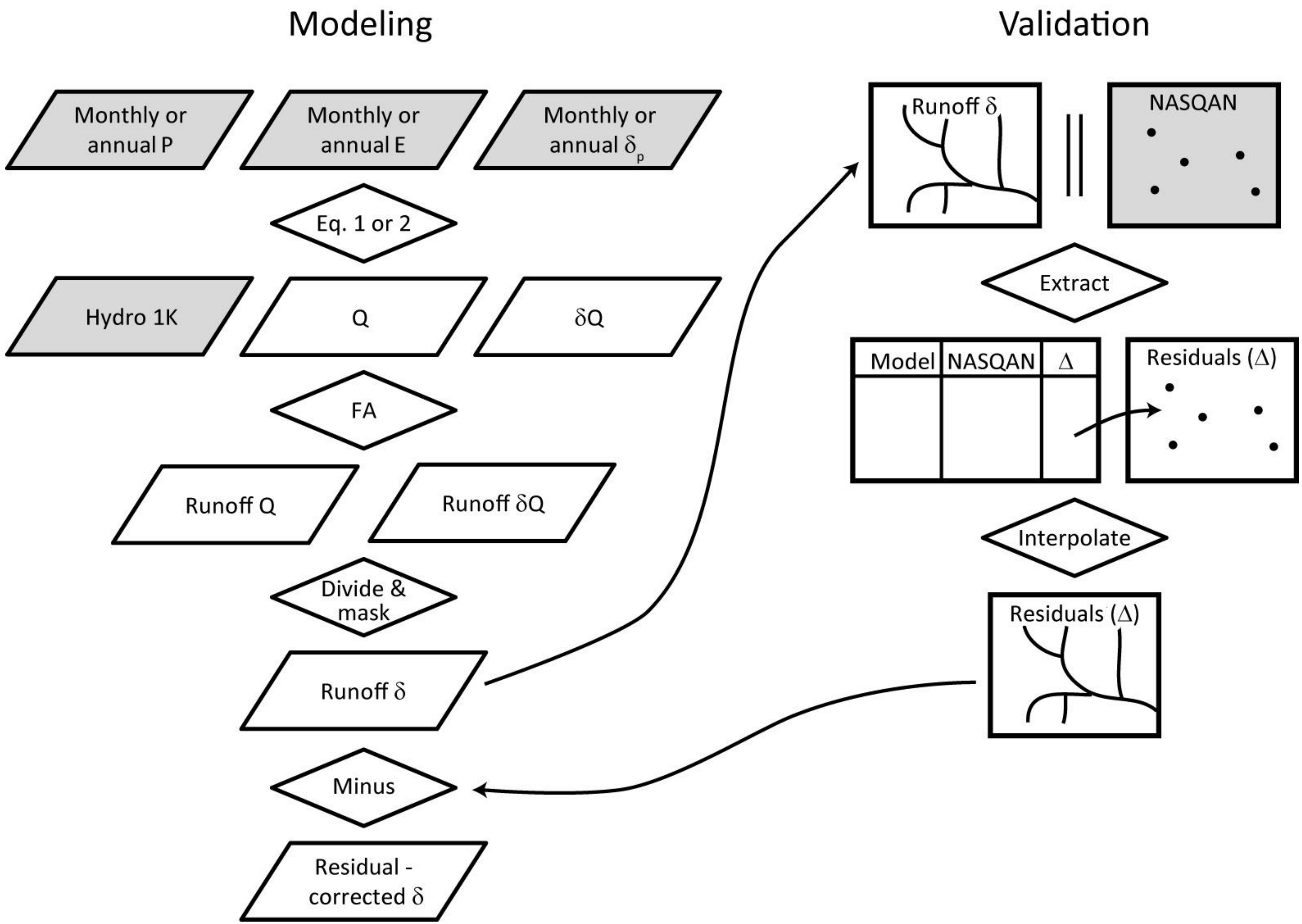
Topography



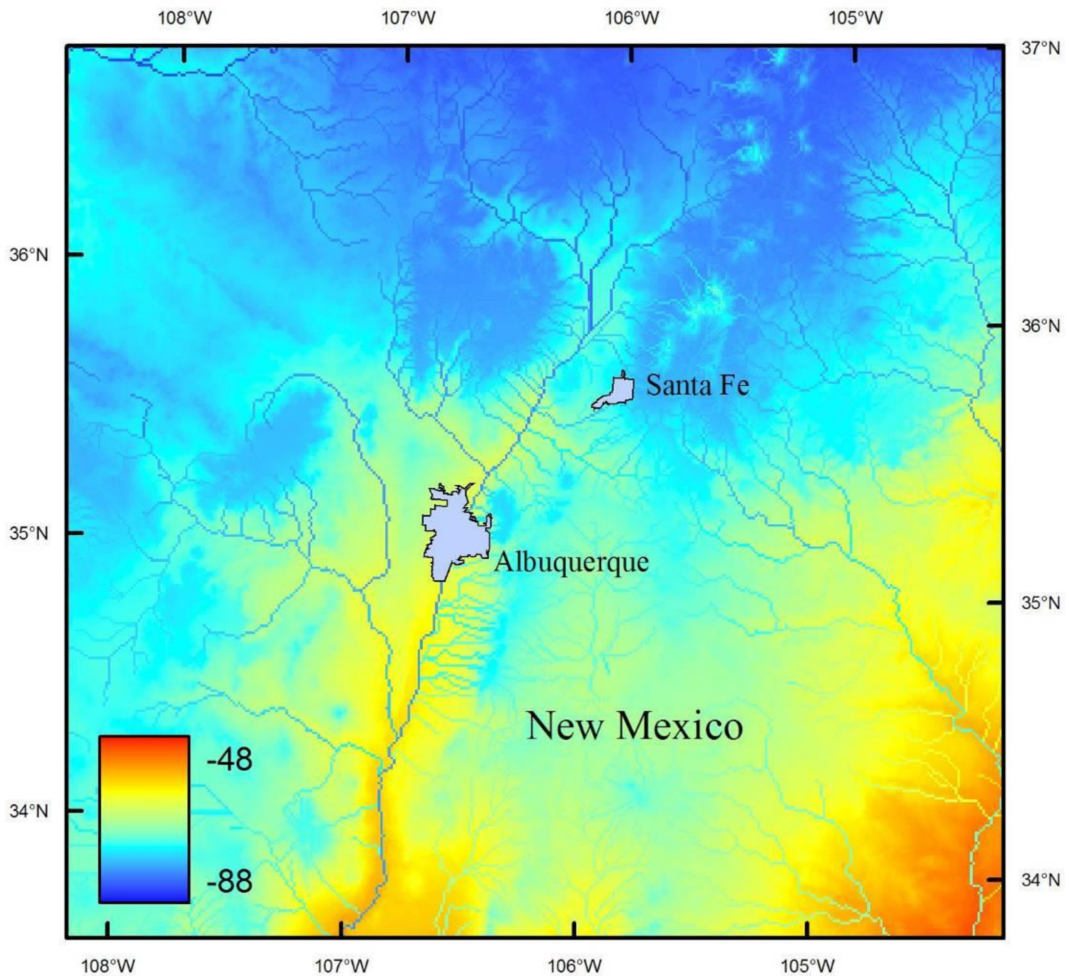
Runoff amount



Bowen et al., 2011, *JGR*

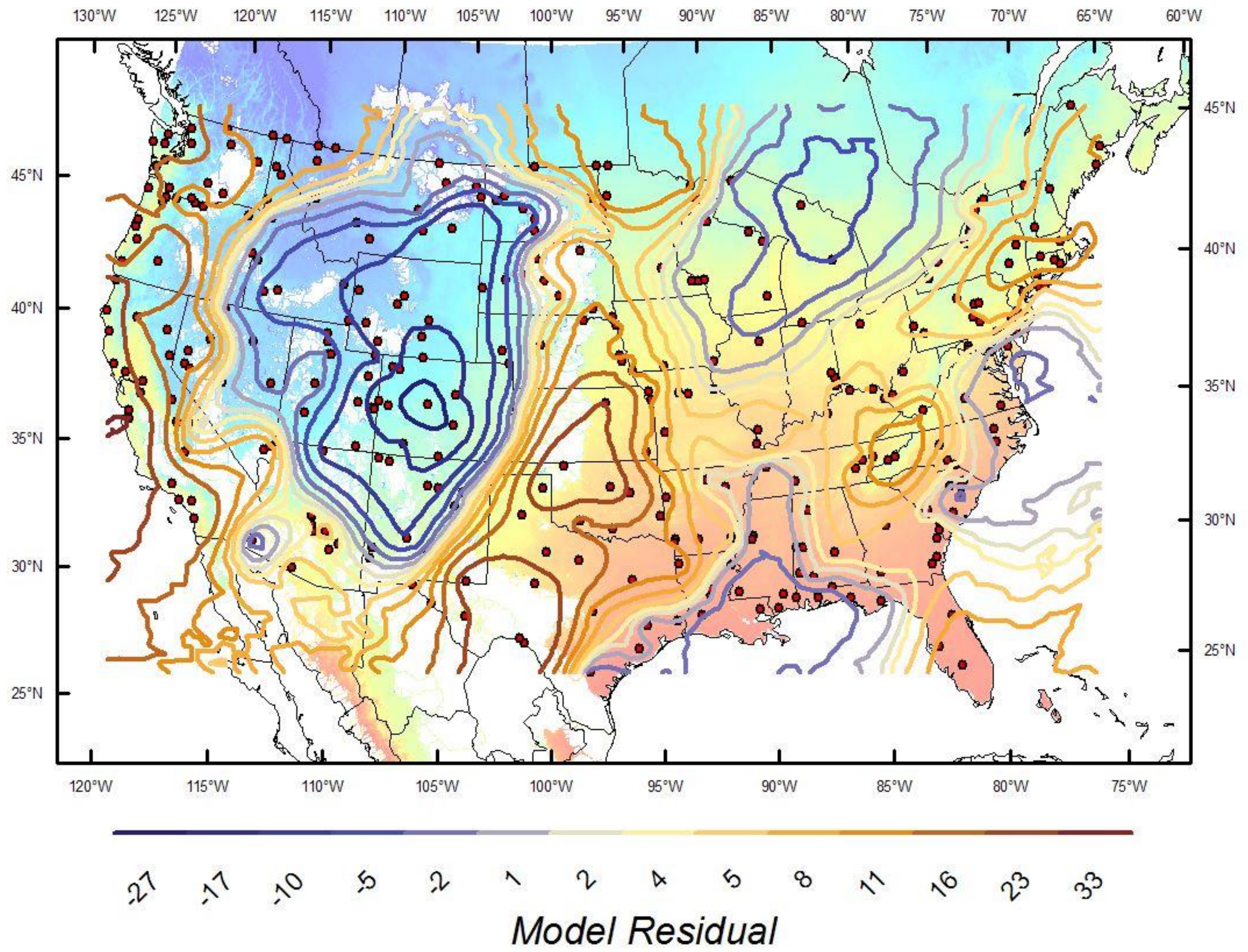

Modeling
Validation
Monthly or annual P
Monthly or annual E
Monthly or annual δ_p
Eq. 1 or 2
Hydro 1K
Q
δQ
FA
Runoff Q
Runoff δQ
Divide & mask
Runoff δ
Minus
Residual - corrected δ
Runoff δ
NASQAN
Extract
Model
NASQAN
Δ
Residuals (Δ)
Interpolate
Residuals (Δ)

Runoff model



Predicted river δ²H values superimposed on precipitation δ²H values

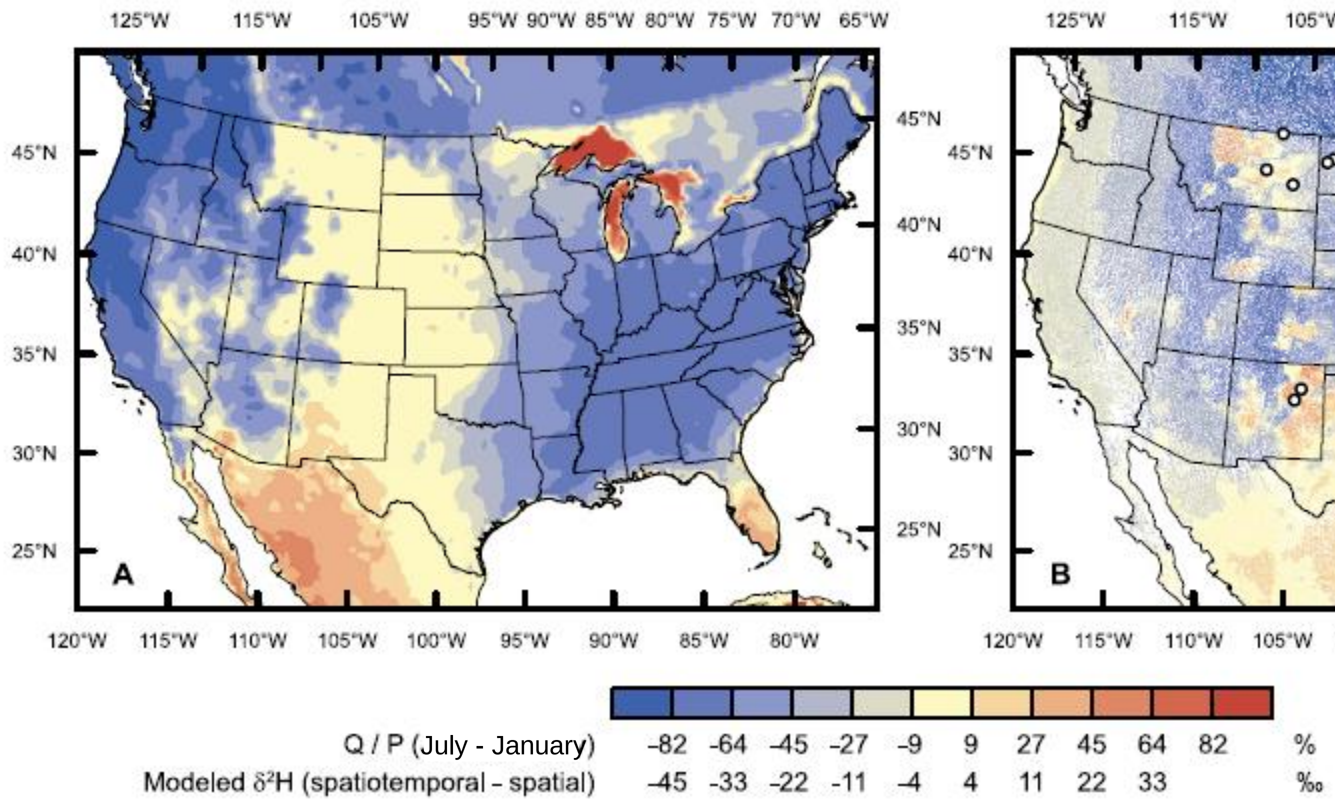
Runoff model residuals - why?



Data: Kendall and Coplen, 2001

Sensitivity testing ET patterns

Impact of accounting for different % loss of precipitation to ET by month

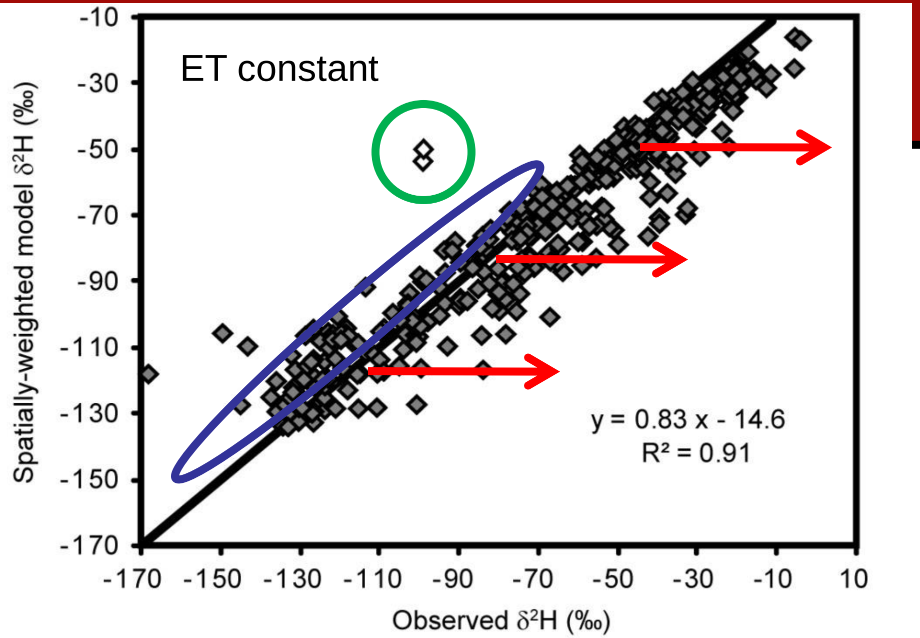


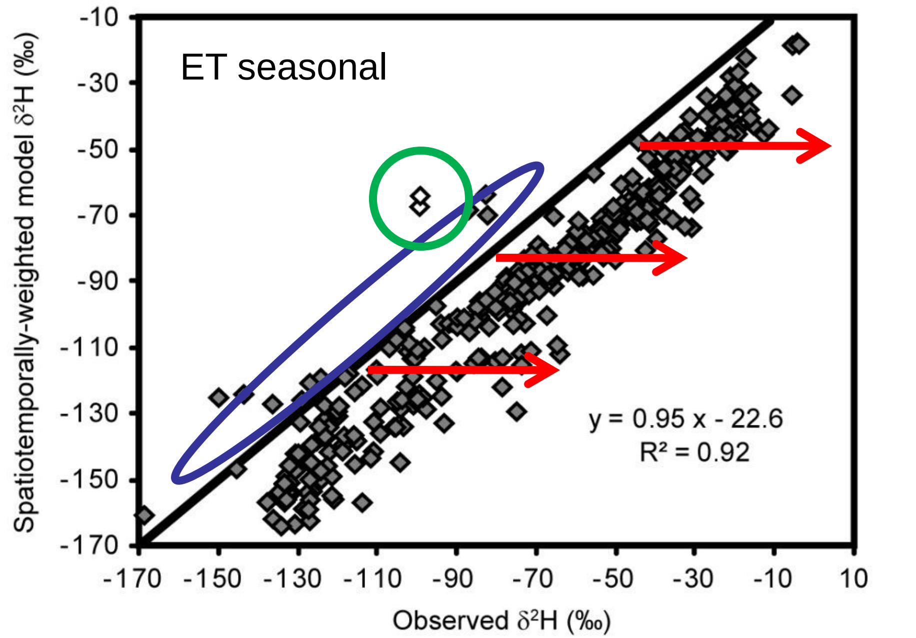
Bowen et al., 2011, *JGR*

Interrogating water source

- Evaporation
- Winter-biased runoff
- Imported water

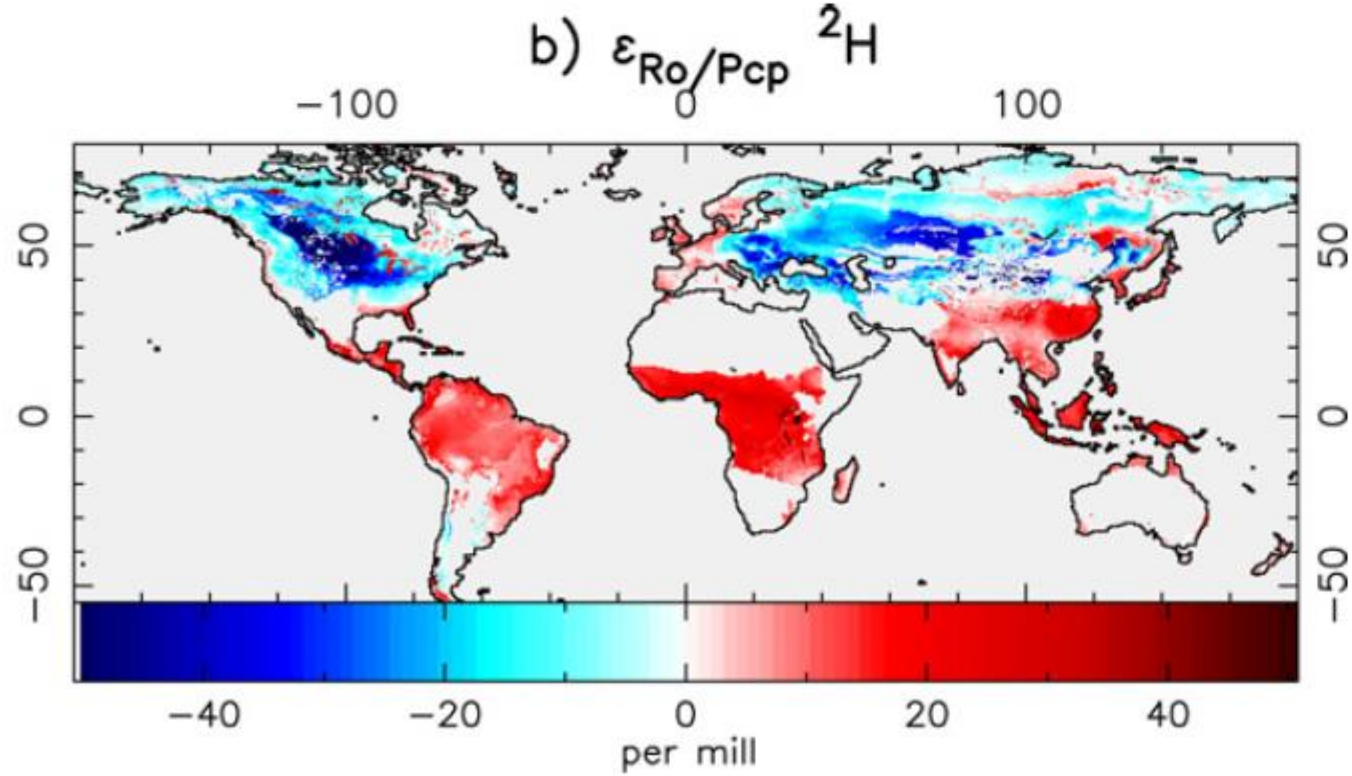
- Provides basis for quantifying (and monitoring) seasonal or elevation bias of runoff generation
- Identifies non-local water sources





Distributed hydrology model w/ water isotopes

- Same effect predicted by more sophisticated rainfall-runoff models (WBM)
- Note contrasting pattern in N. America



Fekete et al. 2006

8. Lake basins evaporate, but even more they transpire

- Like rivers, lakes are great integrators of catchment properties, with differences
  - Residence time
  - Evaporation

Isotope mass balance - lakes

- Water isotopes add tracer to underconstrained mass balance
  - No fractionation associated with discharge (Q)
  - Evaporation (E) depleted in heavy isotopes
- At steady state - leads to simple mass balance equation
- Challenge – getting the parameter values right…

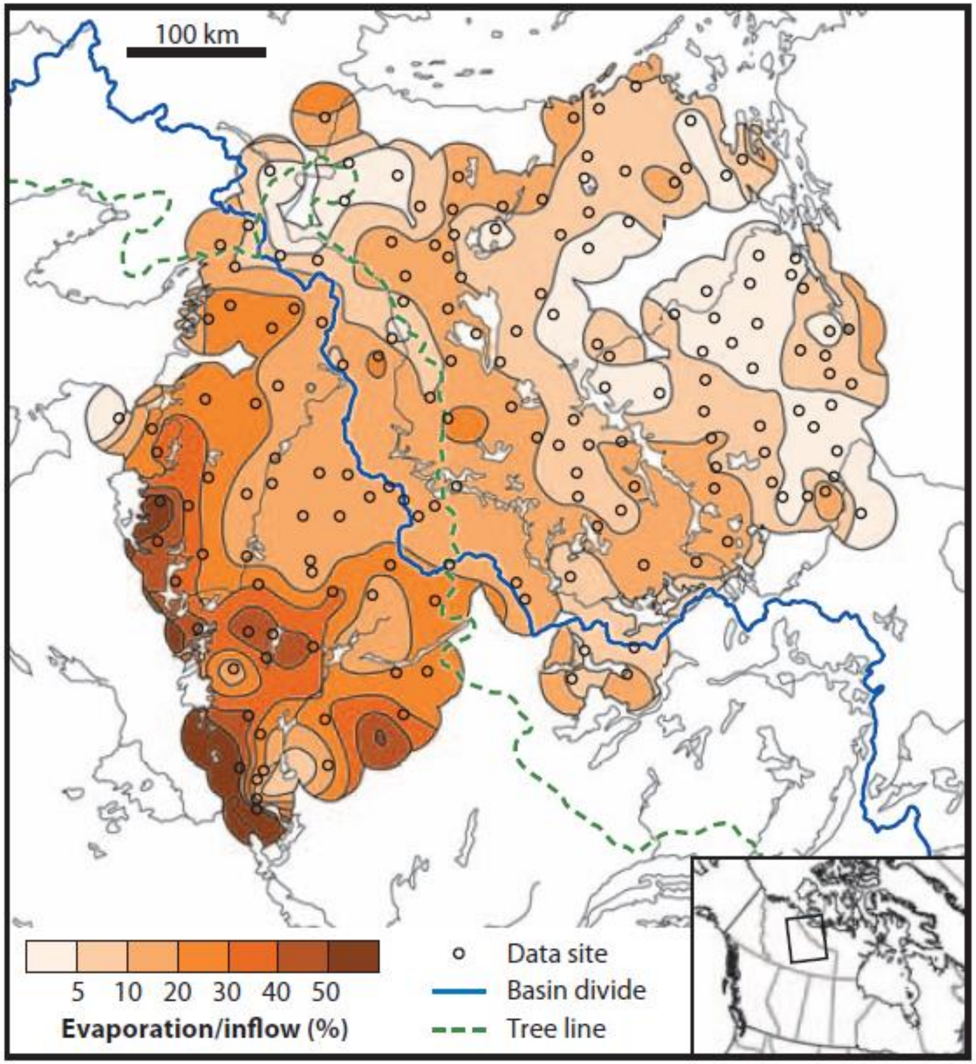
$$I_L = Q_L + E_L$$

$$I_L\delta_I = Q_L\delta_Q + E_L\delta_E$$

$$\frac{E_L}{I_L} = \frac{\delta_I - \delta_L}{\delta_E - \delta_L}$$

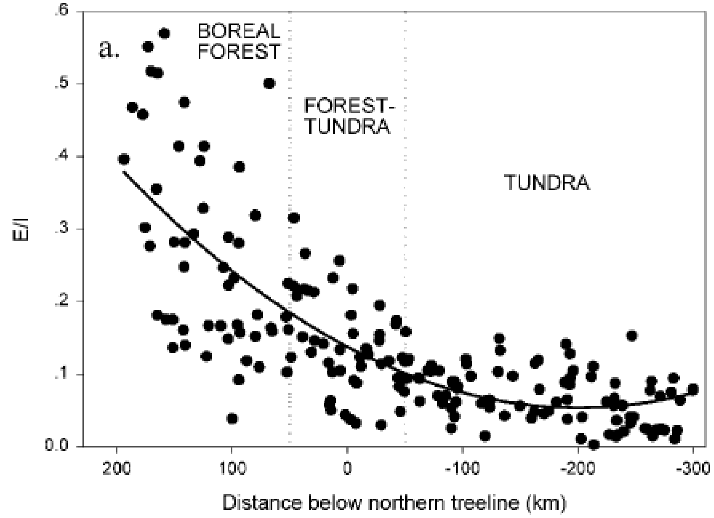
$$\delta_E = \frac{\alpha^*\delta_L - h\delta_A - \varepsilon}{1 - h + 10^{-3}\varepsilon_K}$$

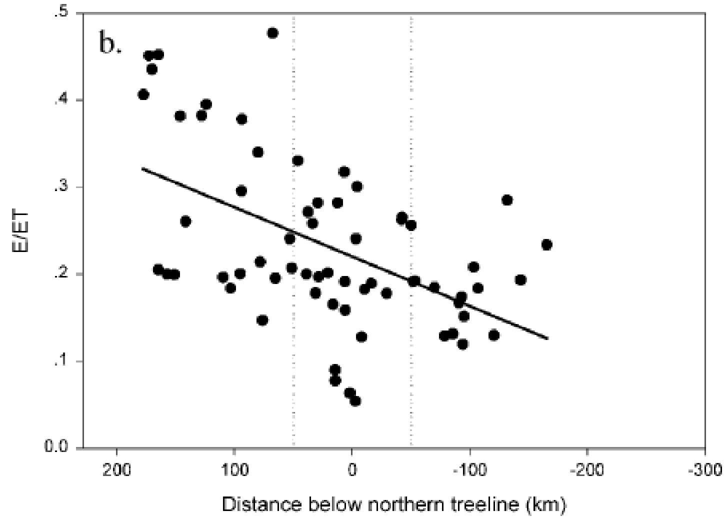
Isoscape-based E/I, Canadian Arctic



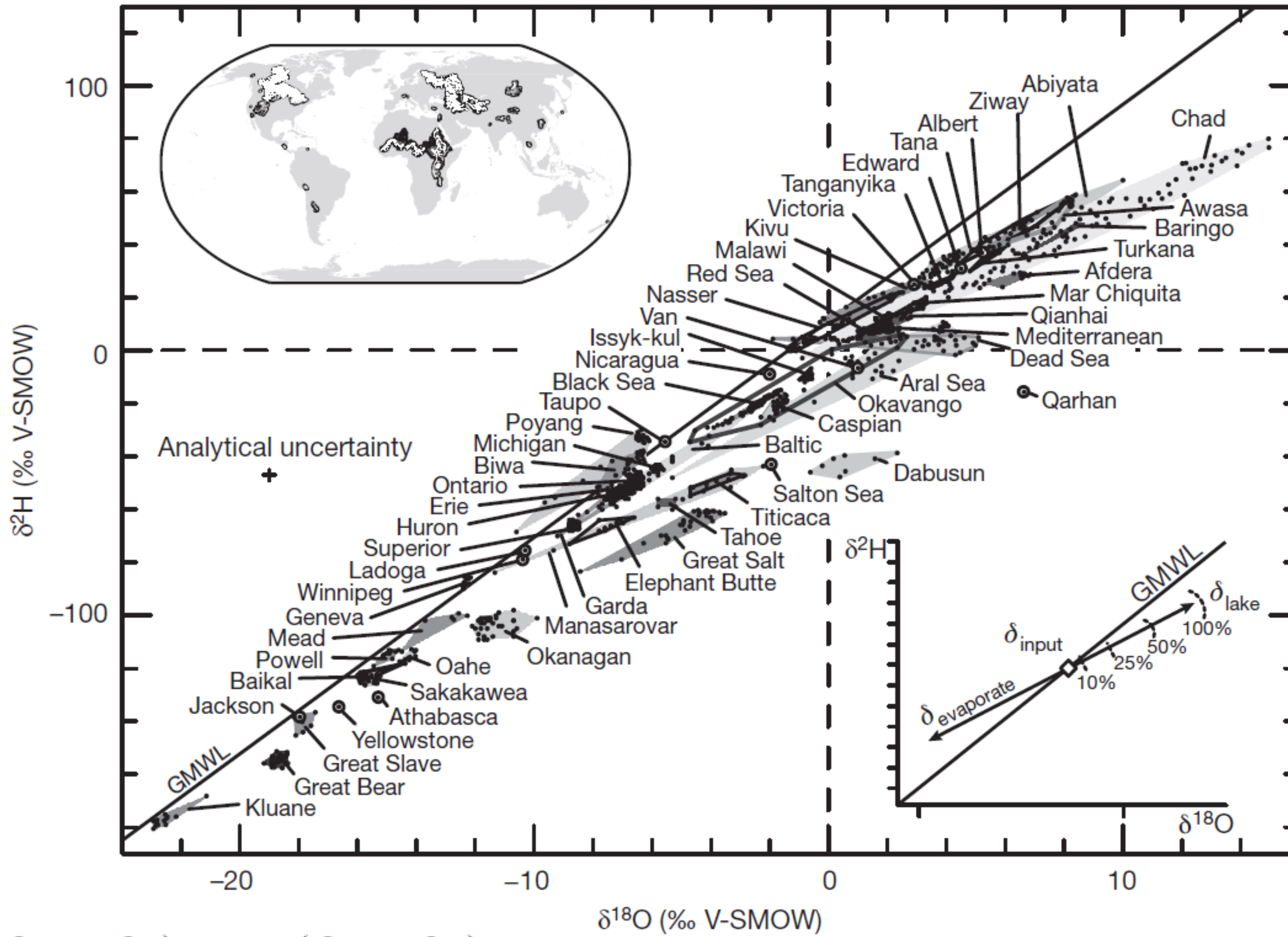
Gibson and Edwards, 2002, *GBC*

Water balance of Arctic lakes





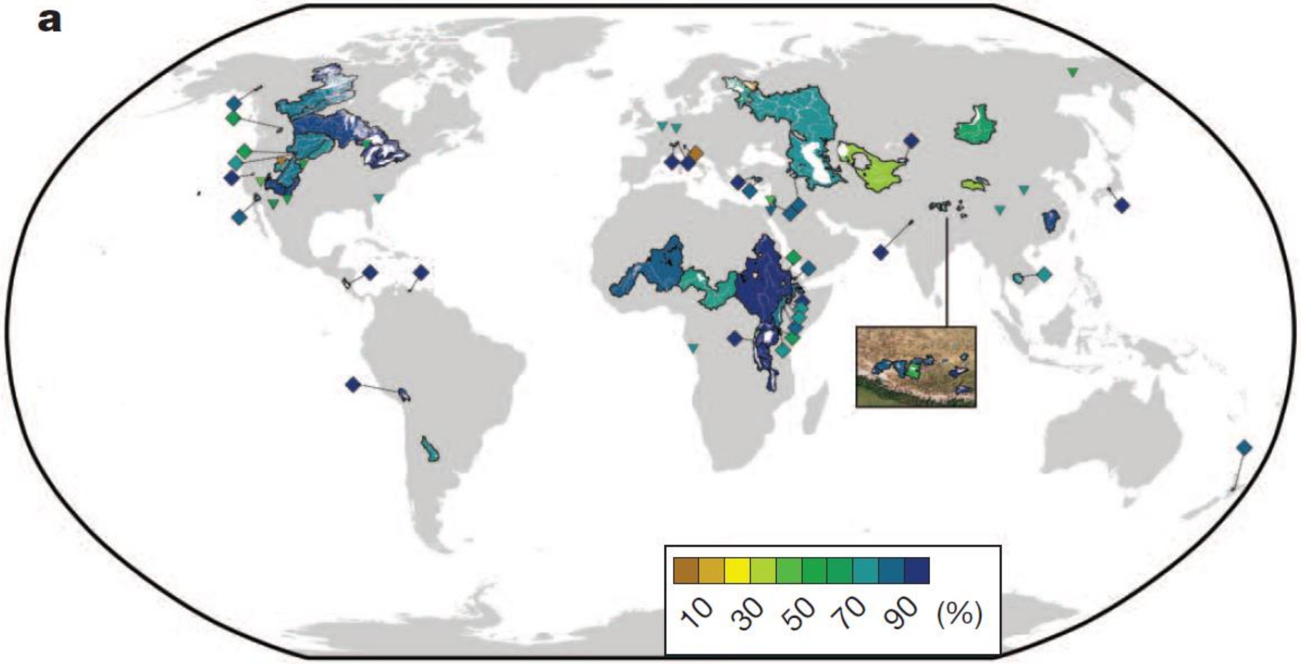
What about the global scale?



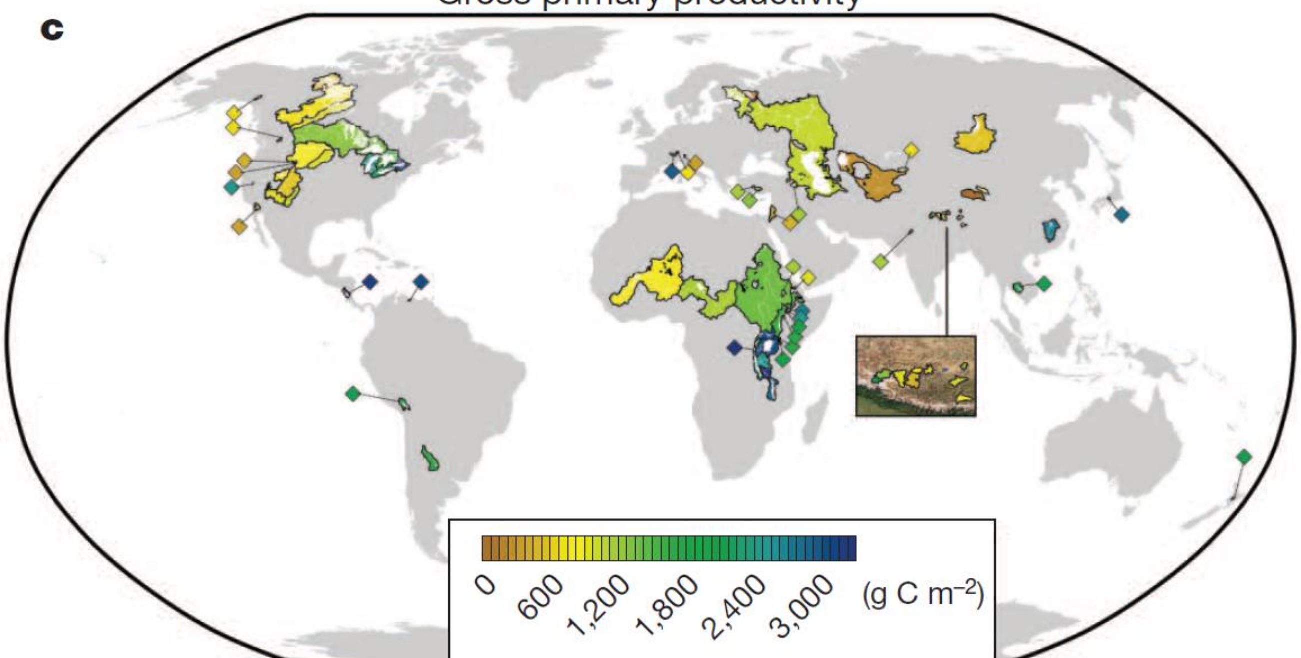
$$T = \frac{I(\delta_I - \delta_E) - Q(\delta_Q - \delta_E) - xP(\delta_P - \delta_E)}{\delta_T - \delta_E}$$

Jasechko et al., 2013, *Nature*

Transpiration relative to evapotranspiration



Gross primary productivity



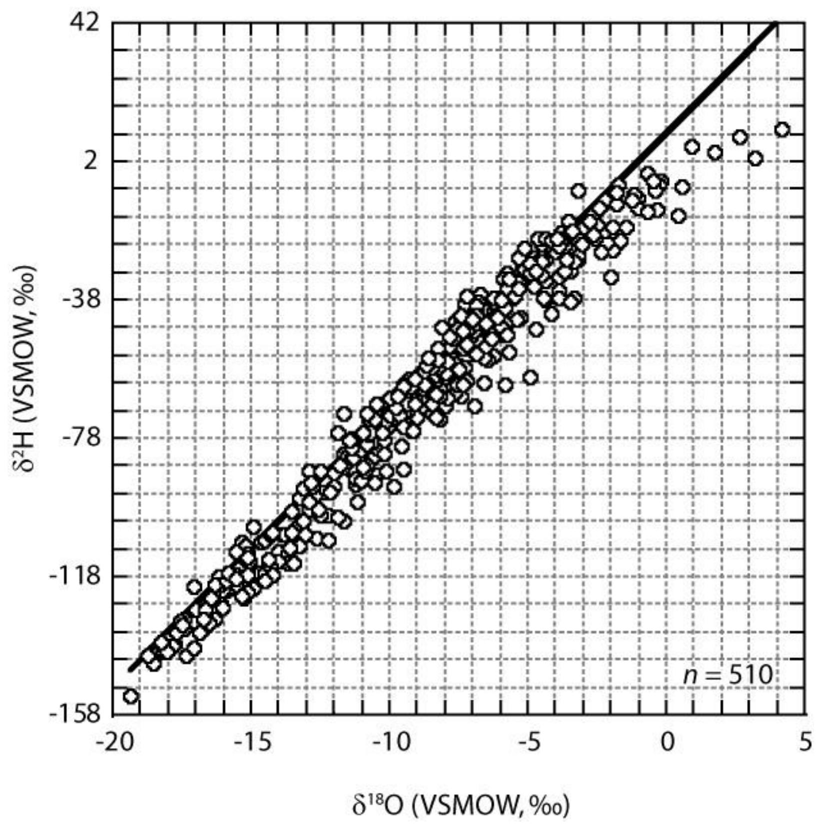
9. The water we drink often comes a long way to reach us

- Where does your water come from?
  - The faucet
  - Yes, but…
- With spatial information isotopes can
  - Establish connectivity
  - Document what happens between the source and sink



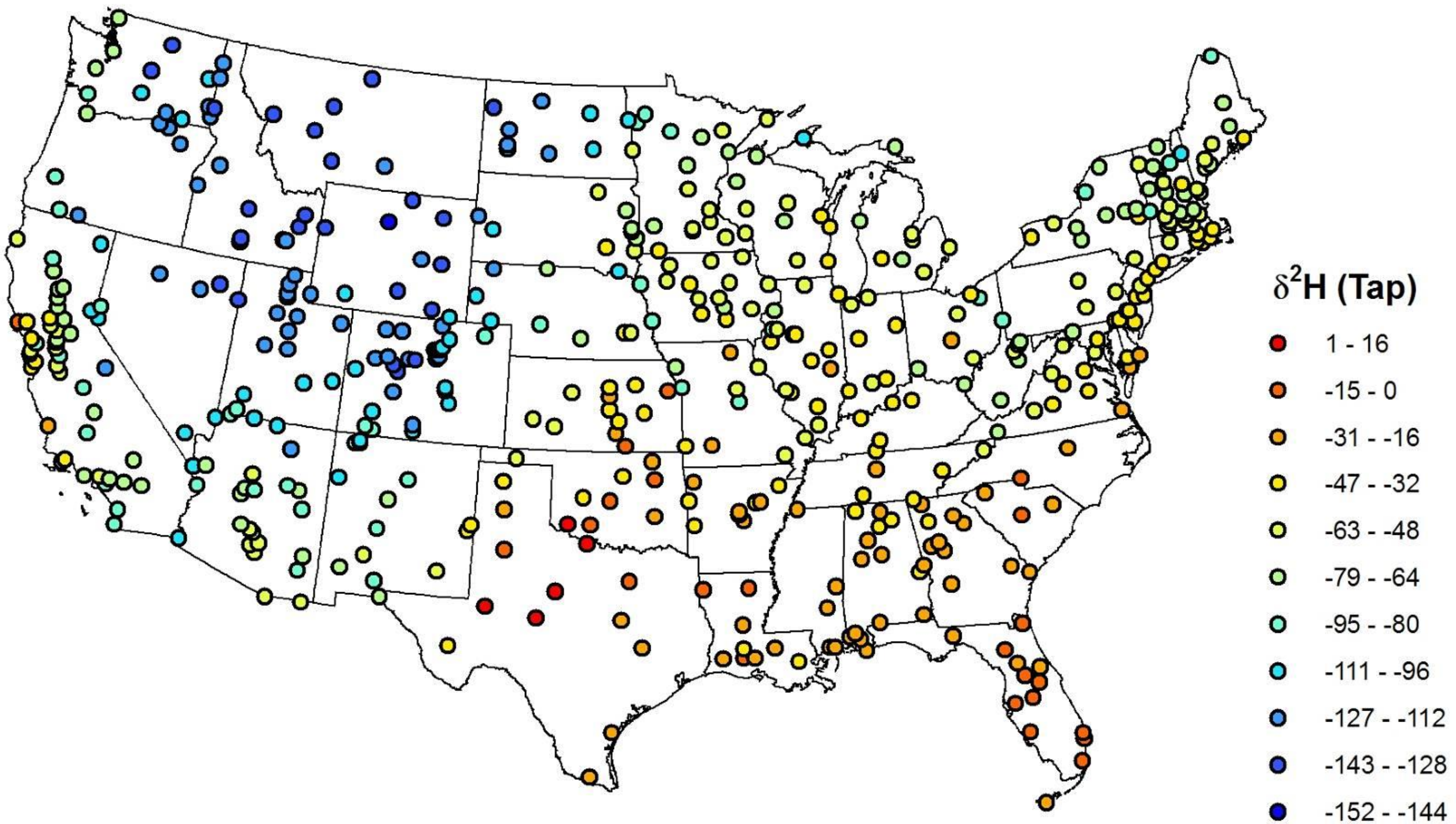
US tap water isotope ratios

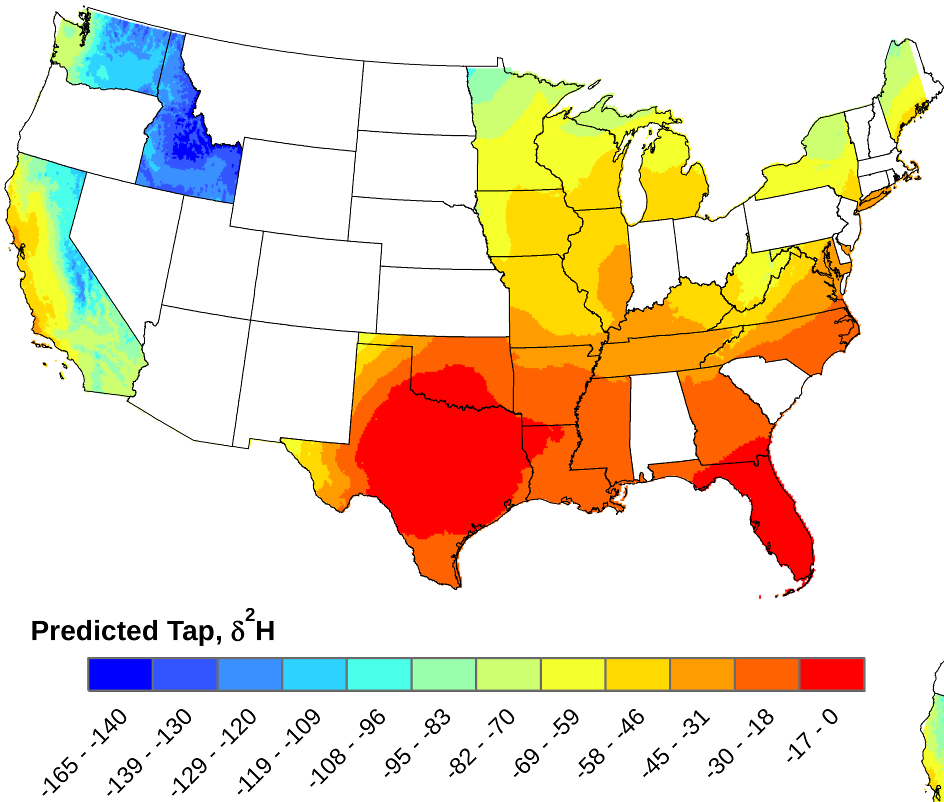
- Range
  - $-152‰ < \delta^2H < +11‰$
  - $-19.4‰ < \delta^{18}O < +4.2‰$
- Cluster near the GMWL
- Average d-excess value of 5 not significantly different from 10

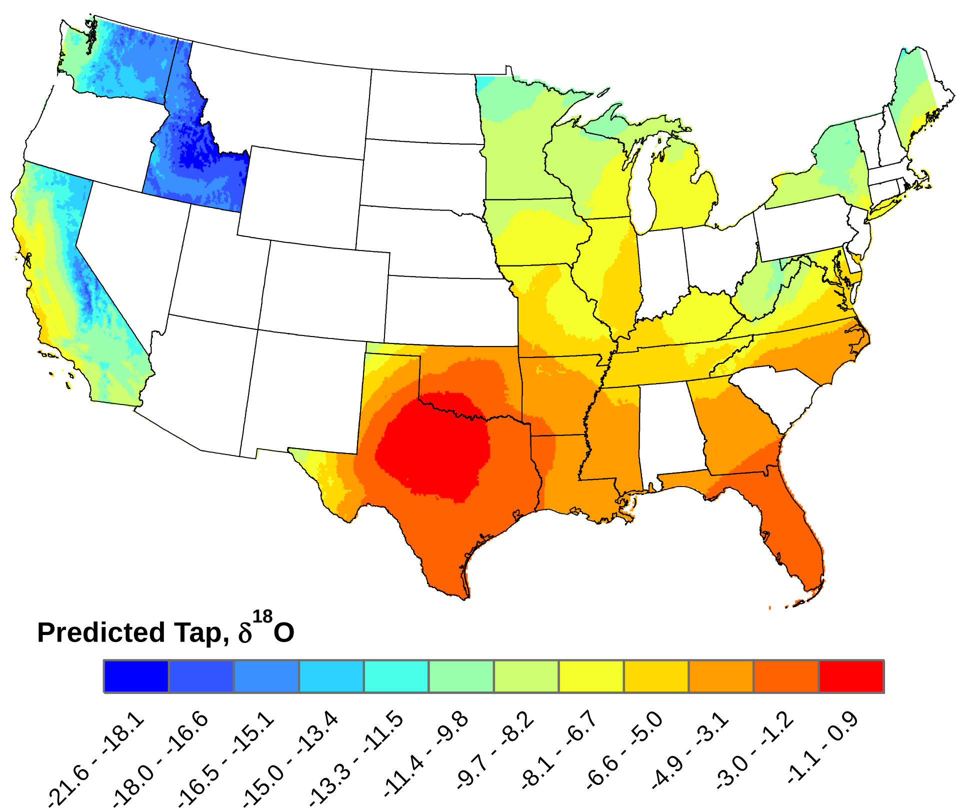


Bowen et al., 2007, *WRR*

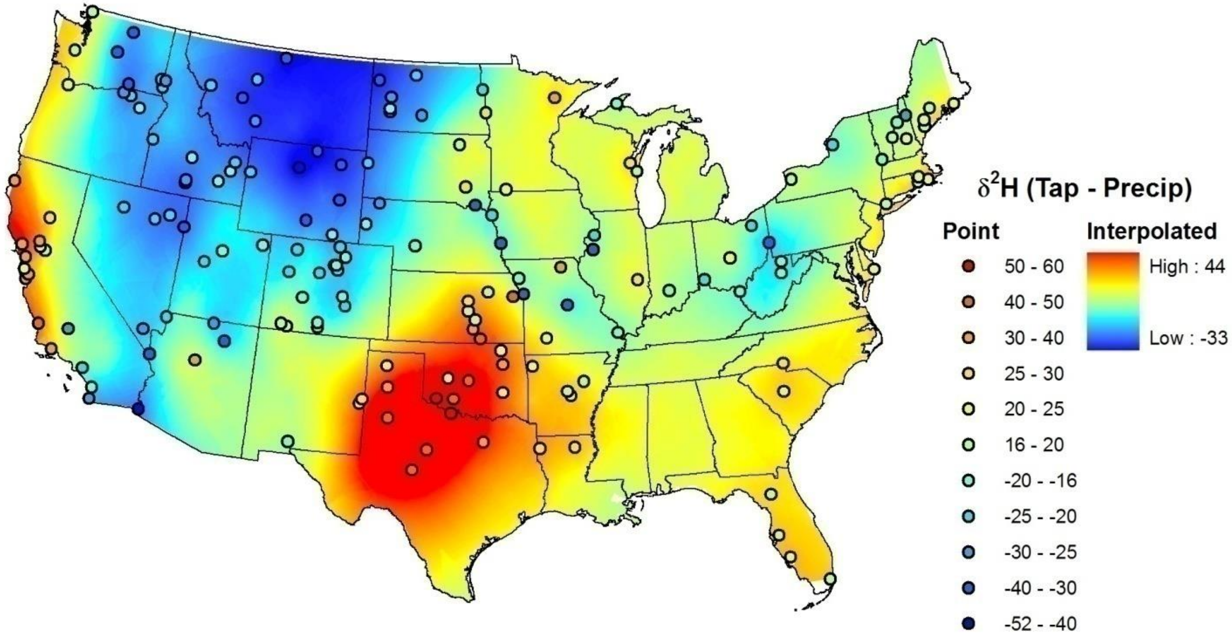
Isotope ratios of US tap waters

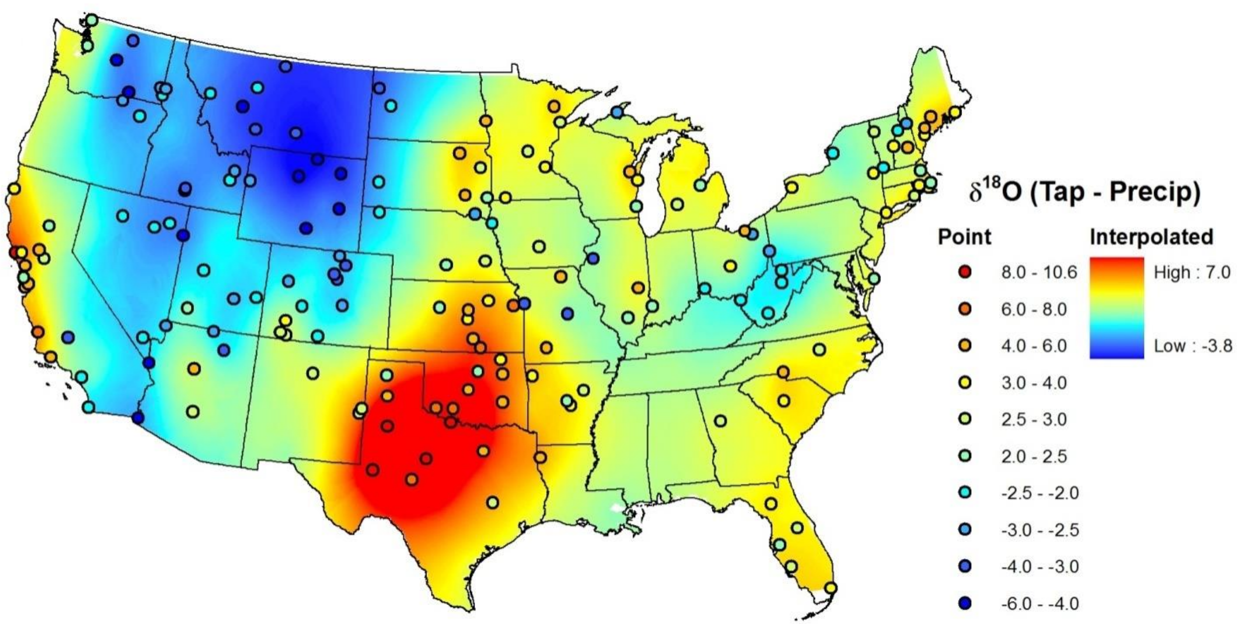



Predicted Tap, δ2H
-165 - -140
-139 - -130
-129 - -120
-119 - -109
-108 - -96
-95 - -83
-82 - -70
-69 - -59
-58 - -46
-45 - -31
-30 - -18
-17 - 0

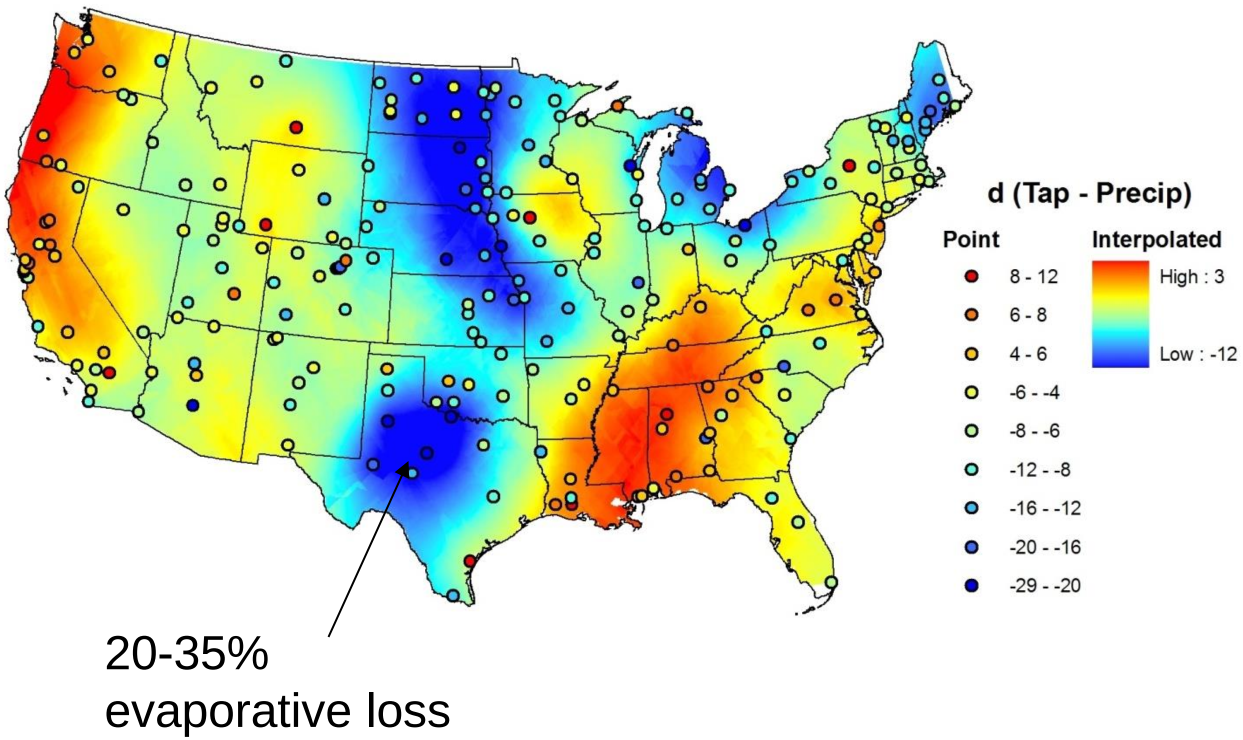

Predicted Tap, δ18O
-21.6 - -18.1
-18.0 - -16.6
-16.5 - -15.1
-15.0 - -13.4
-13.3 - -11.5
-11.4 - -9.8
-9.7 - -8.2
-8.1 - -6.7
-6.6 - -5.0
-4.9 - -3.1
-3.0 - -1.2
-1.1 - 0.9

Tap water vs. local precipitation



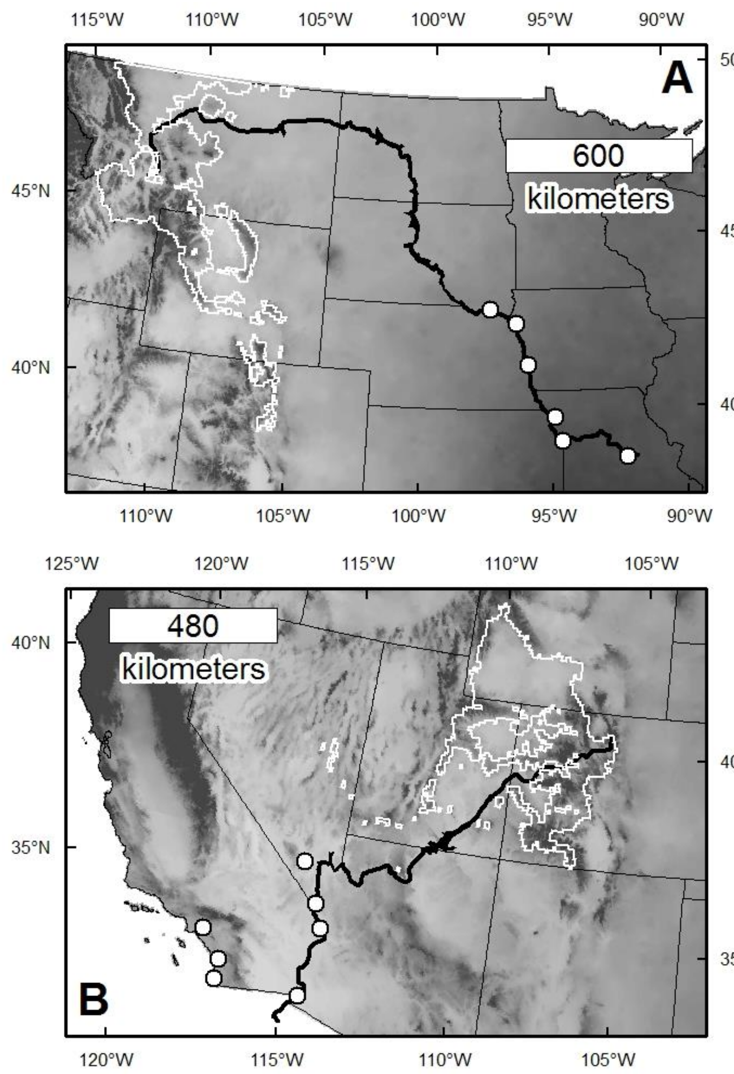


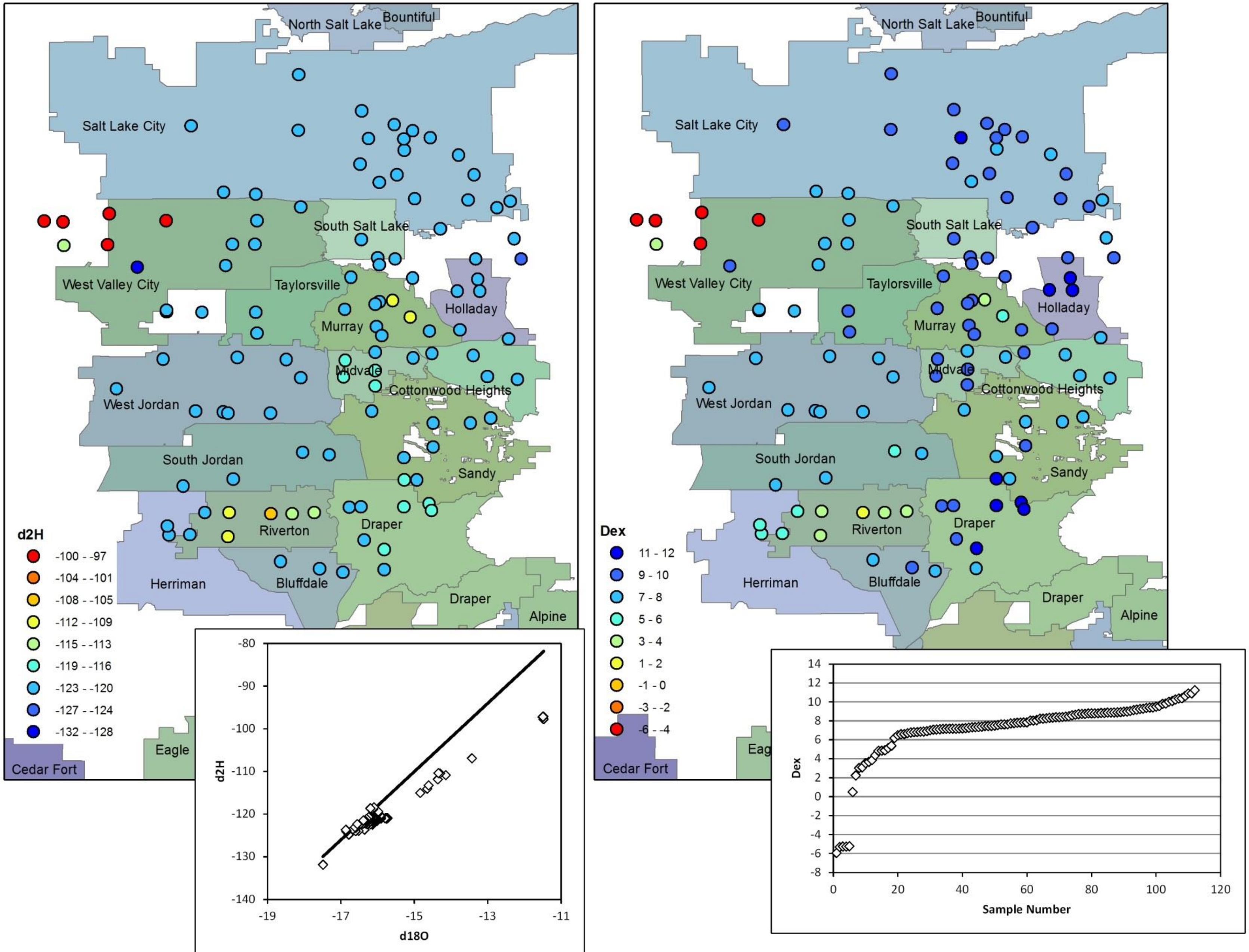
Tap water d values compared to precipitation



Catchment areas: source/sink connectivity

- Characterize source region for water supply
- Map supply footprint of source
- Water sinks 1000+ km removed from mean sources





North Salt Lake
Bountiful
Salt Lake City
South Salt Lake
West Valley City
Taylorsville
Holladay
Murray
Midvale
Cottonwood Heights
West Jordan
South Jordan
Sandy
Draper
Riverton
Herriman
Bluffdale
Alpine
Eagle
Cedar Fort
d2H
-100 - -97
-104 - -101
-108 - -105
-112 - -109
-115 - -113
-119 - -116
-123 - -120
-127 - -124
-132 - -128
d2H
d18O
-80
-90
-100
-110
-120
-130
-140
-19
-17
-15
-13
-11
Dex
11 - 12
9 - 10
7 - 8
5 - 6
3 - 4
1 - 2
-1 - 0
-3 - -2
-6 - -4
Dex
Sample Number
14
12
10
8
6
4
2
0
-2
-4
-6
-8
0
20
40
60
80
100
120